This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

EU Framework Program for Research and Innovation actions (H2020 LCE-21-2015)

Project Nr: 691287

Guiding European Policy toward a low-carbon economy. Modelling sustainable Energy system Development under Environmental And Socioeconomic constraints

D4.2 (D14) MEDEAS European model

Version 1.0.0

Due date of deliverable: 28/02/2108 Actual submission date: 28/02/2018

Disclaimer of warranties and limitation of liabilities

This document has been prepared by MEDEAS project partners as an account of work carried out within the framework of the EC-GA contract no 691287.

Neither Project Coordinator, nor any signatory party of MEDEAS Project Consortium Agreement, nor any person acting on behalf of any of them:

(a) makes any warranty or representation whatsoever, express or implied,

- (i). with respect to the use of any information, apparatus, method, process, or similar item disclosed in this document, including merchantability and fitness for a particular purpose, or
- (ii). that such use does not infringe on or interfere with privately owned rights, including any party's intellectual property, or
- (iii). that this document is suitable to any particular user's circumstance; or

(b) assumes responsibility for any damages or other liability whatsoever (including any consequential damages, even if Project Coordinator or any representative of a signatory party of the MEDEAS Project Consortium Agreement, has been advised of the possibility of such damages) resulting from your selection or use of this document or any information, apparatus, method, process, or similar item disclosed in this document.

MEDEAS

MODELING THE RENEWABLE ENERGY TRANSITION IN EUROPE

Document info sheet

Lead Beneficiary: University of Valladolid

WP: 4, Model building and models implementation

Task: 4.2, MEDEAS European model

Authors:

Ignacio de Blas (UVa)

Iñigo Capellán-Pérez (UVa)

Oscar Carpintero (UVa)

Carlos de Castro (UVa)

Fernando Frechoso (UVa)

Luis Fernando Lobejón (UVa)

Pedro L. Lomas Huertas (UVa)

Margarita Mediavilla (UVa)

Luis Javier Miguel (UVa)

Jaime Nieto (UVa)

Paula Rodrigo González (Uva)

Dissemination level : Public

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Table of contents

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Abstract

This document describes the MEDEAS-Europe simulation model. This model is the main object of deliverable 4.2 of the MEDEAS project. The MEDEAS-Europe model is an integrated energy-economy-environment assessment model that has been developed with the systems dynamics methodology. The model, which has been programmed with the Vensim software, uses as input the results of the simulation of the MEDEAS-World model, with which it is linked. The structure of both models is similar and consists of 7 modules: Economy, Energy, Infrastructures, Materials, Land Use, Social and Environmental Impacts Indicators and GHG Emissions. Among the main novelties of this model with respect to other IAMs are the integration of input-output matrices, feedback between vaiables of the environmental, economic and energy modules and the estimation and feedback of the EROI. In particular, the adaptation to the regional European level includes the representation of trade (at both final goods/services and primary energy level) with the rest of the worls, as well as a simplified representation of the land-use system.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

List of abbreviations and acronyms

2RIOT	Two-region Input-Output tables
BAU	Business as Usual
BG	Best guess
BGS	British Geological Survey
BP	British Petroleum
CAP	Capital compensation
CGE	Computable general equilibrium
Cp	Capacity factor
CSP	Concentrated solar power
EC	European Commission
EJ	Exajoules
EROI	Energy return on energy invested (also EROEI)
EROIext	EROI extended
EROIpou	EROI point of use
EROIst	EROI standard
EU	European Union
EU27	European Union 27 countries
EU28	European Union 28 countries
EV	Electric Vehicle
EXP	Exports

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

FAO	United Nations-Food and Agriculture Organization
FD	Final demand
FEC	Final energy consumption
FED	Final energy demand
FES	Final energy supply
GDP	Gross domestic product
GDPpc	Gross domestic product per capita
GE	Government expenditures
GFCF	Gross fixed capital formation
GHG	Greenhouse Gases
Gm^2	Square gigameters (10^9 m^2)
GWP	Global warming potential
HDI	Human Development Index
HH	Households
HVDC	High voltage direct current
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
IMP	Imports
INVENT	Stock changes
IOA	Input-output analysis
IOT	Input-output table
IPCC	Intergovernmental Panel on Climate Change

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

IRWR	Internal renewable water resources
JRC	European Union Joint Research Center
km^3	Cubic kilometer
ktoe	Thousands of equivalent oil tons
kWh	Kilowatt-hour
LAB	Labor compensation
LPG	Liquefied petroleum gases
Mha	Million hectares
MRIO	Multi-regional input-output
Mt	Million tons
Mtoe	Millions of equivalent oil tons
NRE (NR)	Non-renewable energy
OECD	Organisation for Economic Co-operation and Development
OLT	Optimum level transition
PBL	Netherlands Environmental Assessment Agency
PES	Primary energy sources
PV	Solar photovoltaic energy
RCP	Representative concentration pathways
RES	Renewable energy sources
RF	Radiative forcing
RoW	Rest of the world
RURR	Remaining ultimate recoverable resources

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

SDA	Structural decomposition analysis
SSP	Shared socio-economic pathways
TAX	Taxes
toe	Equivalent-oil tons
TPES	Total primary energy supply
TWe	Electric Terawatt
TWh	Terawatt-hour
UK	United Kingdom
UN	United Nations Organization (also UNO)
UNFCCC	United Nations Framework Convention on Climate Change
UNESCO	United Nations, Educational, Scientific and Cultural Organization
URR	Ultimate recoverable resources
VA	Value Added
WIOD	World input-output database
WIOT	World input-output tables
WP	Work Package

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Executive summary

The objective of the MEDEAS project is to provide simulation tools that facilitate the design of energy policies in Europe to achieve a low carbon economy. One of these key tools is the integrated assessment model (IAM) for Europe, which is the Deliverable 4.2 of the MEDEAS project described in this document.

The MEDEAS-Europe model is not a completely independent model of the MEDEAS-World model, because many of the variables that affect Europe are global variables (for example, global oil resources or the increase in the average temperature of the planet). Therefore, the starting point of the simulations of the MEDEAS-Europe model will be the data obtained from the simulation of the MEDEAS-World model for the corresponding scenarios. The MEDEAS-World model was described in the document corresponding to deliverable 4.1 and it has been taken as reference to build the European model. Both models have been built with the methodology of systems dynamics integrating the economic structure through the Input-Output Tables (IOT). The initial programming of both models has been developed with the Vensim DSS software, but it wiil be translated to python, in order to provide a model in open-source software.

By default, the simulation model of MEDEAS-Europe is designed to be run in the 1995-2050 time window, being the year the unit of time, although internally the simulation has a lower sampling period. Conceptually, the MEDEAS-Europe model is structured in 7 modules:

- Economy and population: the economy of MEDEAS is modelled following a post-Keynesian approach assuming disequilibrium (i.e. non-clearing markets), demand-led growth and supply constraints. The economic structure is capture by the integration of IOA (35 industrial sectors and households).
- Energy: this module includes the renewable and non-renewable energy resources potentials and availability taking into account biophysical and temporal constraints. In total, 5 final fuels are considered (electricity, heat, solids, gases and liquids) and a diversity of energy technologies is modelled. A net energy approach has been followed.
- Energy infrastructures represent the infrastructures of power plants to generate electricity and heat.
- GHG Emissions: this module projects the GHG emissions in the European Union generated by human activities.
- Materials: estimation of the materials required for the construction and O&M of the alternative energy infrastructures.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

- Land-use: it is a simple model oriented to obtain information to estimate the potential for biomass and the potential for solar energy.
- Social and environmental impacts: this module translates the "biophysical" results of the simulations into metrics related with social and environmental impacts. The objective of this module is to contextualize the implications for human societies in terms of well-being for each simulation.

These modules have been programmed in approximately 100 simulation windows and using more than 5,000 variables. The modules of economy and energy are the most extensive and reach the highest degree of disaggregation. The model consists of a modular and flexible structure, where each module can be expanded/simplified/replaced by another version or submodel, new modules can be added, etc.

The scope of the model covers all the challenges that were proposed in the project. Some of these relevant challenges are:

a) Use of information generated by the MEDEAS-World simulation model.
b) Integration of Input-Output Matrices (IOT) in the Economy module.
c) Modeling the commercial relations of Europe through the IOT.
d) EROI estimation and its feedback.
e) Socio-economic indicators model implementation.
f) Supply-demand closures model implementation. The energy shortage determines the feedback between the energy and the economic module.
g) The effects of climate change are feedback into energy consumption.
h) Two standard scenarios have been modelled and implemented. Three other scenarios have been programmed.

Figure 1 shows the Flow chart of the working mode of the European model. The model has shown robustness and consistency in the experimental tests carried out. The first results show a behavior of the European model similar to that obtained in the results of the world model.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

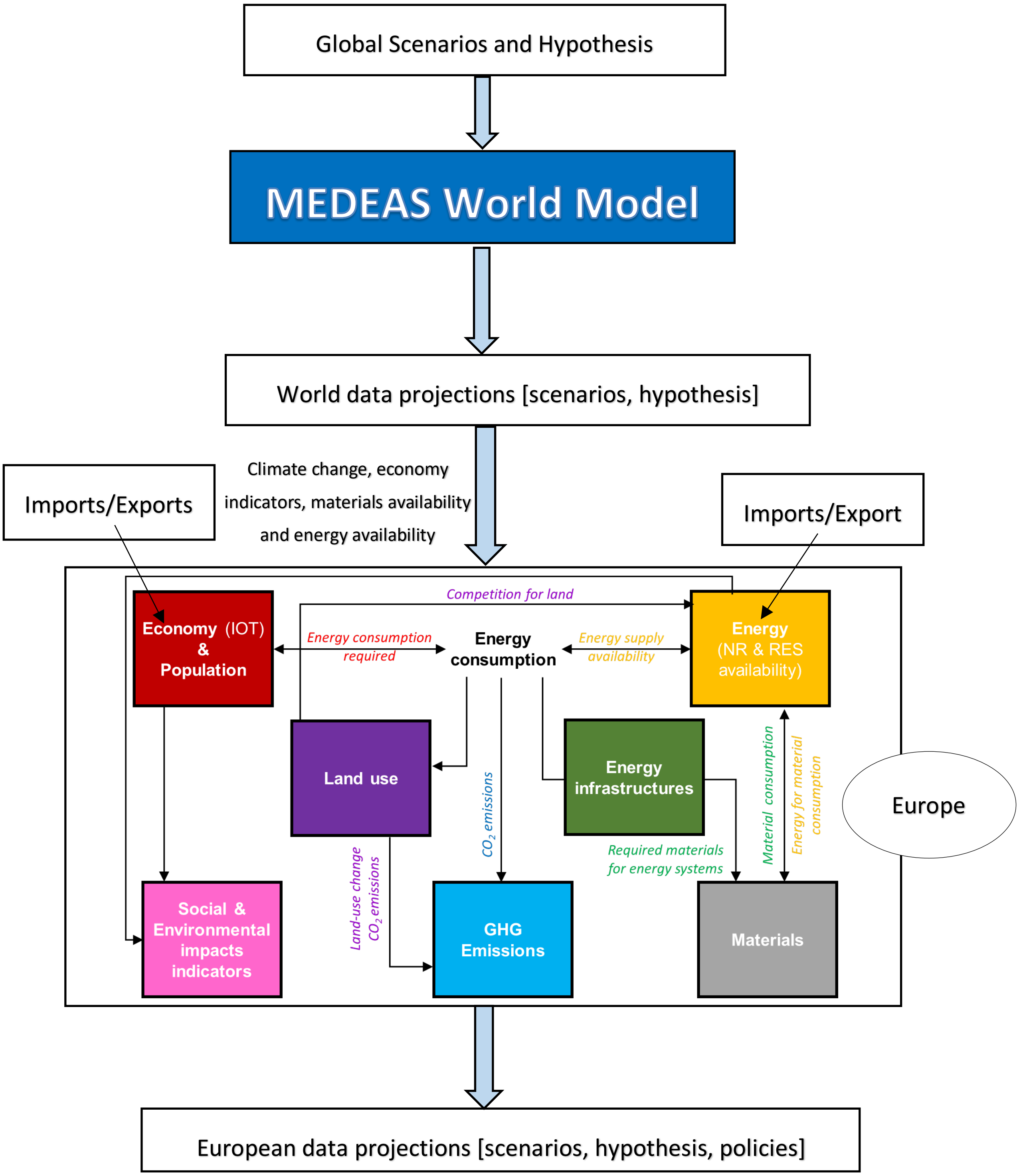


Figure 1. Flow chart representing the working mode of the European model.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

1. Introduction

The main result of this deliverable is a simulation model based on system dynamics that integrates economic, energy and environmental variables at the European Union level (MEDEAS-Europe).

As in the case of World model, it has been programmed in the Vensim software for this first version. The simulation model can be read and run with a Model Reader software that is freely distributable at no cost, licensed by Ventana Systems, Inc.

Conceptually, the model has been divided into 7 submodules: Economy, Energy, Infrastructures, Materials, Land Use, Social and Environmental Impacts Indicators and Emissions. These submodules have been programmed in approximately 100 simulation windows and using more than 5000 variables. The modules of economy and energy are the most extensive and reach the highest degree of disaggregation. The scope of the model covers all the challenges that were proposed in the project. Some of these relevant challenges are:

a) Integration of Input-Output Matrices in the Economy sub-model.
b) EROI estimation and feedback.
c) Socio-economic indicators model implementation.
d) Supply-demand closures model implementation. The energy shortage determines the feedback between the energy and the economic submodule.
e) The effects of climate change are feedback into energy consumption.
f) Two standard scenarios have been modelled and implemented. Three other scenarios have been programmed.

The model obtained can still be modified and expanded, depending on the availability of new data or new information, but the current version provides a solid enough basis to serve as a framework for the European scale model.

Despite the challenges encountered, there are still many limitations and uncertainties. For this reason, the interpretation of the results must be done with caution. This model is not intended to predict the future, but rather to guide qualitatively the best options for the energy transition towards a low-carbon economy. It is a tool to explore strategies, not specific policies, since the latter are applied at a different (reduced) political scale. Despite these limitations, the qualitative interpretation of the results, supported by tools such as the sensitivity analysis, allows guiding the decision making to guide the best possible energy transition.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2. Methodology

2.1. Integration of MEDEAS-EU with MEDEAS-World model

2.1.1. General framework

MEDEAS-Europe model has been built for the European Union spatial context. When referring to European Union, we allude to the European Union-28, which is composed by the following countries (December 2017): Germany, Austria, Belgium, Bulgaria, Cyprus, Croatia, Denmark, Slovakia, Slovenia, Spain, Estonia, Finland, France, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, The Netherlands, Poland, Portugal, United Kingdom, Czech Republic, Romania, and Sweden.

MEDEAS-world and MEDEAS-Europe present differences but are also related. MEDEAS-Europe model will be conceptually integrated in the World model (for more details about world model, see Deliverable 4.1), as represented in the next flow chart (Figure 2).

First, the global hypothesis and scenarios considered in WP3 are introduced to the MEDEAS World model. The results of the World level are the World data projections based on the previous scenarios and hypothesis. These projections, represented here as vectors, are introduced, along with data obtained by the World model, into the MEDEAS European model.

At this stage we need to take into account trade and energy exchanges. In order to do so, imports and exports in economic and energy terms are introduced in the model. In the economy module, imports and exports are introduced through the Input-Output matrix using, at the same time, four submatrices.

As shown in the diagram, the climate change module does no longer exist; therefore, we consider the GHG emissions module instead. The results are the European data projections taking into consideration the scenarios, hypothesis and the related policies.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

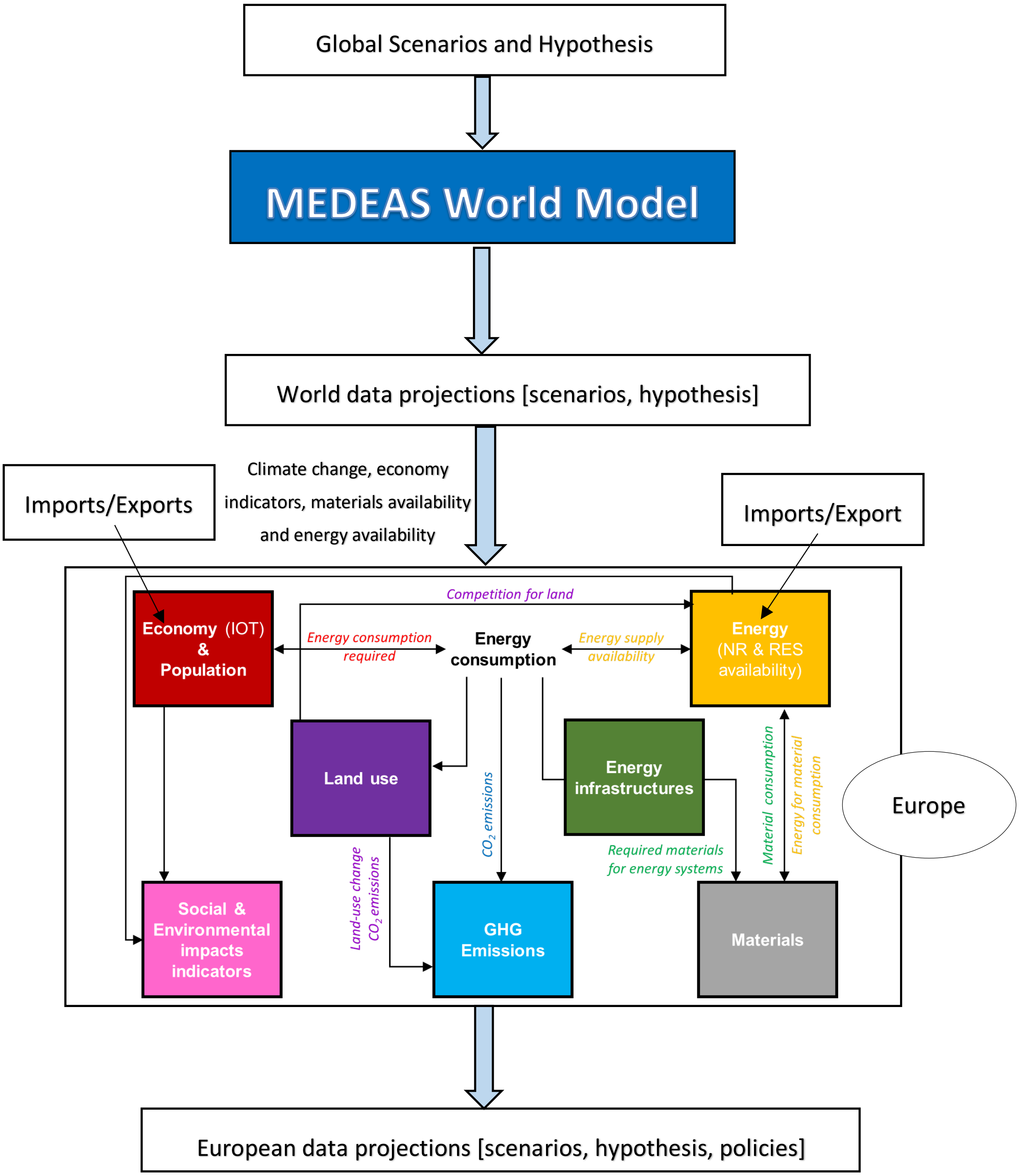


Figure 2. Flow chart representing the working mode of the European model.

The European model structure will be mainly based on the world model. Although the deliverable 4.1 gives a detailed description of the general structure of this model, we will explain the main ideas of each submodule for the European model.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

MEDEAS European model, whose timeframe is 2050, is conceptually structured as shown in Figure 3, with different interrelated modules (represented by boxes). The main variables connecting the different modules are also represented by arrows. Hence, the relationships and feedback in MEDEAS Europe may evolve in the future.

MEDEAS estimates the future "Energy consumption" as a result of confronting the "Final energy consumption required" from the economy (demand side) and the "Final energy supply availability" from the energy systems (supply side). Thus, this adjustment runs feedback over variables in all the modules that eventually have an impact on the economy and energy systems. The feedback-rich structure of the model creates inputs and outputs to the modules.

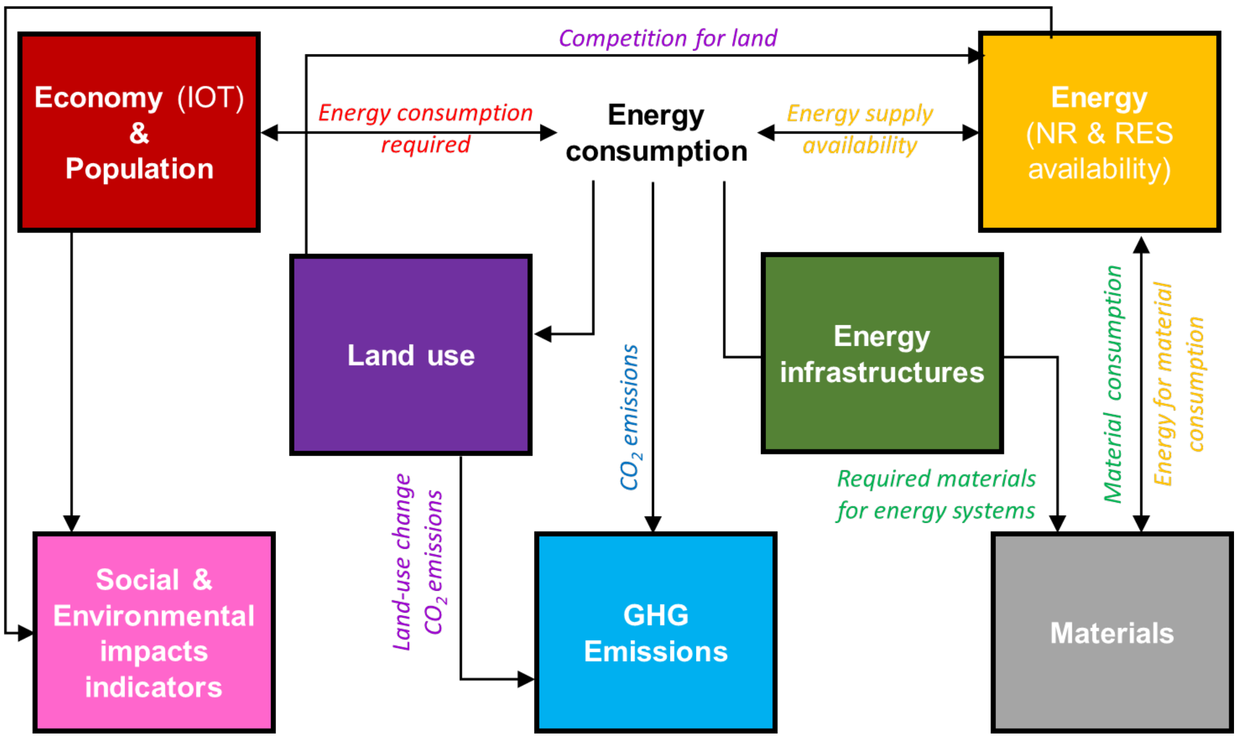


Figure 3. Schematic module interactions within MEDEAS-Europe.

Furthermore, we have to consider imports and exports in the economy and energy modules for the European model. Consequently, "Final energy supply availability" results from the domestic European resources or from abroad (from the rest of the world as a result of imports). Energy consumption is disaggregated in different types of renewable (RES) and non-renewable (NR) energy resources. At the same time, the model computes the Energy Return On Energy Investment (EROEI), the net energy available after discounting the energy invested in its generation. This is a novelty in the field of energy modelling, since most models consider EROEI instead as an exogenous input.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Input-Output Analysis (IOA) is the core of the Economy module. Throughout the Input Output Tables (IOT) and an econometric sectoral demand function, sectorial requirements of consumption and production are going to be estimated. Therefore, Energy consumption is not only expressed by type of energy, but also by economic sectors. In addition, energy intensities will be forecasted for each sector and final energy type, according to the technological and economic development.

The land-use module will consider the required land for renewable sources of energy.

Social and environmental impact indicators will also be obtained for each simulation, which could eventually provide feedback for the economy module. The model takes into account the CO_2 emissions. These emissions are the main input for the GHG emissions module. The materials required for deploying RES and NR technologies will be an important input for the Energy module, as well. In fact, the model is flexible enough to allow any user to apply the data and trends, as they prefer.

Although policies are not represented in Figure 2, they will ultimately be relevant for the model. Policies will provide the framework in which each module develops and let the model run different scenarios.

Generally, the structure of the variables included in each module will follow a similar outline to the ones described for the world model in the Deliverable 4.1

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.1.2. Indicators

In this section, we will go through some indicators related to the world and the European Union, according to the Figure 1. The main goal is to compare both in a quantitative way in order to estimate the European Union's share of each indicator with respect to the world. The following indicators have been considered in total and per capita values:

- Population
- Gross Domestic Product
- Total primary energy consumption
- Oil consumption
- Gas consumption
- Coal consumption
- Electricity consumption
- Wind energy production
- Solar energy production
- Oil reserves
- Gas reserves
- Coal reserves
- CO_2 emissions

The latest available data for these indicators is shown below with a table and a figure representing the EU's share or worldwide values (blue area) for each of them (orange area).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Population

The first indicator considered is the World and European Union population. The total population of a country consists of all people falling within the scope of the census. In the broadest sense, the total may comprise either all the usual residents of the country and all the people present in the country at the time of the census (OECD, 2005). Data for the period between 2010 and 2015 are presented in the Table 1.

Table 1. World and European Union population data. Source: OECD iLibrary

	2010	2011	2012	2013	2014	2015	Percentage
World Population (million people)	6,913.42	6,996.35	7,079.34	7,163.59	7,248.66	7,346.63	100%
EU Population (million people)	503.65	504.77	505.96	506.94	508.13	509.67	7.11%

As shown in the table, the European Union population represents 7.11% out of the total world population. These data are represented in the Figure 4, in which the blue area represents the world, while the orange represents the European Union.

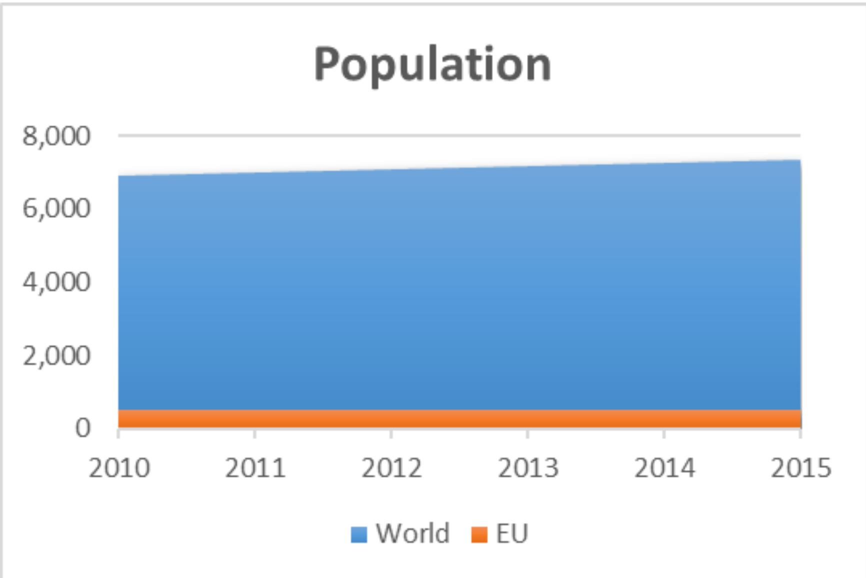


Figure 4. Evolution of the population for the World and the EU-28.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Gross Domestic Product (GDP)

The GDP is an aggregate measure of production, and it equals to the sum of the gross values added by all resident institutional units engaged in production (plus any taxes, and minus any subsidies, on products not included in the value of their outputs) (OECD, 2005).

Gathered data shows the period 2010-2015 (Table 2). In this case, the European Union represented during this period 24.5% out of the world GDP. The data are shown in the Figure 5.

Table 2. World and European Union GDP data (billion 2010 USD using exchange rates). Source: OECD iLibrary.

	2010	2011	2012	2013	2014	2015	Percentage
World GDP	66,018.05	68,104.59	69,797.99	71,590.77	73,547.18	75,488.96	100%
EU GDP	16,977.90	17,260.78	17,179.36	17,217.56	17,504.64	17,889.61	24.50%

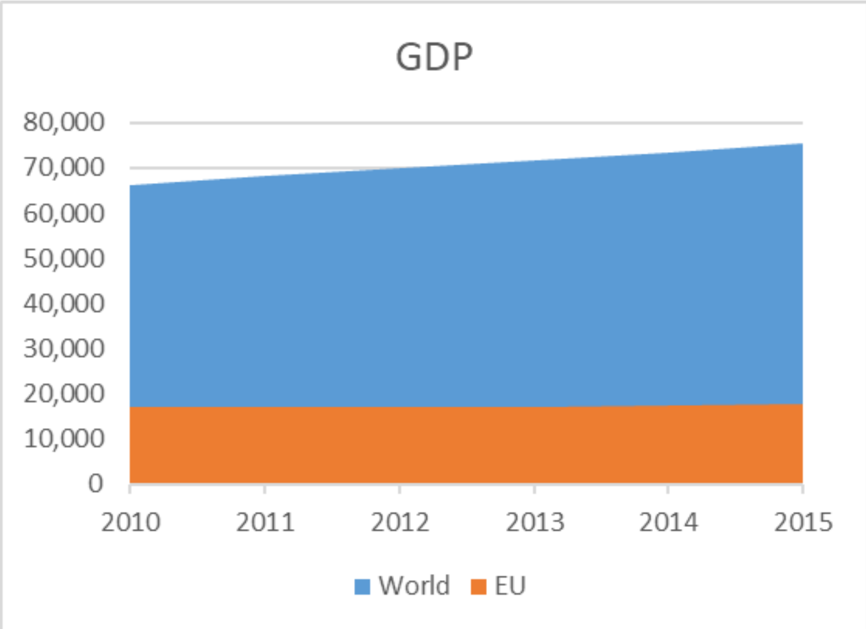


Figure 5. Evolution of the GDP for the World and the EU-28.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Total primary energy consumption

Primary energy comprises commercially traded fuels, including modern renewables used to generate electricity. Oil remains the world's dominant fuel, making up roughly a third of all energy consumed (BP, 2017). Gathered data for the period from 2010 to 2016 measured in million tons of oil equivalent.

Table 3. World and European Union total primary energy consumption data. Source: BP.

	2010	2011	2012	2013	2014	2015	2016	Percentage
World Total primary energy consumption (Mtoe)	12,170	12,455	12,634	12,866	12,989	13,105	13,276	100%
EU Total primary energy consumption (Mtoe)	1,755	1,696	1,681	1,669	1,605	1,627	1,642	13.04%

As seen in the Table 3 and the Figure 6, the European Union consumes 13.04% out of the total world primary energy consumption.

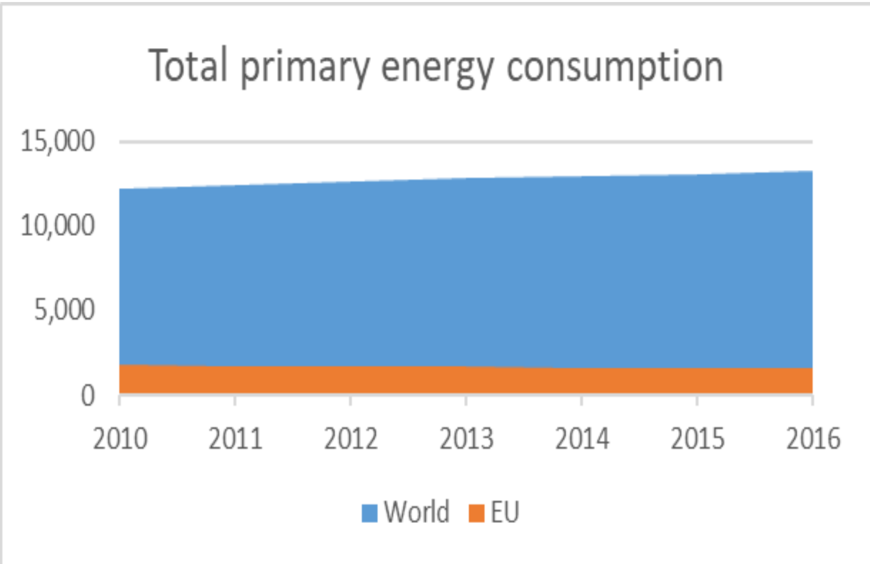


Figure 6. Evolution of the Total Primary Energy consumption in the World and the EU-28.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Oil consumption

Oil remained the world's leading fuel, accounting for a third (33.3%) of global energy consumption. Inland demand plus international aviation and marine bunkers and refinery fuel and loss. Consumption of biogasoline (such as ethanol), biodiesel and derivatives of coal and natural gas are also included (BP, 2017). Data for years 2010 to 2016 are given in millions of metric tons (Table 4).

Table 4. World and European Union oil consumption data. Source: BP.

	2010	2011	2012	2013	2014	2015	2016	Percentage
World Oil consumption (million tons)	4,085.42	4,125.73	4,176.18	4,220.85	4,254.83	4,340.96	4,418.25	100%
EU Oil consumption (million tons)	664.98	644.46	618.75	601.73	590.78	600.56	613.28	14.63%

The European Union accounts for 14.63% out of the total world oil consumption (Figure 7).

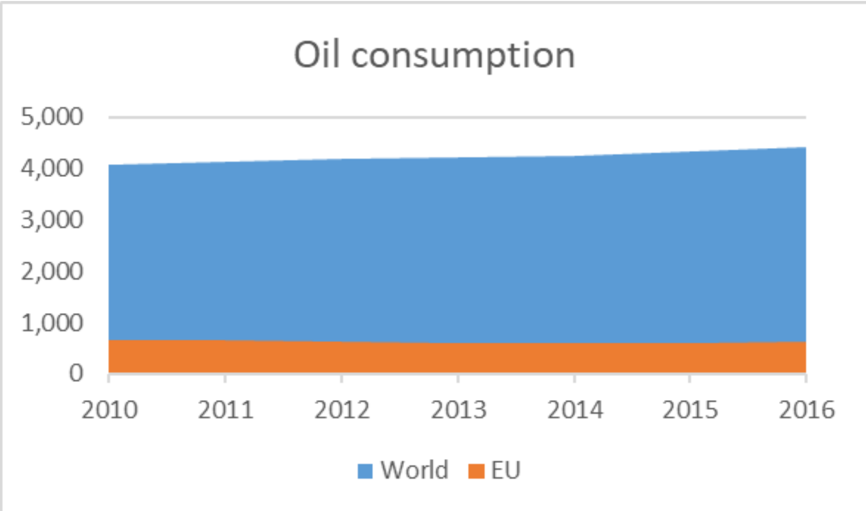


Figure 7. Evolution of the oil consumption in the World and the EU-28.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Gas consumption

Natural gas consumption excludes natural gas converted to liquid fuels, but includes derivatives of coal as well as natural gas consumed in gas-to-liquids transformation (BP, 2017). Gathered data for the period between 2010 and 2016 expressed in million tons of oil equivalent (Mtoe) (Table 5).

Table 5. World and European Union gas consumption data. Source: BP.

	2010	2011	2012	2013	2014	2015	2016	Percentage
World Natural Gas Consumption (Mtoe)	2,874.25	2,926.32	3,010.51	3,054.36	3,072.99	3,146.75	3,204.14	100%
EU Natural Gas Consumption (Mtoe)	448.09	404.73	394.71	388.08	344.72	359.22	385.91	12.80%

As it can be seen in the table, the European Union represents 12.8% out of the total world natural gas consumption. Data about natural gas consumption is represented in the Figure 8.

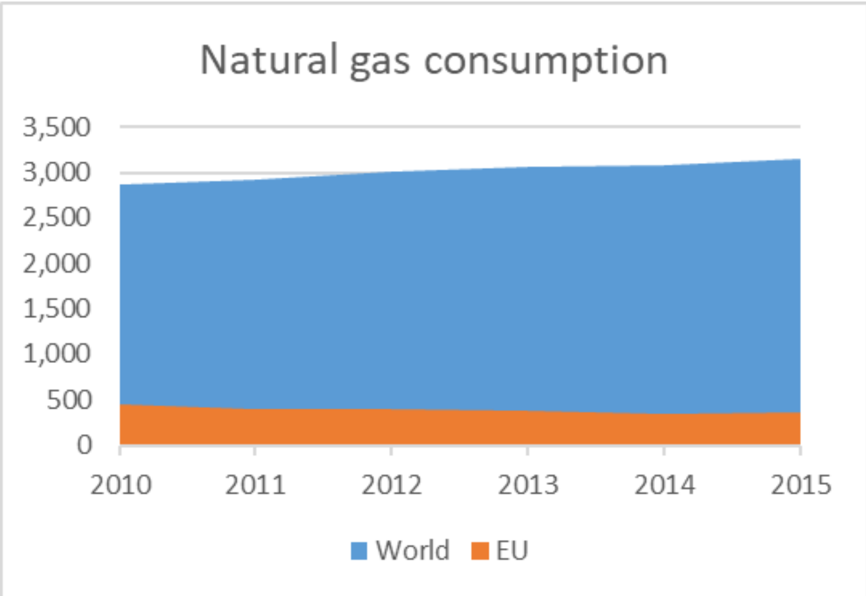


Figure 8. Evolution of Natural gas consumption in the World and the EU-28.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Coal consumption

Coal consumption includes data for solid fuels only. Included in the hard coal category are bituminous and anthracite. The sub-bituminous coal includes lignite and brown coal. Other commercial solid fuels are also included (BP, 2017). We have collected data for the period between 2010 and 2016 expressed in million tons of oil equivalent (Mtoe) (Table 6).

Table 6. World and European Union coal consumption data. Source: BP.

	2010	2011	2012	2013	2014	2015	2016	Percentage
World Coal consumption (Mtoe)	3,635.64	3,807.19	3,817.29	3,886.97	3,889.42	3,784.65	3,732.00	100%
EU Coal consumption (Mtoe)	280.18	288.12	294.30	287.95	268.41	261.15	238.44	7.23%

In this case, the European Union represents 7.23% out of the total world coal consumption, and the data is illustrated in the Figure 9.

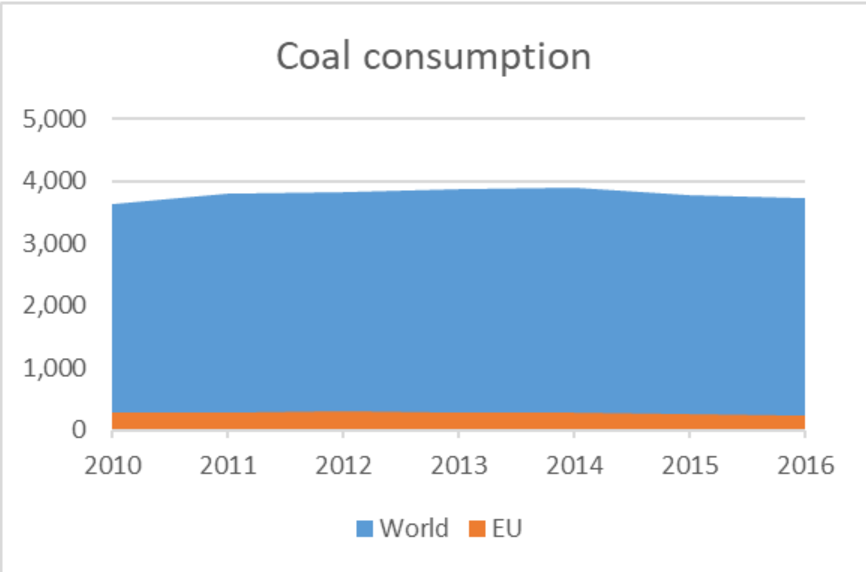


Figure 9. Evolution of Coal consumption in the World and the EU-28.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Electricity consumption

Electricity consumption increased almost 13% worldwide during the five-year period (2010-2015). However, this balance is negative in the European Union, where electricity consumption has decreased by 4%. In the following table, we can see the data collected for the period between 2010 and 2015 in TWh (Table 7).

Table 7. World and European Union electricity consumption data. Source: OECD iLibrary.

	2010	2011	2012	2013	2014	2015	Percentage
World Electricity consumption (TWh)	19,820.13	20,480.55	20,918.95	21,560.32	22,009.77	22,385.81	100%
EU Electricity consumption (TWh)	3,161.25	3,098.76	3,104.5	3,071.66	3,004.15	3,041.08	14.53%

The European Union represents 14.53% out of the total world electricity consumption. This proportion is pictured in the next figure (Figure 10), taking into account data gathered in the table.

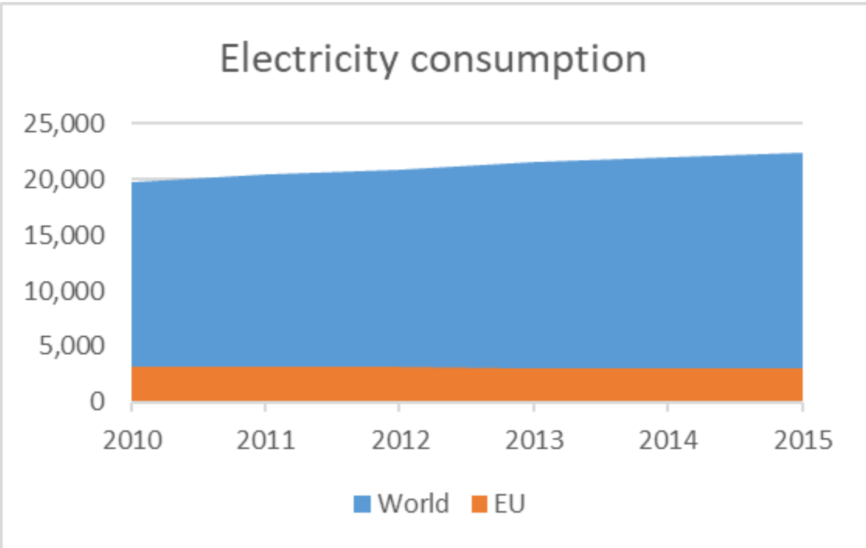


Figure 10. Evolution of the Electricity consumption in the World and the EU-28.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Wind energy production

The next indicator is wind energy production. Regarding the collected data, world wind production has more than doubled in five years (2010-2015). This trend is shared by the European Union, where wind production doubled in the same period (2010-2015). Collected data shown in the next table are presented in thousand tons of oil equivalent (ktoe) (Table 8).

Table 8. World and European Union wind energy production data. Source: OECD iLibrary.

	2010	2011	2012	2013	2014	2015	Percentage
World Wind production (ktoe)	29,355	37,457	45,049	55,533	61,730	72,070	100%
EU Wind production (ktoe)	12,845	15,452	17,718	20,360	21,767	25,961	38.47%

The European Union represents 38.47% out of the total world wind production. This proportion is represented in the Figure 11.

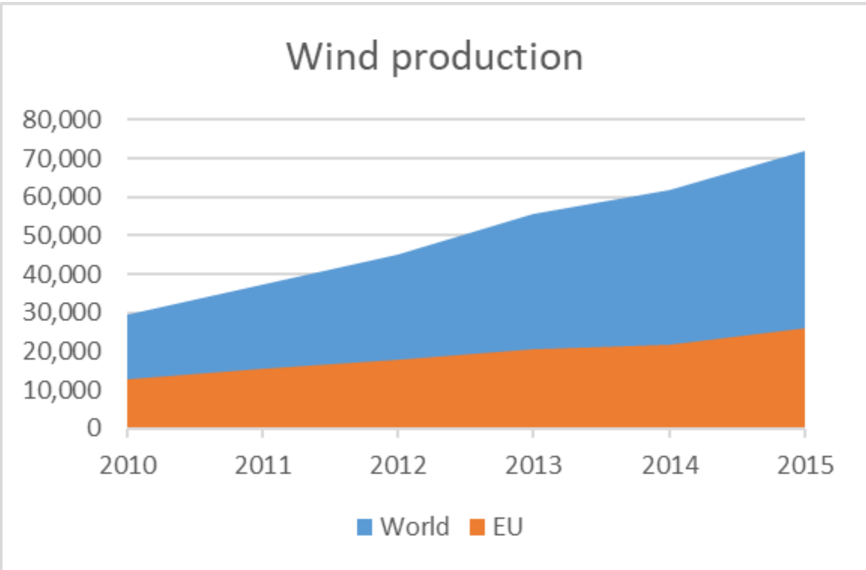


Figure 11. Evolution of Wind energy production in the World and the EU-28.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Solar energy production

Solar energy production has had a substantial increase from 2010 to 2014 both in the world and in the European Union. In the world, solar production has been multiplied by 2.6 and in the European Union solar production has increased 3.2 times during the same period. This information is shown in the next table where the data is given in thousand tons of oil equivalent (ktoe) (Table 9).

Table 9. World and European Union solar energy production data. Source: OECD iLibrary.

	2010	2011	2012	2013	2014	Percentage
World Solar production (ktoe)	18,565.216	24,471.019	31,079.483	41,224.068	47,713.427	100%
EU Solar production (ktoe)	3,716.941	6,037.626	9,009.013	10,643.07	12,008.665	25.40%

The European Union solar production represents 25.4% out of the total world solar production. It can be seen in the Figure 12.

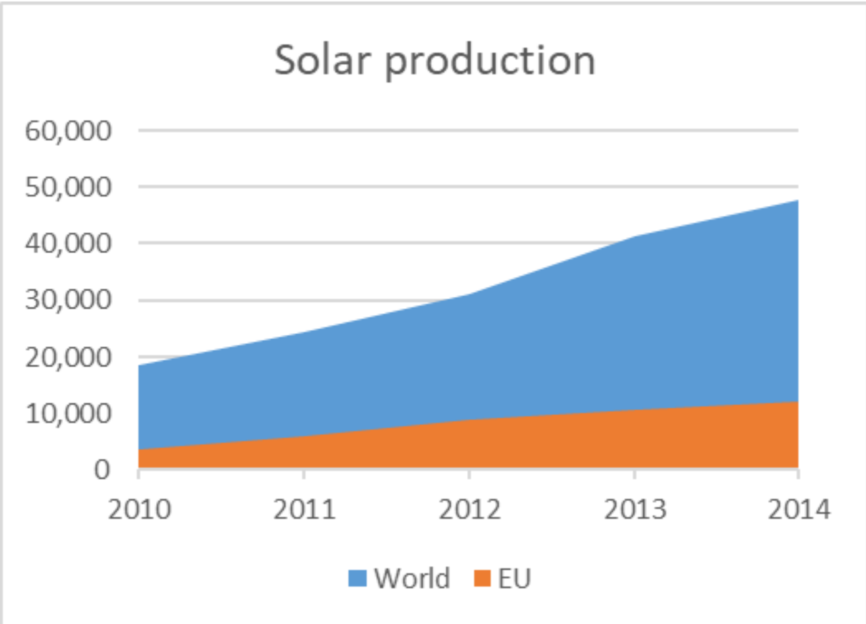


Figure 12. Evolution of Solar energy production in the World and the EU-28.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Oil reserves

Total proved reserves of oil are generally taken to be those quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known reservoirs under existing economic and geological conditions. Oil reserves include field condensate and natural gas liquids as well as crude oil (BP, 2017). In the following table, data for the period between 2010 and 2016 are represented (Table 10).

Table 10. World and European Union oil reserves data. Source: BP.

	2010	2011	2012	2013	2014	2015	2016	Percentage
World Oil reserves (thousand million barrels)	1,642	1,681	1,695	1,702	1,707	1,691	1,707	100%
EU Oil reserves (thousand million barrels)	6.00	6.17	5.95	5.85	5.64	5.23	5.05	0.34%

As it can be seen in the table, the European Union represent only a small and decreasing proportion (0.34%) out of total world oil reserves and is shown in the next figure (Figure 13).

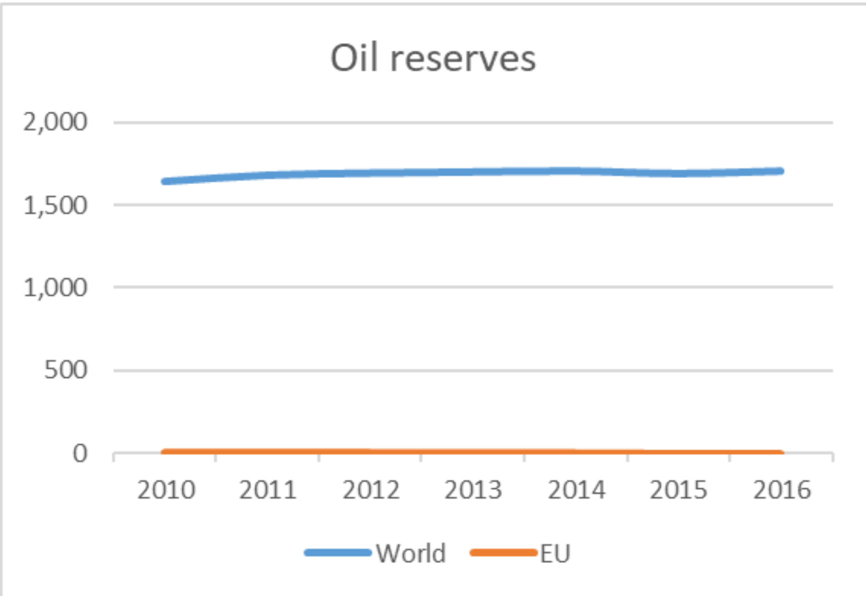


Figure 13. Evolution of Oil reserves in the World and the EU-28.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Gas reserves

Total proved reserves of natural gas are generally taken to be those quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known reservoirs under existing economic and operating conditions (BP, 2017).

Data are measured in trillion cubic meters, and they have been represented for the period between 2010 and 2016 (Table 11).

Table 11. World and European Union gas reserves data. Source: BP.

	2010	2011	2012	2013	2014	2015	2016	Percentage
World Natural Gas: Proved reserves (trillion cubic metres)	176.25	185.39	184.35	185.82	187.18	185.42	186.57	100%
EU Natural Gas: Proved reserves (trillion cubic metres)	2.36	1.78	1.52	1.44	1.31	1.30	1.28	0.85%

As shown in the table, the EU natural gas reserves mean 0.85% out of the total world natural gas reserves. The pattern of depletion is represented in the Figure 14.

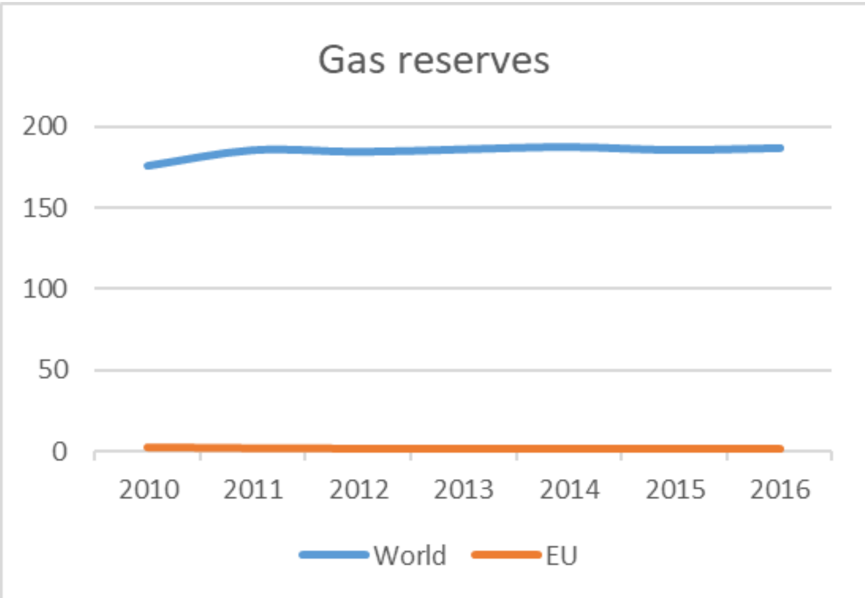


Figure 14. Evolution of Gas reserves in the World and the EU-28.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Coal reserves

Total proved reserves of coal are generally taken to be those quantities that geological and engineering information indicates with reasonable certainly can be recovered in the future from known deposits under existing economic and operating conditions. Total proved coal reserves are shown for anthracite and bituminous (including brown coal) and sub-bituminous and lignite (BP, 2017). Coal reserves data are presented in million tons and given for the end of 2015 (Table 12).

Table 12. World and European Union GDP data. Source: BP.

	End 2015	Percentage
World Coal: Proved reserves (million tons)	891,531	100%
EU Coal: Proved reserves (million tons)	56,082	6.29%

The EU coal reserves take up 6.29% out of the total world coal reserves. Data are represented by a barcode in this case (Figure 15).

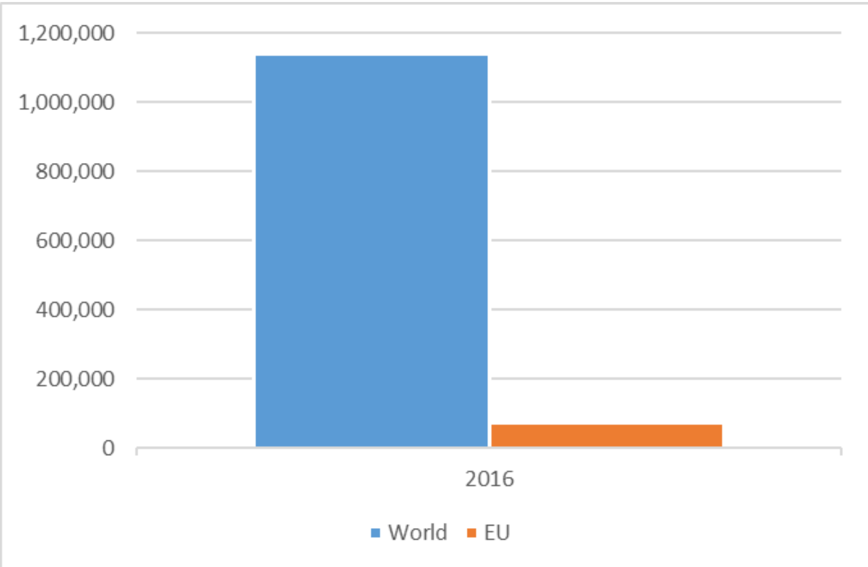


Figure 15. Coal reserves in 2016 for the World and the EU-28.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

CO_2 emissions

In this case, world carbon dioxide emissions have increased by 6% during the last seven years (2010-2016), whereas European Union CO_2 emissions have decreased by 11%. These data are shown in the Table 13.

Table 13. World and European Union CO_2 emissions data. Source: BP.

	2010	2011	2012	2013	2014	2015	2016	Percentage
World Carbon Dioxide emissions (million tons carbon dioxide)	31,528	32,413	32,760	33,226	33,343	33,304	33,432	100%
EU Carbon Dioxide emissions (million tons carbon dioxide)	3,933	3,805	3,739	3,655	3,443	3,477	3,485	11.1%

The European Union CO_2 emissions represent 11.1% out of the total world carbon dioxide emissions. This proportion can be seen in the Figure 16.

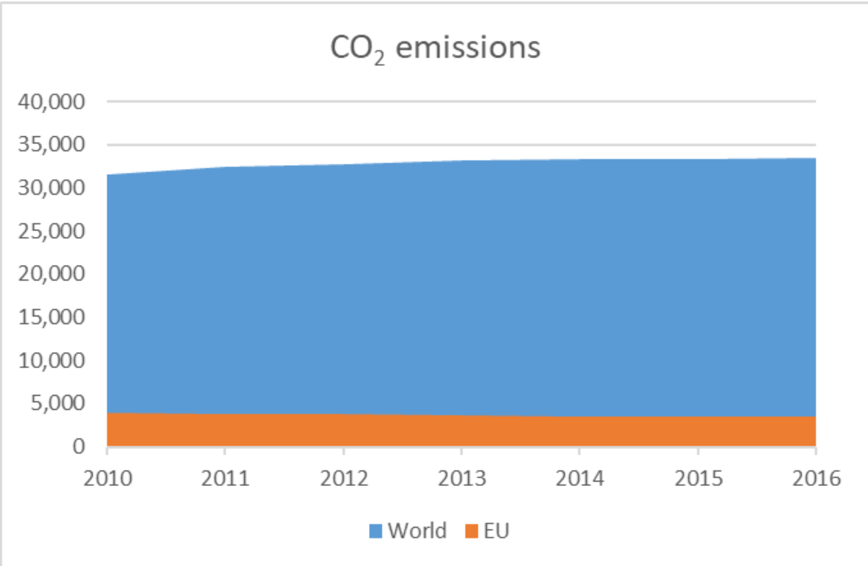


Figure 16. Evolution of CO_2 emissions in the World and the EU-28.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Gross Domestic Product per capita

For the period between 2010 and 2015, the total world GDP per capita has increased by almost 8%. The European Union has increased its GDP per capita by 4%. These data are shown in the following table and expressed in constant 2010 US$.

Table 14. World and European Union GDP per capita data. Source: World Bank.

	2010	2011	2012	2013	2014	2015	Ratio
World GDP per capita (constant 2010 US$)	9,549.5	9,735	9,859.7	9,994.8	10,148.2	10,293.3	1.00
EU GDP per capita (constant 2010 US$)	33,709.7	34,195.3	33,952.6	33,960.4	34,448.5	35,105.2	3.45

As shown in the table, the GDP per capita in the European Union is almost 3.5 times higher than the GDP per capita in the world. This relation is shown in the Figure 17.

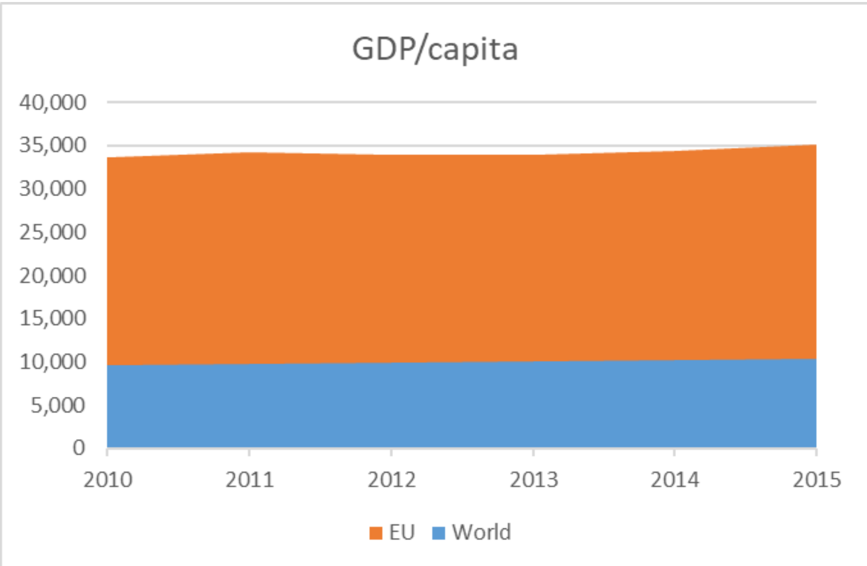


Figure 17. Evolution of GDP per capita in the World and the EU-28.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Primary energy consumption per capita

The data of primary energy consumption per capita represented in the table for the period between 2010 and 2015 is expressed in tons of oil equivalent per capita (toe per capita) (Table 15). The primary energy consumption per capita in the world has undergone a small increase of about 1.5%, whereas the primary energy consumption per capita in the European Union has experienced a decrease of 8%.

Table 15. World and European Union primary energy consumption per capita data. Source: Own elaboration with data from BP and OECD iLibrary.

	2010	2011	2012	2013	2014	2015	Ratio
World Primary energy per capita consumption (toe per capita)	1.76	1.78	1.78	1.80	1.79	1.79	1.00
EU Primary energy per capita consumption (toe per capita)	3.48	3.36	3.32	3.29	3.16	3.19	1.85

As shown in the Table, 15 the primary energy consumption per capita in the European Union is 1.85 times higher than in the rest of the world. This proportion can be seen in the Figure 18.

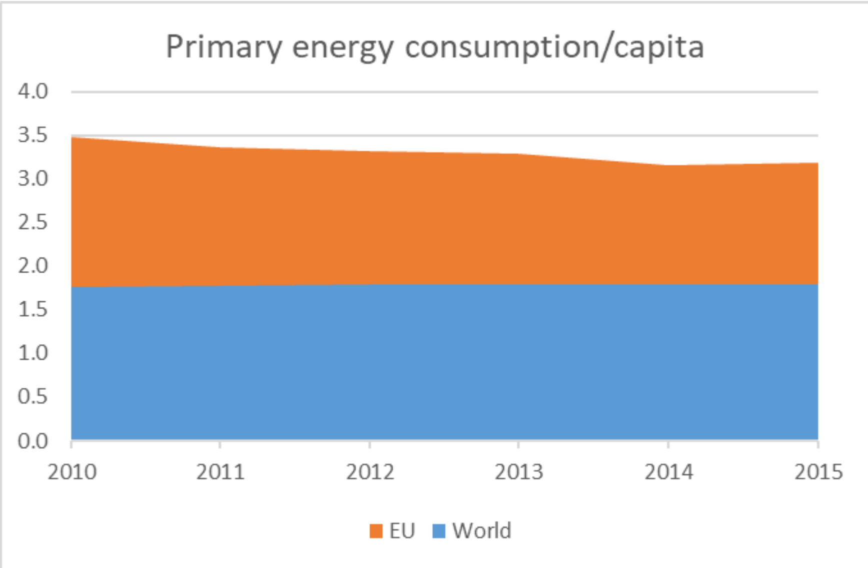


Figure 18. Evolution of Primary Energy consumption per capita in the World and the EU-28.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Oil consumption per capita

The average oil consumption per capita in the world has been constant over the last years (from 2010 to 2015). However, the European Union oil consumption per capita has decreased by 10%. Data for this period are represented in the Table 16, and expressed in tons per capita.

Table 16. World and European Union oil consumption per capita data. Source: Own elaboration with data from BP and OECD iLibrary.

	2010	2011	2012	2013	2014	2015	Ratio
World Oil consumption per capita (tons per capita)	0.5910	0.5897	0.5899	0.5893	0.5871	0.5919	1.00
EU Oil consumption per capita (tons per capita)	1.3203	1.2767	1.2229	1.1869	1.1626	1.1785	2.08

The European Union oil consumption per capita is twice as high as the world oil consumption per capita. This can be represented in the Figure 19.

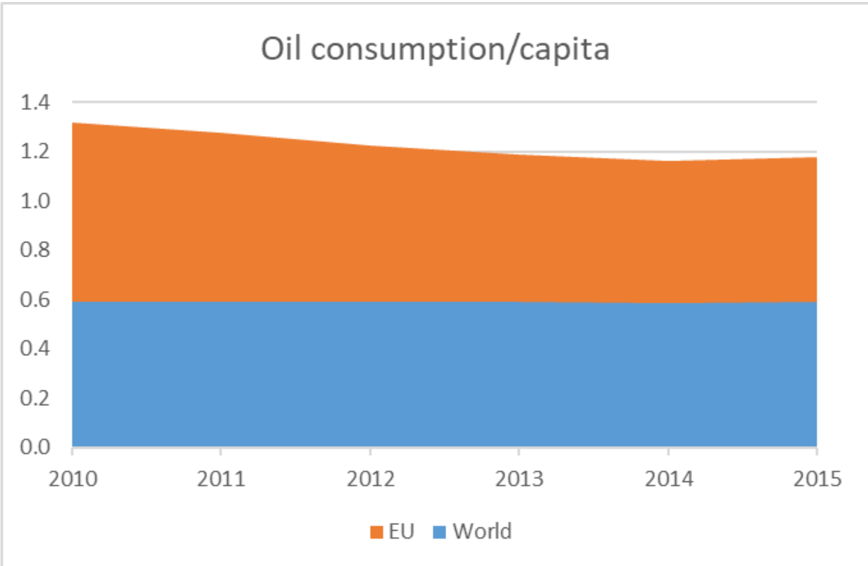


Figure 19. Evolution of Oil consumption per capita in the World and the EU-28.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Gas consumption per capita

The worldwide gas per capita consumption increased by 3%, whereas the European Union consumption decreased more than 20%. Data are represented in the next table, and expressed in tons of oil equivalent per capita (Table 17).

Table 17. World and European Union gas consumption per capita data. Source: Own elaboration with data from BP and OECD iLibrary.

	2010	2011	2012	2013	2014	2015	Ratio
World Gas consumption per capita (toe per capita)	0.4158	0.4183	0.4253	0.4264	0.4240	0.4291	1.00
EU Gas consumption per capita (toe per capita)	0.8897	0.8018	0.7801	0.7655	0.6784	0.7049	1.83

As presented in the table, the gas consumption per capita in the European Union is 1.83 times higher than in the world. It is shown in the Figure 20.

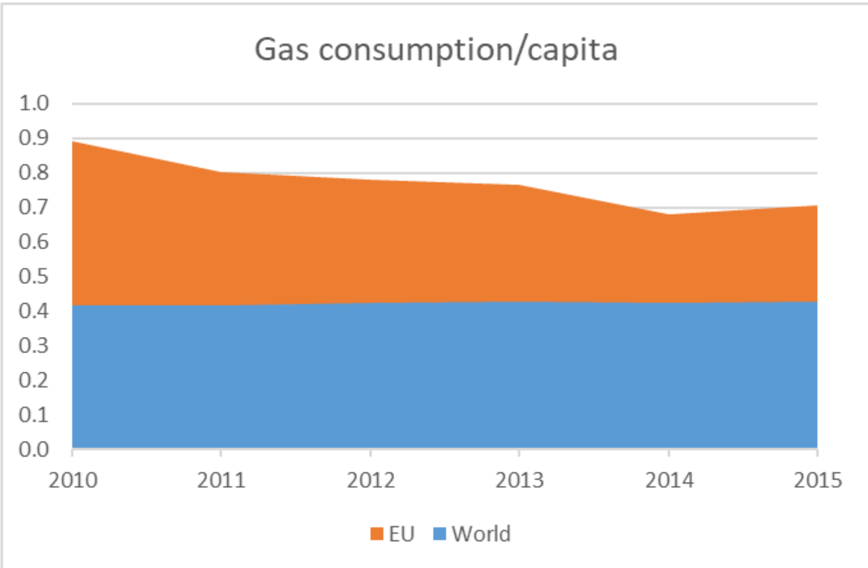


Figure 20. Evolution of the Gas consumption per capita in the World and the EU-28.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Coal consumption per capita

Coal consumption per capita in the world has experienced a small decrease of about 2% for years 2010 to 2015. Moreover, the European Union has also decreased its coal consumption per capita, representing a reduction of 8%. Data, for the period between 2010 and 2015 expressed in tonnes of oil equivalent per capita, are represented in the Table 18.

Table 18. World and European Union coal consumption per capita data. Source: Own elaboration with data from BP and OECD iLibrary.

	2010	2011	2012	2013	2014	2015	Ratio
World Coal Consumption per capita (toe per capita)	0.5259	0.5442	0.5392	0.5427	0.5367	0.5161	1.00
EU Coal Consumption per capita (toe per capita)	0.5563	0.5708	0.5816	0.5680	0.5282	0.5125	1.035

As it is represented in the table, the coal consumption per capita in the world and the European Union is almost the same. The pattern of change is presented in the Figure 21.

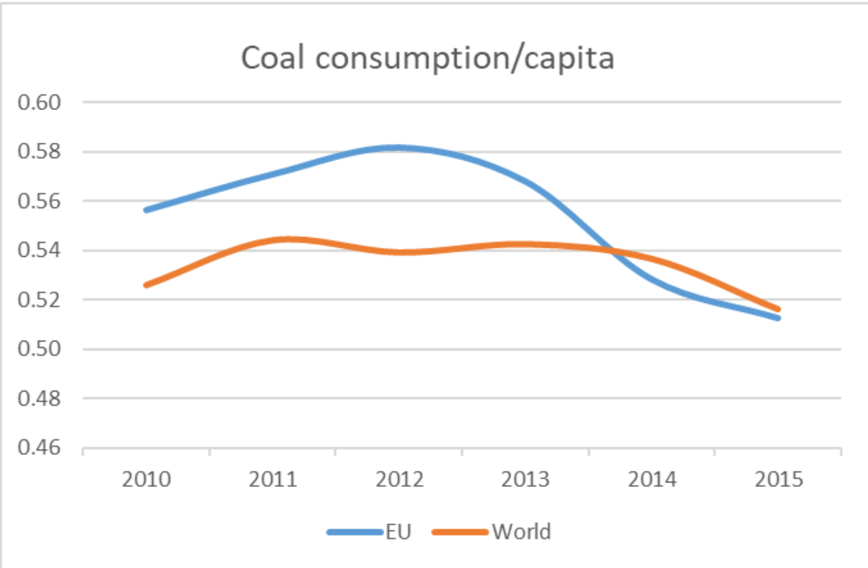


Figure 21. Evolution of the Coal consumption per capita in the World and the EU-28.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Electricity consumption per capita

Worldwide electricity consumption per capita has increased by 6% during the period between 2010 and 2015. Instead, the European Union consumption has decreased by 5% during the same period. Data expressed in kWh per capita for the period between 2010 and 2015 can be seen in the following table (Table 19).

Table 19. World and European Union electricity consumption per capita data. Source: Own elaboration with data from OECD iLibrary.

	2010	2011	2012	2013	2014	2015	Ratio
World Electricity consumption per capita (kWh per capita)	2,867.00	2,927.50	2,955.00	3,010.00	3,036.90	3,052.40	1.00
EU Electricity consumption per capita (kWh per capita)	6,276.70	6,138.90	6,135.70	6,058.70	5,912.10	5,967.60	2.06

As represented in the table, the European Union electricity consumption per capita is twice as high than the world consumption during this period. Data are represented in the Figure 22.

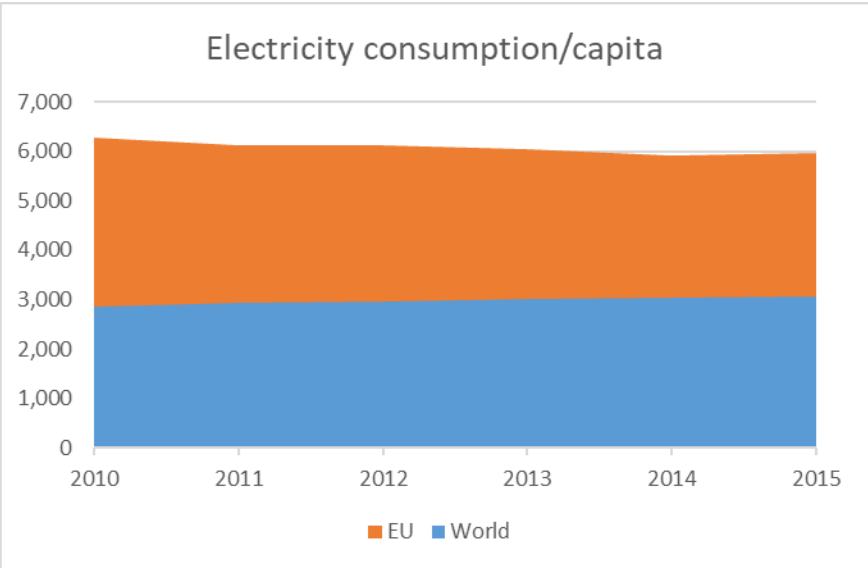


Figure 22. Evolution of Electricity consumption per capita in the World and the EU-28.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Wind energy production per capita

Wind energy production per capita has experienced a significant increase during last years (from 2010 to 2015). In other words, it has been multiplied by 2.3. The same happened in the European Union where the wind energy production per capita has approximately doubled since 2010. Data are shown in Table 20 and expressed in kg of oil equivalent per capita.

Table 20. World and European Union wind energy production per capita data. Source: Own elaboration with data from OECD iLibrary.

	2010	2011	2012	2013	2014	2015	Ratio
World Wind energy production per capita (kg of oil equivalent per capita)	4.25	5.35	6.36	7.75	8.52	9.83	1.00
EU Wind energy production per capita (kg of oil equivalent per capita)	25.50	30.61	35.02	40.16	42.84	50.94	5.40

Taking into account the mean values of each region, the European Union wind energy production is 5.4 times higher than the worldwide wind energy production per capita. This proportion is illustrated in the Figure 23.

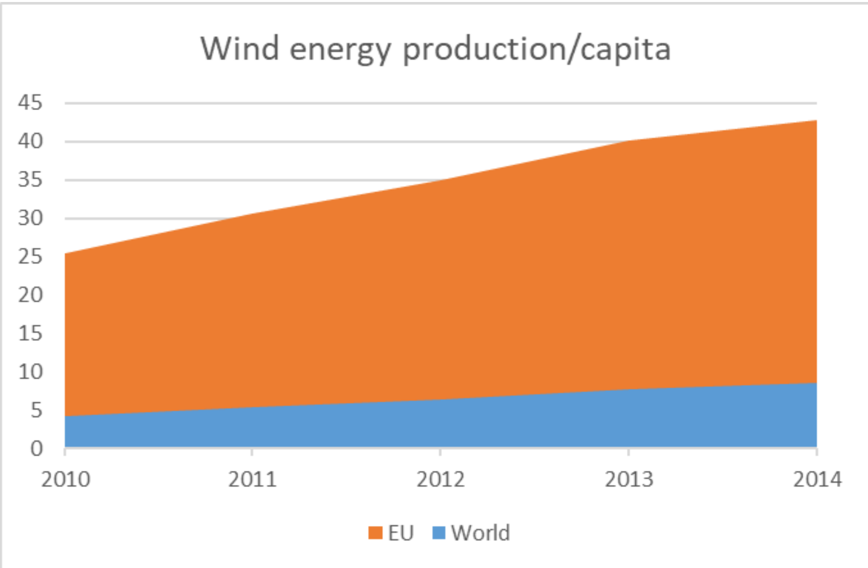


Figure 23. Evolution of the Wind power generation per capita in the World and the EU-28.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Solar energy production per capita

World solar energy production per capita has been multiplied by 2.45 in five years (from 2010 to 2014). Moreover, the European Union has experienced a higher increase as its solar energy production per capita has been multiplied by 3.2 in the same period. Data is represented in the table 21.

Table 21. World and European Union solar energy production per capita data. Source: Own elaboration with data from OECD iLibrary.

	2010	2011	2012	2013	2014	Ratio
World Solar energy production per capita (kg of oil equivalent per capita)	2.6854	3.4977	4.3902	5.7547	6.5824	1.00
EU Solar energy production per capita (kg of oil equivalent per capita)	7.38	11.96	17.81	20.99	23.63	3.57

Taking into account the mean values of each region, the European Union solar energy production is 3.57 times higher than the world solar energy production per capita. This proportion is shown in the Figure 24.

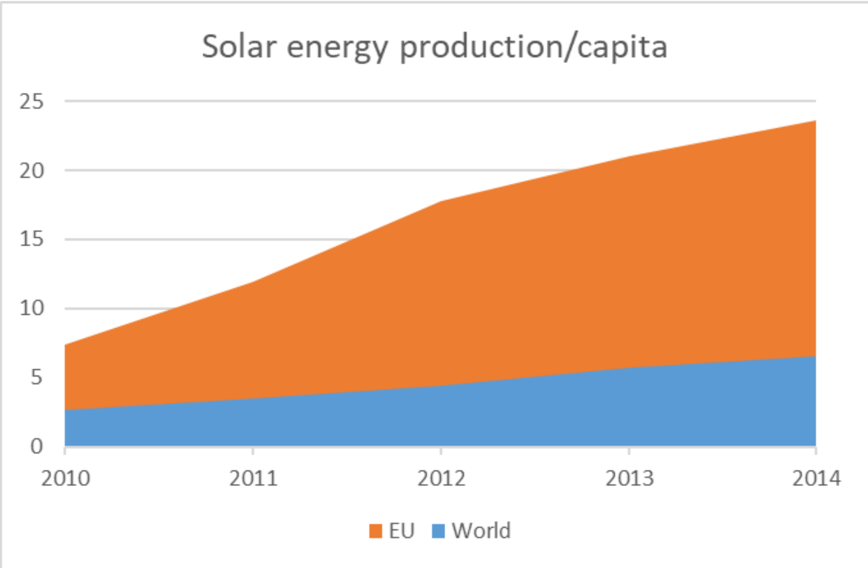


Figure 24. Evolution of Solar power generation per capita in the World and the EU-28.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Oil reserves per capita

Oil reserves per capita in the world have been constant from 2010 to 2015. However, the European Union oil reserves have experienced a decrease of around 7% during the same period. Data, for both regions, are shown in the Table 22. They are represented in thousand barrels per capita.

Table 22. World and European Union oil reserves per capita data. Source: Own elaboration with data from BP and OECD iLibrary.

	2010	2011	2012	2013	2014	2015	Ratio
World Oil reserves per capita (thousand barrels per capita)	0.2376	0.2403	0.2394	0.2376	0.2355	0.2306	1.00
EU Oil reserves per capita (thousand barrels per capita)	0.0119	0.0122	0.0118	0.0115	0.0111	0.0103	0.05

As shown in the table, the European Union oil reserves per capita are only 5% of the total world oil reserves per capita. Data are illustrated in the Figure 25.

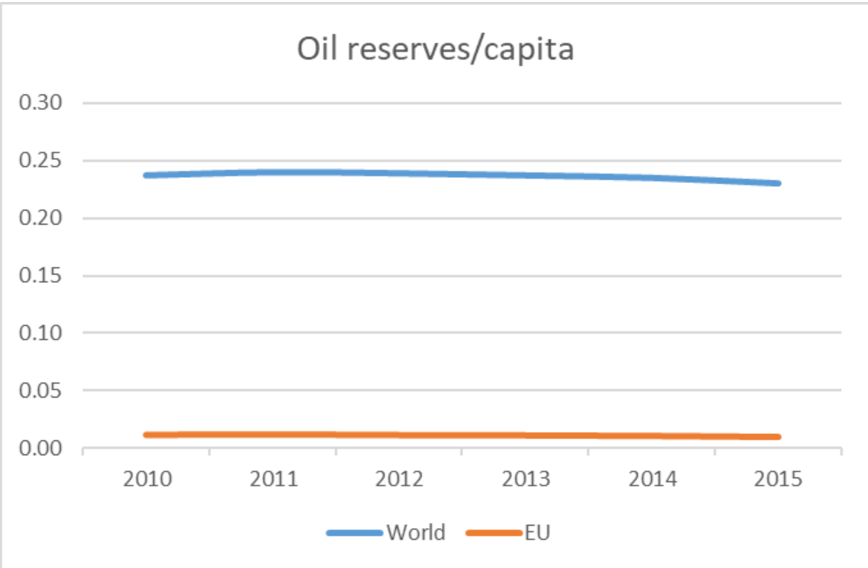


Figure 25. Evolution of the Oil reserves per capita in the World and the EU-28.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Gas reserves per capita

The next indicator are gas reserves per capita, which have been constant in the world during the last six years (from 2010 to 2015). Nevertheless, the European Union gas reserves per capita have decreased by 45% during the same period. These data are represented in the Table 23.

Table 23. World and European Union gas reserves per capita data. Source: Own elaboration with data from BP and OECD iLibrary.

	2010	2011	2012	2013	2014	2015	Ratio
World Gas reserves per capita (million cubic meters per capita)	0.0255	0.0265	0.0260	0.0259	0.0258	0.0253	1.00
EU Gas reserves per capita (million cubic meters per capita)	0.0047	0.0035	0.0030	0.0028	0.0026	0.0026	0.12

As it can be deducted from the table, the European Union gas reserves per capita are 12% of the total world gas reserves per capita. According to these data, the pattern is illustrated in the Figure 26.

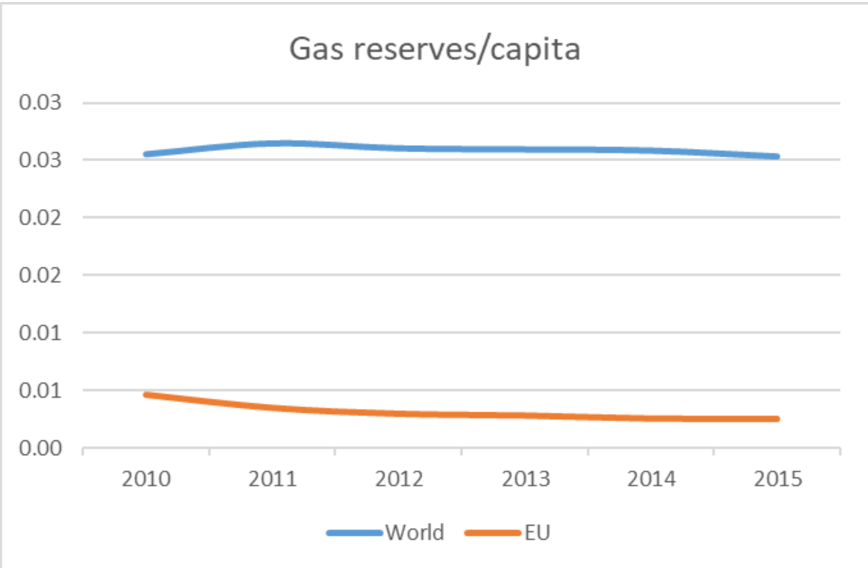


Figure 26. Evolution of Gas reserves per capita in the World and the EU-28.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Coal reserves per capita

When it comes to coal reserves per capita, there is data for the end of the year 2015 for both the world and the European Union. These data are represented in the Table 24.

Table 24. World and European Union coal reserves per capita data. Source: Own elaboration with data from BP and OECD iLibrary.

	End 2015	Ratio
World Coal reserves per capita (t of coal per capita)	121.57	1
EU Coal reserves per capita (t of coal per capita)	110.05	0.91

As shown in the table, the European Union coal reserves per capita are 91% of the total world coal reserves per capita. The temporal pattern of change can be seen in the Figure 27.

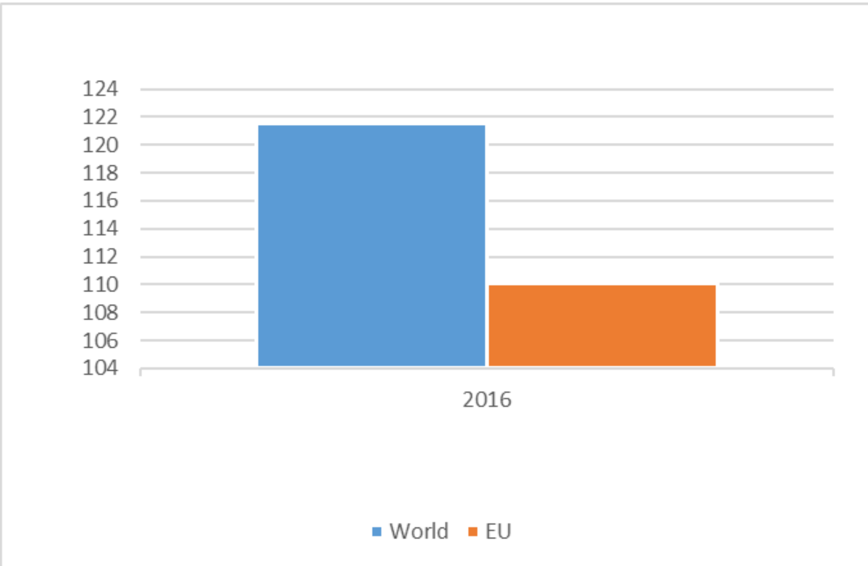


Figure 27. Coal reserves per capita in 2016 for the World and the EU-28.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

CO_2 emissions per capita

The last indicator is carbon dioxide emissions per capita. These emissions have been constant in the world during last years (from 2010 to 2015). However, carbon dioxide emissions per capita have decreased by 14% in the European Union in this period. These data are shown in Table 25.

Table 25. World and European Union CO_2 emissions per capita data. Source: Own elaboration with data from BP and OECD iLibrary.

	2010	2011	2012	2013	2014	2015	Ratio
World CO_2 emissions per capita (t of carbon dioxide per capita)	4.5606	4.6332	4.6277	4.6387	4.6007	4.5412	1.00
EU CO_2 emissions per capita (t of carbon dioxide per capita)	7.8080	7.5381	7.3887	7.2086	6.7750	6.8230	1.58

As it can be deducted from the table, the European Union CO_2 emissions per capita are 1.58 times higher than the world CO_2 emission per capita. This proportion is shown in the Figure 28.

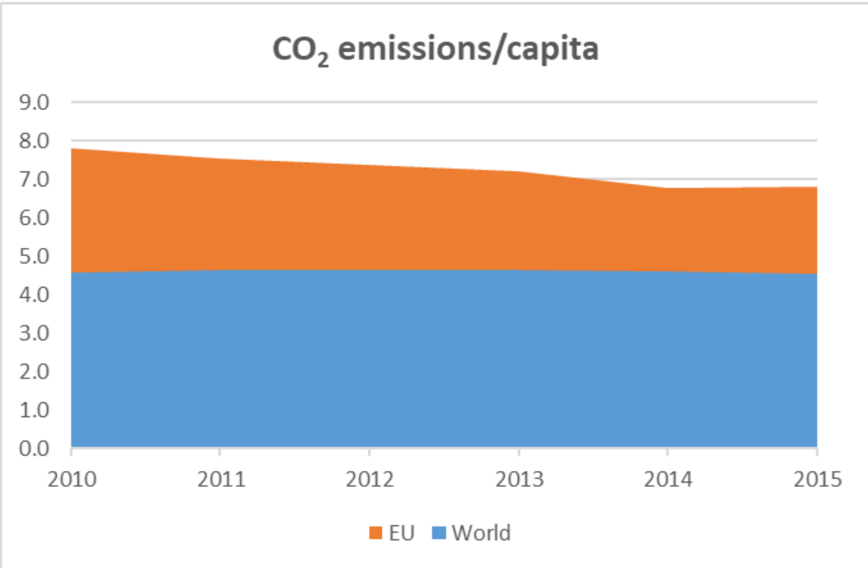


Figure 28. Evolution of the CO_2 emissions per capita in the World and the EU-28.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.1.3. Boundary variables from MEDEAS-W

As aforementioned, MEDEAS-W will be used as a ("parent model") which will provide the boundary conditions within which the MEDEAS-EU model ("child model") will evolve. This paragraph describes which boundary variables from MEDEAS-W are used (and how) in MEDEAS-EU. A total of 14 variables are used. The nomenclature from MEDEAS-W 1.1 is used. We describe them in relation to their role in each module of the EU version of the model:

Economic Module

- "Real demand by sector"
- "Real total output by sector"
- "Real final energy by sector and fuel"
- "Annual GDP growth rate"

These global variables are used in MEDEAS-EU to estimate the EU and RoW final energy intensities, the EU and RoW imports and exports and to estimate the final energy footprint.

The "share E-losses CC" refer to the impacts from climate change and are used to estimate the final energy available for society in UE after accounting for these impacts.

Energy Module

- "Total extraction NRE EJ"
- "PES nat. gas"
- "PES oil EJ"
- "Extraction coal"
- "Extraction uranium EJ"
- "Share conv vs total gas extraction"
- "Share conv vs total oil extraction"

These global variables are used in MEDEAS-EU to estimate the imports of EU from RoW of primary non-renewable fuels such as oil, gas, coal and uranium.

Materials module

- "Current mineral resources Mt"
- "Current mineral reserves Mt"

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

These global variables are used in MEDEAS-EU to compare the EU demand of minerals with the global level of current resources and reserves.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.2. Economy module

2.2.1. Literature review

The approach chosen for modelling Economy in MEDEAS-EU has involved a revision of literature in the field to establish the most proper scope.

It is possible to find different approaches which can be encompassed under the general definitions of optimisation/simulation models and top-down/hybrid/bottom-up models (Scrieciu et al., 2013). Optimisation models usually rely on neoclassical –or, more generally, conventional- economics and thus, computable general equilibrium (CGE). They assume clearing markets via price adjustments which, in turn, ensures full employment and productive capacity (Sterman et al., 2012). Furthermore, they consider optimal growth, which is supply-led through the optimisation of a production function dependent on factors capital and labour, and technological progress. In contrast, simulation models describe intertwines between energy-economy-climate, which allows examining the propagation of disturbances into the system and evaluating the different outcomes of policies. The most known contribution to simulation models was the pioneering World3 model of *Limits to Growth* (Meadows, 1972).

Beyond optimisation-simulation, there are different (but related) approaches regarding the main driver of economy. Optimisation models tend to be supply-led, using the availability of productive factors, i.e. capital, labour and, eventually, natural capital as the engine of modelling. Conversely, demand-led models are usually sustained in post-Keynesian economics assuming disequilibrium, meaning non-clearing markets, demand-led growth and supply constraints (Lavoie, 2014; Taylor et al., 2016). Demand-led models start modelling demand, i.e. the direct and real expression of the productive factors capacity. In these models, however, supply can act as a constraint for the economic activity. As simulation better fits with dynamic modelling and disequilibrium economics, a number of models have been grounded on these approaches. Some examples are the non-equilibrium E3MG model (Pollit, 2014), ICAM (Dowlatabadi, 1998), GTEM (Kemfert, 2005) AIM (Kainuma, 2003; Masui et al., 2006; Morita et al., 2003) and IMAGE (Alcamo et al., 1998; Bouwman et al., 2006; E. Stehfest et al., 2014).

Other useful categorization distinguishes between top-down, hybrid and bottom-up models. The former one implies a macroeconomic perspective where policies and main macro-magnitudes are the essential drivers of the model outcomes. The latter, conversely, represents a partial

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

equilibrium –throughout technologies competition- in the energy sector. Hybrid models, on the other hand, combine a detailed macroeconomic and energetic view of technologies.

While at the early times, top-down optimisation models where dominant, critical observations have been made to this approach. The assumption of perfect substitutability between factors has been widely criticised from ecological economics, which considers that complementarity better fits reality (Christensen, 1989; Farley and Daly, 2003; Stern, 1997). In addition, there is a lack of economic sectoral disaggregation which does not allow models to capture the relevance of economic structure in energy-environment-economy interactions (De Haan, 2001; James et al., 1978). Moreover, optimisation reveals as an unrealistic approach to model complex, dynamic systems in which feedbacks and time matters (Capellán-Pérez, 2016; Uehara et al., 2013). Nevertheless, the majority of demand-led models account with a sequential structure instead of the feedback-rich structure of SD models.

Regarding this body of literature, MEDEAS-EU economy module is defined as a simulation and hybrid model (Scrieciu et al., 2013) (Figure 29). Furthermore, MEDEAS-EU economy module is demand-led, sartorially disaggregated and based on a disequilibrium approach and Input-Output Analysis (IOA). The MEDEAS framework considers demand-led approach more realistic than supply-led, since the latter implies non-reasonable assumptions about the productive factors' utilisation capacity. By adopting a demand-led approach, MEDEAS contributes to widen this demand-side body of literature. Moreover, it is a more realistic procedure, as demand represents the actual economic activity deployed by the productive factors, whether they are in equilibrium or not. However, demand-led models tend to underestimate or directly not take into consideration biophysical supply-side constraints, so GDP is able to keep growing unhindered. The main contribution of MEDEAS in that way is the inclusion of supply constraints and climate change, which feedback the economy throughout energy availability, and emissions.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

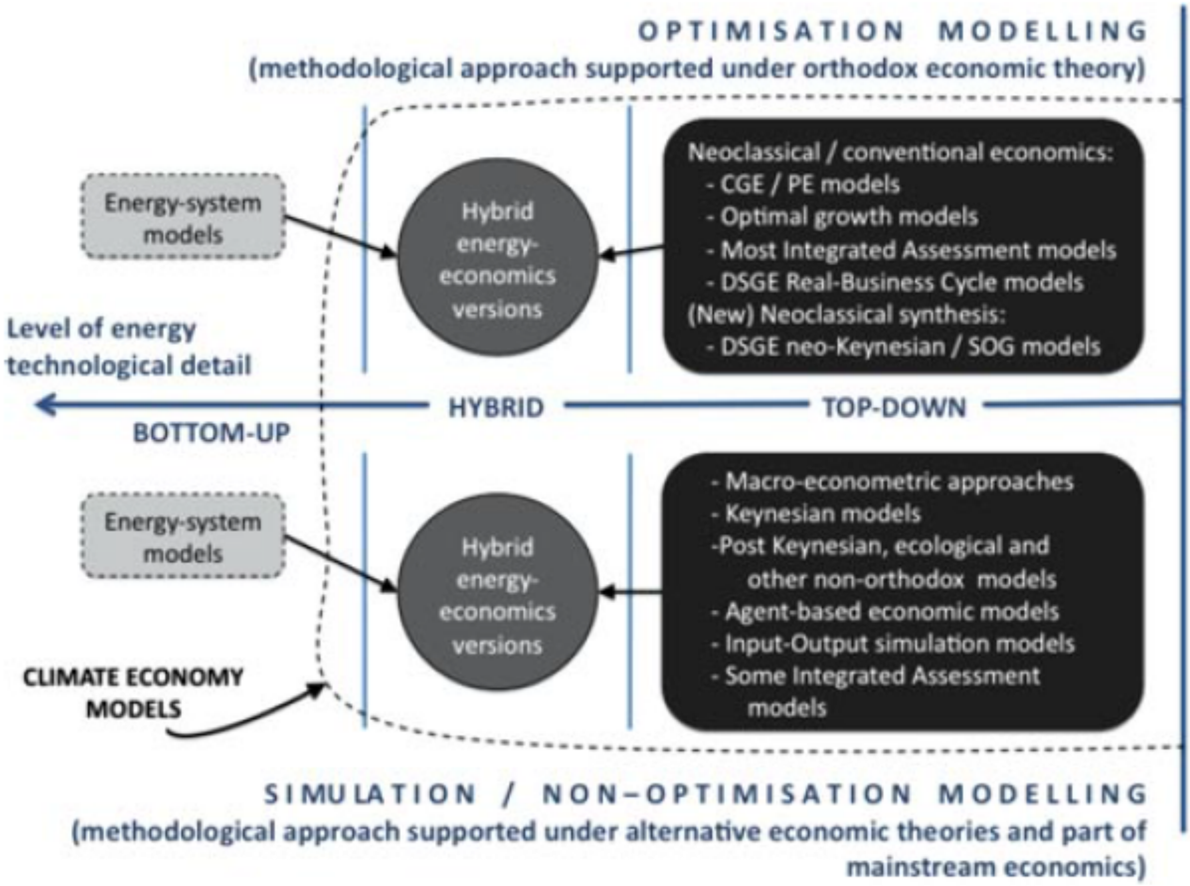


Figure 29. Macro-economic modelling in IAMs.

IOA reveals itself as a powerful tool to assess the direct and indirect effects in sectoral production given an economic structure and the evolution of demand (Leontief, 1970; Miller and Blair, 2009). In addition, IOA allows including environmental hybrid approaches and has been combined with system dynamics in energy-economy-climate modelling (Briens, 2015; Cordier et al., 2017). By using IOA to start the demand modelling, MEDEAS not only can make a sectoral analysis of its results, but it also assumes disequilibrium and it is able to capture structural conditioners in transitions, something that it is often missing from macro-economic modelling. IOT does not make assumptions on equilibrium neither in the goods market nor in the factors market but reveals the actual nature of economic evolution.

Trying to model disequilibrium in factors market necessarily leads to make unrealistic assumptions. For instance, modelling labour supply as a positive function of wages considers implicitly perfect mobility of labour and/or the societal capacity to permanently sustain a significant share of inactive population. MEDEAS, on the contrary, considers disequilibrium in factors market as given in the data, reacting each economic variable according to implicit

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

unemployment and under-utilisation of capital. The model overcomes the main limitations of energy-economy-environment modelling that rely on optimisation, sequential structure, neoclassic production function regardless of disequilibrium and economic structure, and lacks biophysical constraints. MEDEAS-EU Economy-module can be seen as a contribution to the now emerging field of ecological macroeconomics (Hardt and O'Neill, 2017; Rezai and Stagl, 2016).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.2.2. Overview of the economy module

Economy module in MEDEAS-Europe is quite similar to the economy module of MEDEAS-World (see more details in Deliverable 4.1) but including trade and the influence of the other regions. For instance, as is carefully described below (see section 2.2.3.1), final demand now includes exports by sector. Likewise, Input-Output Analysis with trade requires the inclusion of the rest of the world (RoW) final demand and provides its production as an output. As can be seen in Figure 30, RoW final demand by sector influences the expected production in the European Union-28 (EU28) as described in subsection 2.2.3.2. An energy feedback (see section 2.2.3.4.) is also taking into account, but in MEDEAS-Europe considering the net energy supply availability not only inside its boarders, but also abroad.

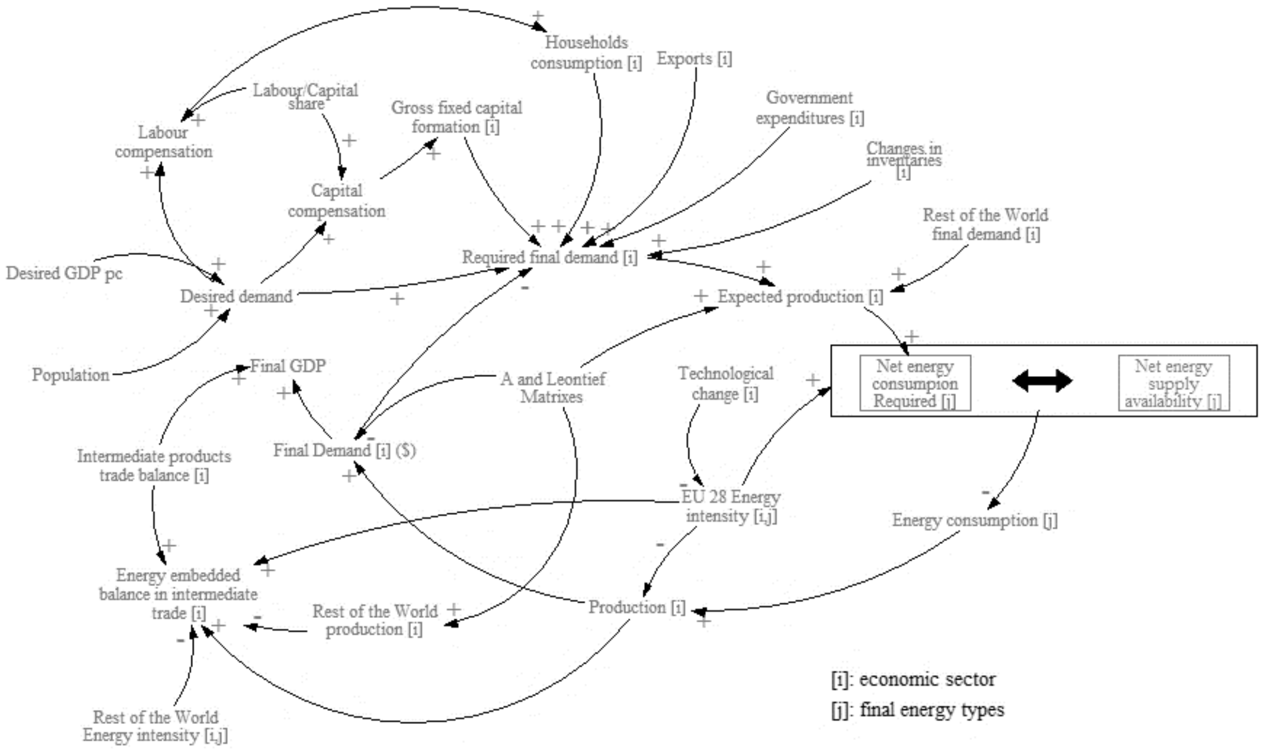


Figure 30. Overview of MEDEAS-Europe economy module.

Through IOA with trade, MEDEAS-Europe is able to estimate the energy embedded balance in trade, by using not only EU28 energy intensities, but also RoW's. Since GDP is defined as the total final demand of EU28 products plus the intermediate trade balance, is necessary to also estimate the latter. Finally, inputs to final demand function come from income (labor and capital compensation), obtained thanks to exogenous income share scenarios (see section 2.2.3.2.).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Moreover, there are other exogenous variables used as inputs for exports, such as the real effective exchange rate and the world GDP, loaded directly from MEDEAS-World.

Schematically, the economy module follows a structure like shown in Figure 31. The user of MEDEAS-Europe can input exogenous scenarios of GDP per capita and population growth, as well as different estimates for income shares (a measure of inequality). Then, demand function comes into motion, providing the IOA with the demand shock that it requires to estimate production. In MEDEAS-Europe, IOA includes trade, meaning that there is not only one interpretation for A and Leontief matrixes, but also one interpretation for each of the sub-matrixes in which it is divided. Trade and RoW's economic structure also matters to determine the production required to satisfy demand in EU28. Hereafter, through energy intensities, energy consumption required by the economic system is estimated and faced to the energy availability. That delivers the feasible energy, production and demand under biophysical constraints. Back into IOA, that feasible demand is estimated and then, the final GDP, which allows the model to estimate the energy carriers of its demand.

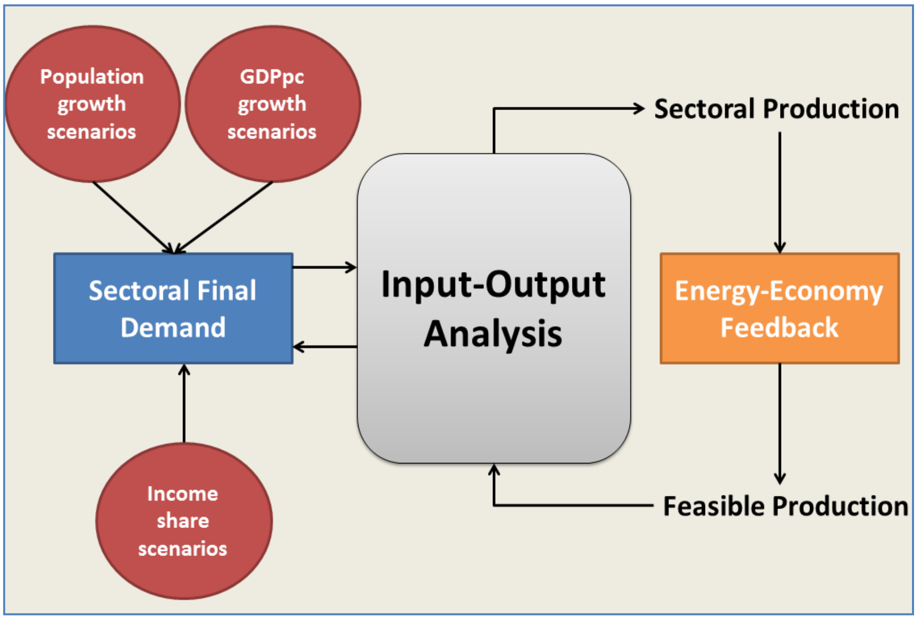


Figure 31. Schematic overview of MEDEAS-Europe economy module.

Thus, this section describes the functioning of each economy module's stage, regarding its main features: i/final demand function; ii/ Input-Output Analysis with trade; iii/ Energy-Economy feedback; iv/ Income.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.2.3. Description of the economy module

2.2.3.1. Demand Function

MEDEAS-Europe is a demand-led model, as explained before. Exogenous final demand growth provides inputs to the final demand function, whose commitment is distributing this final demand change amongst sectors. MEDEAS-World (Deliverable 4.1.) final demand (FD) does not include trade, since at the world level imports offset exports. Input-Output Analysis (IOA) used by the economy module afterwards imposes a particular final demand point of view. Because IOA is oriented to estimate production in the objective region, it is necessary to measure the final demand of this region's products. This way, FD in MEDEAS-Europe consists of domestic and foreign demand of EU28 products, i.e., domestic demand and exports. It is worth to emphasize that FD is not referred to final demand made by European agents, since this would imply to include final imports. However, although final imports are not produced in EU28 and thus, not included in FD, they play a crucial role in MEDEAS-Europe, as explained in section 2.2.3.2. Therefore, final demand for each industry follows Eq. 1:

$$FD_{it} = HH_{it} + GFCF_{it} + GE_{it} + INVENT_{it} + EXP_{it} \qquad i \in 1\ldots35 \qquad (1)$$

Being i the subscript for each industry, t the time subscript; HH the households' consumption, GFCF the gross fixed capital formation, GE the government expenditures, INVENT the changes in inventories and EXP final exports (not included intermediate exports). While all the categories mentioned are referring to the final consumption of EU28 products made by each institutional sector, GFCF does not follow the same approach. GFCF is the final consumption of investment products made by any agent. For example, a household purchasing its primary residence is GFCF in sector 18 (Construction). Likewise, real estate investment made by a corporation or the purchase of a building made by the government are also GFCF in sector 18. This feature directly affects to the GFCF econometric estimation chosen for the model.

Whilst HH_{it}, $GFCF_{it}$, and EXP_{it} (more than 95% of total final demand except on sectors 26 and 30-34) can be estimated throughout econometric functions, GE_{it} and $INVENT_{it}$ remains as a constant share of total final demand based on the time series values. Thus, regarding the structure of the data used (Dietzenbacher et al., 2013) with 35 industries and 15 years, we have a panel with 525 observations. Econometric functions with panel data and auto-correlation corrected have been estimated for each of the mentioned variables. The inputs used in them have been chosen according to the literature and conditioned by the limits imposed by the data source used. For this reason, HH_{it} and $GFCF_{it}$ depend on the evolution of income (labour and capital compensation

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

respectively) obtained in the model as described in section 2.2.3.3. Although further developments will include variables such as real interest rates to estimate $GFCF_{it}$, for the sake of simplicity, income remain as the only explanatory variable. The case of EXP_{it} is rather different. Exports of final consumption goods and services basically depends on exchange rates and the income of the rest of the world (Hassan et al., 2016; Ho, 2012). The indicator used to explain exchange rates is the real effective exchange rate, which takes into account relative prices of the main EU28 commercial partners and it is a measure of competitiveness. Furthermore, because the RoW gross domestic product (GDP) is calculated each year t as the difference between world GDP (data loaded directly from MEDEAS-W) and EU28 GDP, RoW GDP in year t cannot be used to estimate exports in year t. Since it would not make economic sense to estimate year t exports as a function of RoW GDP in t-1, it is a more reasonable approach to make it depend on world's GDP. Although, of course, world's GDP includes EU28 GDP, it is comparatively more explained by RoW GDP than EU28's, a dynamic that tends to deepen.

Hence, the equations that estimate the three main components of final demand in MEDEAS-Europe are the following (Eq. 2-4):

$$lnHH_{it} = \beta_0 + \beta_{1i}Sec_i + \beta_2 lnLab_t \qquad i \in 1 \ldots 35 \qquad (2)$$

$$lnGFCF_{it} = \beta_0 + \beta_{1i}Sec_i + \beta_2 lnCap_t \qquad i \in 1 \ldots 35 \qquad (3)$$

$$lnEXP_{it} = \beta_0 + \beta_1 Sec_i + \beta_2 reer_t + \beta_3 lnworld\_gdp_t \qquad i \in 1 \ldots 35 \qquad (4)$$

Sec_i is a dichotomous variable whose value is 1 when calculating each sector and 0 if it is any other sector. For instance, for sector households' consumption in sector 3, Sec_3 equals 1, so just $\beta_{1,3}$ is applied. Besides, because β_{1i} are estimated as a measure of the incidence of the particulars of each sector in the explanation of the dependent variable, their value is defined in reference to one sector, which here is sector 1. It means that $\beta_{1,0}$is always equal to 0 and β_{1i} has a value different to zero, according to the different effect of each sector on the dependent variable, regarding that of the sector 1. So, there are 34 different β_{1i} as shown in Tables 26-28. *Lab* stands for labour compensation for the whole economy. There is no economic justification to assume that wages paid in one sector will be expended in the same sector. We use labour compensation instead of disposable income because it is not possible to estimate it inside the model, while primary income is obtained as described below. Cap stands for capital compensation and, following the definition of gross fixed capital formation given above, it must be used the total capital compensation of the whole economy, not just that of the sector. $reer$ is the real effective exchange rate, which must be estimated exogenously for the out-of-sample period across the

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

different scenarios. Finally, $world\_gdp$ is the GDP of the world, charged from MEDEAS-World. All the variables except of $reer$ are provided in logarithms (ln) in order to avoid non-linear relationships between variables. The $reer$ is an index expressed in times one, being 1995 the base year.

Tables 26-28 show the parameters of the robust panel data for the three main components of final demand. β_0 value is that in the first column (Coef.) and the last row (_cons). β_{1i}values are given in the first column (Coef.) from sector 2 to 35. For sector 1, β_1 is always equal to 0. β_2 is provided by the value in the first column and first row (log_labworld for Lab and log_capworld for Cap). All β_1 are significant at 5%, but sectors 6 and 19 for GFCF and, in that cases, β_1 equals 0.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Table 26. Households' consumption panel data regression.

ln_hh	Coef.	Panel-corrected Std. Err.	z	P>|z|	[95% Conf.	Interval]
ln_lab	.6778991	.0514513	13.18	0.000	.5770564	.7787418
sector						
2	-3.132168	.1746171	-17.94	0.000	-3.474411	-2.789925
3	1.123761	.0339278	33.12	0.000	1.057264	1.190258
4	-.4057796	.0765651	-5.30	0.000	-.5558445	-.2557148
5	-1.850538	.0823779	-22.46	0.000	-2.011996	-1.68908
6	-2.58802	.0421249	-61.44	0.000	-2.670583	-2.505457
7	-.3965889	.0343986	-11.53	0.000	-.464009	-.3291688
8	-.7282185	.0466228	-15.62	0.000	-.8195975	-.6368395
9	-.3721037	.0417231	-8.92	0.000	-.4538794	-.290328
10	-1.583764	.0298986	-52.97	0.000	-1.642365	-1.525164
11	-1.999981	.0431326	-46.37	0.000	-2.084519	-1.915443
12	-1.556202	.0393489	-39.55	0.000	-1.633324	-1.479079
13	-1.042413	.0353649	-29.48	0.000	-1.111727	-.9730995
14	-.6712651	.0502486	-13.36	0.000	-.7697505	-.5727797
15	.3142421	.0369853	8.50	0.000	.2417523	.386732
16	-.6436642	.0453517	-14.19	0.000	-.7325519	-.5547766
17	.129164	.0527075	2.45	0.014	.0258592	.2324688
18	-1.336307	.0319572	-41.82	0.000	-1.398941	-1.273672
19	-.0263757	.0354701	-0.74	0.457	-.0958958	.0431444
20	.7041985	.0277226	25.40	0.000	.6498632	.7585338
21	.6373543	.026884	23.71	0.000	.5846626	.690046
22	.9152022	.0325756	28.09	0.000	.8513553	.9790491
23	-.1965479	.0375617	-5.23	0.000	-.2701675	-.1229284
24	-2.948299	.0436983	-67.47	0.000	-3.033946	-2.862652
25	-1.491802	.0453768	-32.88	0.000	-1.580739	-1.402865
26	-.990246	.0333368	-29.70	0.000	-1.055585	-.9249071
27	.0645505	.0902568	0.72	0.474	-.1123494	.2414505
28	.6852167	.0808559	8.47	0.000	.5267421	.8436913
29	1.616802	.0236816	68.27	0.000	1.570387	1.663217
30	-.6963911	.0301054	-23.13	0.000	-.7553965	-.6373856
31	-1.71586	.2389462	-7.18	0.000	-2.184186	-1.247534
32	-.5360797	.0366932	-14.61	0.000	-.6079971	-.4641623
33	.290097	.050875	5.70	0.000	.1903838	.3898102
34	.6228922	.0310476	20.06	0.000	.56204	.6837443
35	-1.541552	.0232112	-66.41	0.000	-1.587045	-1.496059
_cons	1.576352	.7924989	1.99	0.047	.0230828	3.129621

The approach followed to translate these equations into system dynamics programming relies on considering it as absolute variations. These variations are the fluxes that feed households final demand (HH_{it}), gross fixed capital formation ($GFCF_{it}$) and exports (EXP_{it}) as stocks. Thus, taking equation 2 for households' consumption in sector i, it can be expressed as (Eq. 5-6):

$$HH_{it} = e^{\beta_0} e^{\beta_{1i} Sec_i} Lab_t^{\beta_2} \quad (5)$$

$$\Delta HH_{it} = e^{\beta_0} e^{\beta_{1i} Sec_i} (Lab_t^{\beta_2} - Lab_{t-1}^{\beta_2}) \quad (6)$$

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Table 27. Gross fixed capital formation panel regression.

ln_gfcf	Coef.	Panel-corrected Std. Err.	z	P>|z|	[95% Conf.	Interval]
ln_cap	1.268449	.1957958	6.48	0.000	.884696	1.652202
sector						
2	-1.678621	.1408706	-11.92	0.000	-1.954723	-1.40252
3	-1.584967	.0446439	-35.50	0.000	-1.672468	-1.497467
4	-1.852438	.0759359	-24.39	0.000	-2.00127	-1.703606
5	-3.962418	.0930604	-42.58	0.000	-4.144813	-3.780023
6	-.5286262	.054374	-9.72	0.000	-.6351973	-.4220552
7	-.7827833	.0626663	-12.49	0.000	-.905607	-.6599596
8	-2.585285	.1575044	-16.41	0.000	-2.893988	-2.276582
9	-1.025788	.0583313	-17.59	0.000	-1.140115	-.9114605
10	-.9166757	.057525	-15.94	0.000	-1.029423	-.8039289
11	-1.138974	.0772438	-14.75	0.000	-1.290369	-.9875795
12	1.628664	.0583067	27.93	0.000	1.514384	1.742943
13	2.573675	.0451355	57.02	0.000	2.485211	2.662139
14	2.37552	.0571061	41.60	0.000	2.263594	2.487446
15	2.428932	.0624213	38.91	0.000	2.306588	2.551275
16	.7296413	.0610803	11.95	0.000	.609926	.8493565
17	-.077121	.0547792	-1.41	0.159	-.1844862	.0302443
18	4.304366	.0398625	107.98	0.000	4.226237	4.382495
19	.3954664	.0433846	9.12	0.000	.3104342	.4804985
20	1.931302	.0407145	47.44	0.000	1.851503	2.011101
21	1.693442	.0390225	43.40	0.000	1.61696	1.769925
22	-2.186798	.0467966	-46.73	0.000	-2.278518	-2.095078
23	.095919	.0951406	1.01	0.313	-.0905531	.2823912
24	-2.89669	.0956638	-30.28	0.000	-3.084188	-2.709192
25	-3.063519	.1114182	-27.50	0.000	-3.281895	-2.845144
26	-1.575843	.0967499	-16.29	0.000	-1.76547	-1.386217
27	-.5027087	.1125717	-4.47	0.000	-.7233452	-.2820723
28	-1.163246	.1065767	-10.91	0.000	-1.372133	-.9543594
29	1.538815	.0566672	27.16	0.000	1.427749	1.64988
30	2.770212	.04998	55.43	0.000	2.672254	2.868171
31	-.2939297	.1646052	-1.79	0.074	-.6165499	.0286905
32	-3.006637	.0579659	-51.87	0.000	-3.120248	-2.893026
33	-2.952246	.085682	-34.46	0.000	-3.120179	-2.784312
34	.2798261	.0509532	5.49	0.000	.1799597	.3796926
35	-11.32751	.1000009	-113.27	0.000	-11.52351	-11.13151
_cons	-9.960998	2.985201	-3.34	0.001	-15.81188	-4.110111

Equivalently, $GFCF_{it}$would be expressed equally but using Cap instead of Lab and EXP_{it} follows a similar approach. In order to calculate in the model, the new final demand flow to their respective stocks, the variation is taken. Although some coefficients are not individually significant with p-values over 0.10, all the models are jointly significant. In addition, their sample forecasts demonstrate to be consistent enough, even though it is worth to remember that the objective of system dynamic models is not to predict, but to estimate overall tendencies under different sets of policies and scenarios.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Table 28. Exports panel data regression.

ln_exp	Coef.	Panel-corrected Std. Err.	z	P>|z|	[95% Conf.	Interval]
reer_1	.327065	.2618571	1.25	0.212	-.1861654	.8402954
log_gdpw	1.408751	.2237457	6.30	0.000	.9702173	1.847284
sector						
2	-3.517977	.7349144	-4.79	0.000	-4.958383	-2.077571
3	2.050762	.0830348	24.70	0.000	1.888016	2.213507
4	1.30901	.1322885	9.90	0.000	1.049729	1.56829
5	.2279982	.1394693	1.63	0.102	-.0453566	.5013529
6	-2.347326	.0884834	-26.53	0.000	-2.52075	-2.173901
7	.3975593	.1255019	3.17	0.002	.1515801	.6435386
8	-.088368	.1512591	-0.58	0.559	-.3848304	.2080943
9	1.919586	.1233429	15.56	0.000	1.677839	2.161334
10	-.2184727	.0960843	-2.27	0.023	-.4067945	-.0301509
11	-1.066644	.1701236	-6.27	0.000	-1.40008	-.7332078
12	.3392006	.1104185	3.07	0.002	.1227843	.5556168
13	2.577833	.1094655	23.55	0.000	2.363285	2.792382
14	2.534758	.1340868	18.90	0.000	2.271952	2.797563
15	2.577478	.1350884	19.08	0.000	2.31271	2.842247
16	.9817586	.1482769	6.62	0.000	.6911412	1.272376
17	-1.564876	.1460999	-10.71	0.000	-1.851226	-1.278525
18	-1.152804	.1299712	-8.87	0.000	-1.407543	-.8980654
19	-2.030831	.1085219	-18.71	0.000	-2.24353	-1.818132
20	.5035078	.1163186	4.33	0.000	.2755275	.7314882
21	-.4526686	.1453776	-3.11	0.002	-.7376034	-.1677338
22	-1.761767	.115491	-15.25	0.000	-1.988125	-1.535409
23	-.3321685	.114413	-2.90	0.004	-.5564138	-.1079231
24	.5099993	.1213689	4.20	0.000	.2721206	.747878
25	.0078887	.1614741	0.05	0.961	-.3085947	.324372
26	-1.216204	.1361066	-8.94	0.000	-1.482968	-.9494395
27	-1.562723	.1487967	-10.50	0.000	-1.85436	-1.271087
28	.3697243	.1867938	1.98	0.048	.0036152	.7358333
29	-2.525663	.1894569	-13.33	0.000	-2.896991	-2.154334
30	.2450275	.1031751	2.37	0.018	.042808	.4472471
31	-1.2957	.180464	-7.18	0.000	-1.649403	-.9419971
32	-2.149513	.0998581	-21.53	0.000	-2.345231	-1.953795
33	-3.026274	.119929	-25.23	0.000	-3.261331	-2.791218
34	-1.065372	.1313386	-8.11	0.000	-1.322791	-.8079528
35	-15.72749	.3634951	-43.27	0.000	-16.43993	-15.01506
_cons	-15.92753	3.836001	-4.15	0.000	-23.44595	-8.409106

Once final demand of EU28 products is estimated for year t, Input-Output Analysis (IOA) come into play. As it is explained afterwards, IOA with trade requires not only domestic products final demand variation, but also other regions' change. To sum up, final demand in MEDEAS-Europe relies on inputs provided by an exogenous change in total final demand. Then, income is calculated to provide the inputs for the final demand function, which distributes this change in total final demand amongst the 35 industries. Finally, these sectoral changes activate IOA, which provides the model with the sectoral production required to satisfy the demand. The purpose of the following section is to explain that process.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.2.3.2. Input-output analysis

Trade is a key issue in MEDEAS-Europe and the main difference with the Economy module in MEDEAS-World (Deliverable 4.1). Input-Output Analysis (IOA) is rather different between a one-region Input-Output Table (IOT) and a two-region IOT. Not only the accounting balances are different, but also the procedure needed to be carried out for estimating the main aggregates. Figure 32 shows the general structure of both approaches, which consists of two regions (R and S), and industries by rows (sales) and columns (purchases), i and j respectively.

World IOT

Z_{ij}^{rr}	D_i^{rr}	X_i^{rr}
VA_j^{rr}		
X_j^{rr}		

2-Region IOT

Z_{ij}^{rr}	Z_{ij}^{rs}	D_i^{rr}	D_i^{rs}	X_i^{rr}
Z_{ij}^{sr}	Z_{ij}^{ss}	D_i^{sr}	D_i^{ss}	X_i^{ss}
VA_j^{rr}	VA_j^{ss}			
X_j^{rr}	X_j^{ss}			

$Z_{ij}^{rr/ss}$: Intrarregional (region R/region S) Intermediate Consumption; Z_{ij}^{rs}: Intermediate exports (R→S).

Z_{ij}^{sr}: Intermediate imports (S→R); $D_i^{rr/ss}$: Intra-regional Final Demand (region R/region S).

D_i^{rs}: Final products exports (R→S); D_i^{sr} Final products imports (S→R).

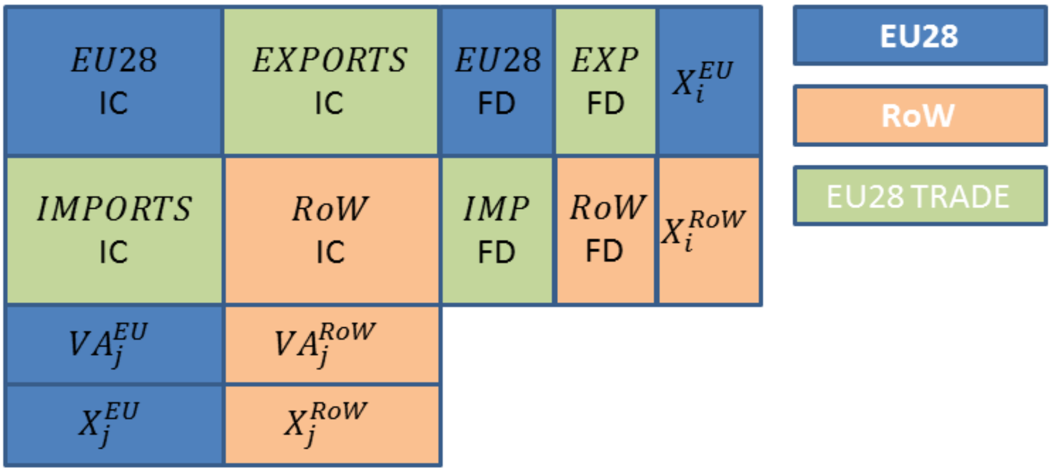
$VA_j^{rr/ss}$: Value added (region R/region S); $X_j^{rr/ss}$: Production (region R/region S).

Figure 32. General structure of World and 2-region Input-Output Tables.

In order to provide a more comprehensive picture of the most relevant economic flows from the European Union 28 (EU28) point of view, the 2-region IOT (2RIOT) has been redesigned (Figure 32). The EU28 IOT has been compiled on the basis of the deflated interregional IOT, which includes the European Union 27 (EU27) countries, 13 other major economies and a Rest of the World (RoW) region. Thus, a systematic process was implemented to obtain the EU28 IOT, comprising three stages for each year in the time series (1995-2009): i/ rearranging the interregional World IOT (WIOT) to put together the EU27 countries both intermediate consumption and final demand; ii/ balancing intermediate and final products purchases and sales between EU27 countries; iii/ apply the previous stage to the other countries to obtain RoW; iv/ add Croatia to EU27 to

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

transform it in EU28 and deduct it in the new RoW region. Once this process is fulfilled, we have a 2RIOT consisting of EU28 and RoW, with different sub-matrixes taking into account the bilateral economic flows between the two regions (Figure 33).



$EU28_{IC}/RoW_{IC}$: Intrarregional (EU28/RoW) Intermediate Consumption; EXP_{IC}: Intermediate exports (EU28→RoW). IMP_{IC}: Intermediate imports (RoW→EU28);

$EU28/RoW_{FD}$: Intrarregional Final Demand (EU28/RoW). EXP_{FD}: Final products exports (EU28→RoW); IMP_{FD}: Final products imports (RoW→EU28).

$VA_j^{EU28/RoW}$: Value added (EU28/RoW); $X_j^{EU28/RoW}$: Production (EU28/RoW).

Figure 33. General structure of EU28-Rest of the World (RoW) Input-Output Matrix.

Since WIOT does not account for commerce, accounting balances are very simple. Gross Domestic Output (GDP) in each IOT is therefore obtained differently. According to the Input-Output methodology, output for each industry can be derived both from supply and demand side. The former is the addition of all intermediate products purchased by the industry plus the value added. The latter can be obtained by adding both intermediate and final products sold by the industry to the other industries and the institutional sectors of the economy respectively. In a 2RIOT, it implies adding trade to both of them. For each region, output from the supply side requires including intermediate product imports and, from the demand side, intermediate and final product exports (Eq.7-8).

$$X_j^{rr} = Z_{ij}^{rr} + Z_{ij}^{sr} + VA_j^{rr} \qquad (7)$$

$$X_i^{rr} = Z_{ij}^{rr} + Z_{ij}^{rs} + D_i^{rr} + D_i^{rs} \qquad (8)$$

Thus, considering that $X_j^{rr} = X_i^{rr}$, we can establish that:

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

$$Z_{ij}^{rr} + Z_{ij}^{rs} + D_{i}^{rr} + D_{i}^{rs} = Z_{ij}^{rr} + Z_{ij}^{sr} + VA_{j}^{rr} \quad (9)$$

And, therefore, rearranging:

$$VA_{j}^{rr} = Z_{ij}^{rs} + D_{i}^{rr} + D_{i}^{rs} - Z_{ij}^{sr} \quad (10)$$

Finally, we can calculate GDP using Eq.10. through the production approach ($GDP = \sum VA$[1]). Thus, GDP in a 2RIOT can be obtained as the sum of final products, domestic and external (exports) demand and intermediate products trade balance (exports less imports). It is worth to mention that imports of final products are included implicitly in the equation. However, since final products imports are included in the demand made by EU28 institutional sector, then they have to be subtracted if GDP wants to be calculated. Thus, both values are cancelled. Therefore, for the sake of simplicity, imports are not required to calculate each region GDP (see Table 26). Nevertheless, it is worth to mention that in the EU28 IOT, final products imports made by the EU28 (IMP_{FD}) are equal to the final products exports made by RoW region. Consequently, as described below, they are a crucial variable to derive the output variation after a demand shock in the IOA applied to a 2RIOT.

Table 29. GDP measure in different IOTs by approach Source. Source: Own elaboration.

Approach	Supply	Income	Demand
World IOT	$X_{j}^{rr} - Z_{ij}^{rr}$	VA_{j}^{rr}	D_{i}^{rr}
2-region IOT	$X_{j}^{rr} - Z_{ij}^{rr} - Z_{ij}^{sr}$	VA_{j}^{rr}	$Z_{ij}^{rs} + D_{i}^{rr} + D_{i}^{rs} - Z_{ij}^{sr}$
EU28 IOT	$X_{j}^{EU28} - EU28_{IC} - IMP_{IC}$	VA_{j}^{EU28}	$EXP_{IC} + EU28_{FD} + EXP_{FD} - IMP_{IC}$

[1] Since Value Added is also the sum of labour compensation (LAB), capital compensation (CAP) and taxes less subsidies on products (TAX), we can also define GDP from the income approach as the VA (see Table 26).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.2.3.2.1. General framework of trade within input-output table

Including trade in the Input-Output framework requires making some changes in the classic equations. What remains unchanged is the demand-led evolution of the economy. In IOA, regardless of the number of regions involved, a demand shock leads to a response in the output necessary to satisfy it. This response shall be different attending to the economy's structure and the underlying technological assumption provided by technical coefficients. Technical coefficients measure the amount of inputs (nationally produced or imported) required to produce 1 unit of output. These values are collected in a matrix named A matrix. Meanwhile in a WIOT there is only one technical coefficient's matrix, the number of sub-matrixes increases exponentially with the number of regions included in the multiregional IOA. There is an A matrix for each purchase matrix following this relationship due to the squared shape of IOTs (Eq. 11):

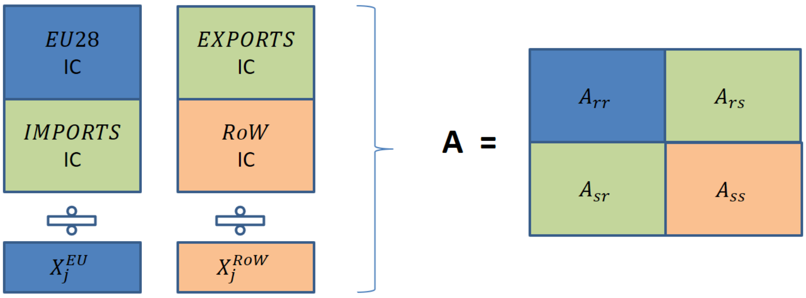
$$N_A = N_r^2 \tag{11}$$

Being N_A the number of A sub-matrixes and N_r the number of regions. Thus, in a 2RIOT the number of sub-matrixes required is 4, as schematically expressed in Figure 34. Given this definition, technical coefficients must be read in terms of purchases (columns). Hence, the EU28 technical coefficients are the intermediate products purchases made by EU28 industries from EU28 industries ($EU28_{IC}$) and abroad (IMP_{IC}). The same applies to the RoW technical coefficients, because their imports are the EU28 exports (EXP_{IC}). The dimensions of this squared A matrix with trade are imposed by the number of industries and regions (Eq. 12):

$$D_A = N_r * N_s; \tag{12}$$

being D_A the dimensions of the A matrix and N_s the number of sectors. In our EU28 IOT using WIOD (Dietzenbacher et al., 2013) as explained before, the A matrix is a 70x70 ($D_A = 2 * 35$) matrix encompassing 4 different submatrixes.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287



$\boldsymbol{A_{rr}}$: Intermediate inputs produced in EU28 required for EU28 production.

$\boldsymbol{A_{rs}}$: Intermediate inputs produced in EU28 required for EU28 exports.

$\boldsymbol{A_{sr}}$: Intermediate inputs imported by EU 28 required for EU28 production.

$\boldsymbol{A_{ss}}$: Intermediate inputs produced in RoW required for RoW production.

Figure 34. Schematic framework for A sub-matrixes in a 2-region IOT.

In this way, MEDEAS-Europe has 4 A sub-matrixes: one for EU28 intermediate consumption without imports ($\boldsymbol{A_{rr}}$), two for EU28 imports ($\boldsymbol{A_{sr}}$) and exports ($\boldsymbol{A_{rs}}$) and another one for intermediate consumption made by countries from RoW inside their boarders and in other countries from RoW region ($\boldsymbol{A_{ss}}$). On one hand, $\boldsymbol{A_{rr}}$ and $\boldsymbol{A_{sr}}$ are the inputs intensity required by EU28 industries to produce its output, purchased to other EU28 industries or RoW industries respectively. On the other hand, $\boldsymbol{A_{ss}}$ and $\boldsymbol{A_{rs}}$ are the domestic and external purchases required by RoW industries per unit of output. With that in mind, IOA with trade differs from IOA without trade in the number of sub-matrixes included in the A matrix. Hence, since trade and economic structure in the other regions matters, obtaining production in each region implies using the interregional sub-matrixes as a whole, following the classic IOA equations (13-15):

$$X = Z + D \quad (13)$$

$$A = Z * \hat{x}^{-1} \rightarrow X = AX + D \rightarrow X = (I - A)^{-1} * D \quad (14)$$

$$(I - A)^{-1} = L \rightarrow X = L * D \quad (15)$$

where X is a column vector representing EU28 and RoW production, Z a matrix consisting of the 4-intermediate consumption sub-matrixes, and D a column vector with the final demand of each regional product (domestic demand and exports) made by both regions. $\hat{x}^{-1}$ is the inverse diagonal matrix of X, A is the interregional A matrix, I the identity matrix and L the new interregional Leontief Matrix.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

As IOA objective is to estimate production in a region, for instance in the EU28 case, it is important to understand that the relevant Final Demand here is the demand of EU28 products made by EU28 (domestic demand) and RoW (final products exports) agents (Miller and Blair, 2009) . This Final Demand is explicitly explained in section 2.2.3.1. Therefore, the new interregional Leontief Matrix (L) consists of 4 sub-matrixes, analogous to those from the interregional A matrix. Interregional L interpretation differs from that of the one region L. The final step for obtaining production in IOA with trade, requires the interregional L matrix and the vector column formed by each region's final demand, as in Eq. 15 and Figure 35 for EU28.

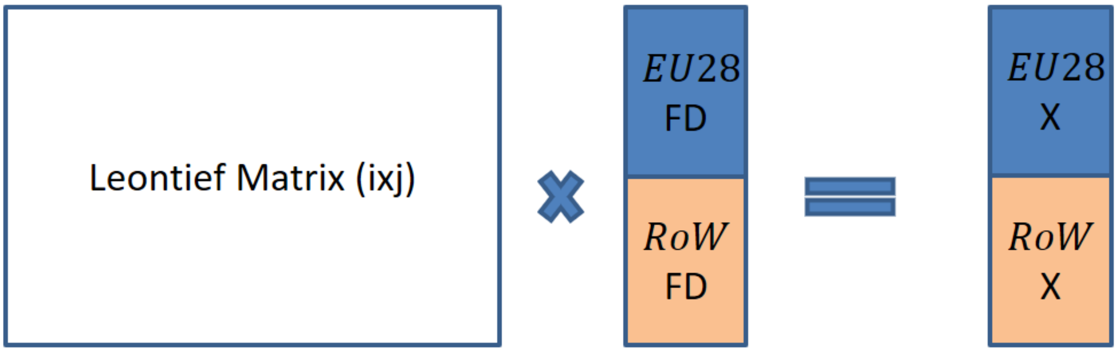


Figure 35. Obtaining EU28 production in the 2-region Input-Output Analysis.

In order to better understand the L matrix interpretation and, therefore, how the IOA with trade works in MEDEAS-Europe, we can follow a simplified example with 3 sectors, 2 regions and aggregated final demand (including all institutional sectors and exports). First, we have the complete IOT with its economic flows (Figure 36) and then, the interregional A matrix (Figure 37) is obtained by dividing each submatrix by its industry output (by columns).

		EU			ROW					
		1	2	3	1	2	3	FD		X
EU	1	25	20	10	8	3	1	25	EU	92
	2	5	12	9	1	9	2	60		98
	3	1	4	7	1	2	10	45		70
ROW	1	6	2	2	15	20	3	43	ROW	91
	2	5	10	1	4	22	4	55		101
	3	1	3	11	2	5	18	38		78
	VA	49	47	30	60	40	40			
	X	92	98	70	91	101	78			

Figure 36. Input-Output Table (2-region example).

Both the A-Matrix and the Leontief Matrix have the same dimensions (6x6) and number of sub-matrixes (4) following Eqs. 11-12. According to this example, sector 1 in EU28 would require 0.2717 units of input from domestic sector 1 and 0.0652 units of imported sector 1 intermediate

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

products, per unit of output. Likewise, for the same sectors, RoW require 0.0879 units of imported intermediate products and 0.1648 of domestic inputs to produce one unit of output. Therefore, the RoW structure determines the EU28 exports and thus, the EU28 production (and vice versa). This is the reason why we need external economic structure and demand to estimate EU28 production.

Arr			Ars		
0,2717	0,2041	0,1429	0,0879	0,0297	0,0128
0,0543	0,1224	0,1286	0,0110	0,0891	0,0256
0,0109	0,0408	0,1000	0,0110	0,0198	0,1282
0,0652	0,0204	0,0286	0,1648	0,1980	0,0385
0,0543	0,1020	0,0143	0,0440	0,2178	0,0513
0,0109	0,0306	0,1571	0,0220	0,0495	0,2308
Asr			Ass		

Figure 37. A matrix (2-region example)

Finally, the Leontief matrix (Figure 38) provides a measure of the production sensitivity to final demand changes, both domestic and external (exports). For instance, in this example, EU28 sector 1's production increases 1.4340 for one additional unit of final demand for their products and 0.1476 of imported units from the same sector. Similarly, if RoW demand is increased in one unit, exports made by EU28 grows by 0.1709 and 1.2365 inside the region.

L-Arr			L-Ars		
1.4340	0.3735	0.3074	0.1709	0.1548	0.1065
0.1095	1.1976	0.2079	0.0409	0.1619	0.0892
0.0331	0.0765	1.1645	0.0283	0.0594	0.2026
0.1476	0.1112	0.1028	1.2365	0.3407	0.1078
0.1257	0.1954	0.0925	0.0906	1.3382	0.1178
0.0437	0.0843	0.2594	0.0510	0.1166	1.3571
L-Asr			L-Ass		

LA_{rr}: Region R's production sensitivity to final demand of Region R products.

LA_{rs}: Region R's production sensitivity to Region S intermediate demand of imports.

LA_{sr}: Region S's production sensitivity to Region R intermediate demand of imports.

LA_{ss}: Region S's production sensitivity to final demand of Region R products.

Figure 38. Leontief matrix (2-region example).

Hence, IOA with trade not only shows the direct and indirect effects on production due to final demand and other industries' requirements (economic structure), but also the direct and indirect effects due to other regions' final demand and economic structure. So, the IOA with trade shows that in an interrelated global economy, production in one region depends not only on domestic

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

demand but also on foreign demand. Moreover, it shows that the products that one region demands from the rest of the world have to be produced according to their economic structure, which is rather different from domestic one. Particularly, this characteristic allows estimating the energy footprint of trade, as explained below.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.2.3.2.2. Input-output analysis with trade in MEDEAS-Europe

The analytical framework described before has to be translated into system dynamics language. The simplified influences diagram for IOA with trade in MEDEAS-Europe is shown in Figure 39.

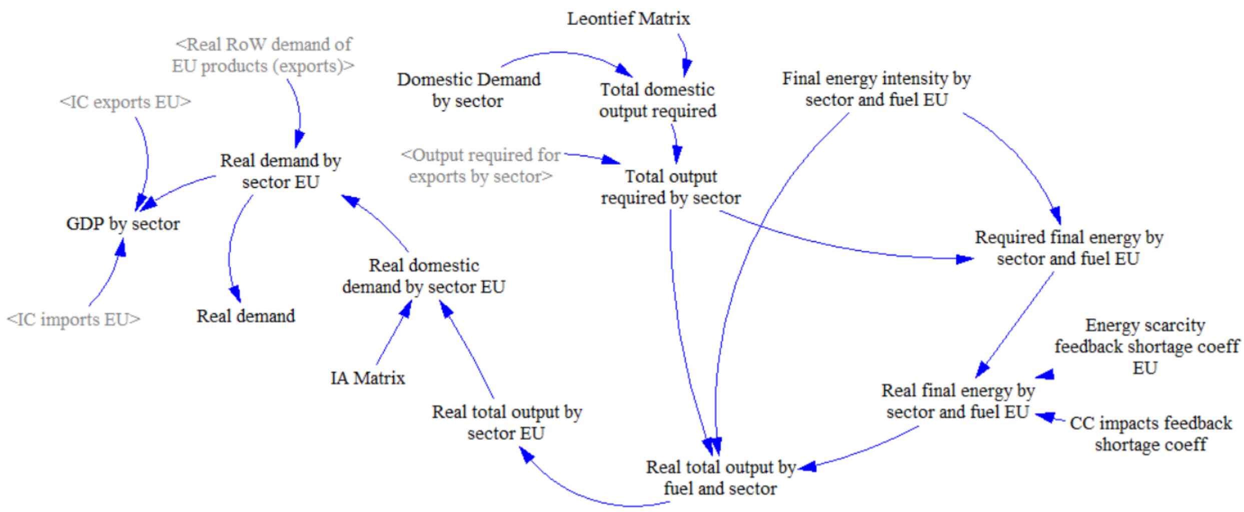


Figure 39. Simplified influences diagram for Input-Output Analysis in MEDEAS-Europe.

Final demand changes exogenously according to the IPCC SSPs (IPCC, 2013) and this variation is distributed amongst sectors in accordance with the final demand function described in section 2.2.3.1. Production in each region is committed to satisfy domestic and foreign, both intermediate and final, demand, that is, domestic intermediate and final consumption and intermediate and final products exports. So, EU28 production depends on domestic and foreign final demand of EU28 products and its production sensitivity to changes in them (LA_{rr}). Moreover, we know that final demand of RoW products is satisfied by RoW production which, in turn, requires the import of intermediate inputs from EU28. Thus, the EU28 production is also affected by the final demand of RoW products and the RoW's production sensitivity to EU28 intermediate demand of imports ($\mathrm{LA_{rs}}$). The result of the addition of both direct and indirect effects (see Eq.16) is the production in EU28.

$$X^{EU28} = FD^{EU28} * LA_{rr} + FD^{RoW} * LA_{rs} \qquad (16)$$

With $FD^{EU28/RoW}$ being the total final demand for each region (both domestic and exports) as defined in final demand section. It is worth to mention that final demand of RoW products is calculated as the difference between the world's final demand and EU28's. The former is loaded directly from MEDEAS-World and the latter has been previously calculated in the model, as

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

explained in section 2.2.3.1. In this way, MEDEAS-Europe economy module is nested into the MEDEAS-World model. The first and second terms in Eq.16 are calculated separately, providing the model with the 'Total domestic output required by sector' and the 'Output required for intermediate exports by sector'. Once aggregated, EU28 production is collected in variable 'Total output required by sector'. Then, the model continues with the energy-economy feedback, as explained in the following section. Basically, production and demand are forced to adapt to final energy availability, since in MEDEAS the economic system is subject to biophysical constraints. Hence, if energy scarcity appears, production has to be shorten throughout the process explained in the following section. Once this adaption is completed (if that is the case), the final demand satisfied by this reduced production has to be necessarily lower. In order to respect the economic structure given by the A Matrix, an inverse process to that showed in Eqs.7-9 has to be followed. In essence, Eq. 13 must be solved for final demand (D) and not for production (X), resulting in Eq.17:

$$D = (I - A) * X \quad (17)$$

$(I - A)$ matrix follows the same rules as the L and A Matrixes for its size and number of sub-matrixes (see Eqs.11-12). However, there is no significant economic meaning of each submatrix. By pre-multiplying $(I - A)$ by the column vector of new productions (both EU28 and RoW), the column vector of final demand is obtained.

Once the feasible or 'real final demand' is estimated, we translate this variable into GDP, by adding intermediate exports (Z_{ij}^{rs}) and subtracting intermediate imports (Z_{ij}^{sr}), following Eq.4. These figures are calculated multiplying both EU28 and RoW productions (X_j^{EU28} and X_j^{RoW}) by $\boldsymbol{A_{sr}}$ and $\boldsymbol{A_{rs}}$. We know that EU28 total imports (both intermediate and final) are produced in RoW and all EU28 exports are produced inside its borders. Given that, by multiplying RoW and EU28 energy intensities (energy consumption per unit of output) by imports and exports respectively, MEDEAS-Europe is able to estimate the energy embedded both in imports and exports. Finally, by subtracting energy embedded in imports from energy embedded in exports, the model estimates the energy balance of trade or the energy trade footprint of EU28.

After that, the EU28 energy footprint can be estimated, as explained in section 2.7.3.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.2.3.3. Income

Previous section 2.2.3.2. has established the definitions for GDP in an economy with external sector. While at the world level this definition is right: GDP=∑VA=FD; at interregional level, one chain is not: GDP=∑VA≠FD. That implies that exogenous GDPpc growth scenarios are no longer valid to directly initiate the economy module. Since GDP is now defined (demand approach) as in Eq. 10, the only difference with GDP at the world level is the inclusion, in addition to total final demand, of the trade balance for intermediate products. For the sake of simplicity and, after observing that both final demand and value-added growth are highly correlated, it has been assumed that GDP growth is the same as final demand growth rate. Figure 40 shows that the differences between both variables are negligible, according to the data from WIOD (Dietzenbacher et al., 2013).

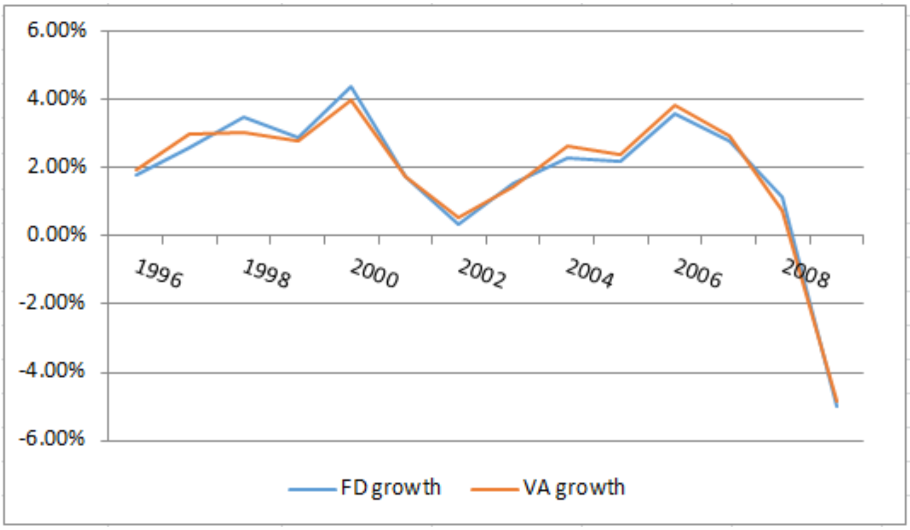


Figure 40. Final demand and value added growth in EU28 (1996-2009).

Moreover, if we estimate the ratio between them, the mean is approximately 1. Therefore, it is reasonable to assume that Value Added growth, i.e., GDP growth is equivalent to final demand growth. This assumption allows us to connect SSP scenarios with MEDEAS-Europe easily and ground them on empirical data (table 30).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Table 30. Final demand and value added growth and their ratio. Source: own elaboration with data from WIOD (Dietzenbacher et al., 2013).

	FD growth/VA growth	FD growth	VA growth
1995	-	-	-
1996	0.927	1.79%	1.93%
1997	0.864	2.58%	2.99%
1998	1.153	3.49%	3.02%
1999	1.042	2.89%	2.77%
2000	1.097	4.38%	3.99%
2001	0.980	1.72%	1.75%
2002	0.672	0.36%	0.53%
2003	1.060	1.54%	1.45%
2004	0.858	2.27%	2.65%
2005	0.926	2.21%	2.39%
2006	0.924	3.57%	3.86%
2007	0.951	2.79%	2.93%
2008	1.598	1.16%	0.72%
2009	1.028	-5.00%	-4.87%
Mean	1.0057	1.84%	1.87%
Standard Deviation	0.2003	0.0215	0.0211

While at the world level it was assumed that gross value added was at cost factor –including taxes less subsidies on production-, here it is disaggregated. Income shares have been estimated using Eurostat data. This made possible not only to obtain labor and capital shares, but also the GDP share on production taxes. Taking gross domestic product (income approach) for EU28 labor compensation (LAB), capital compensation, gross operating surplus, mixed income (CAP) and net taxes on production (TAX) can be used to estimate functional distribution for the period, as in Figure 41.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

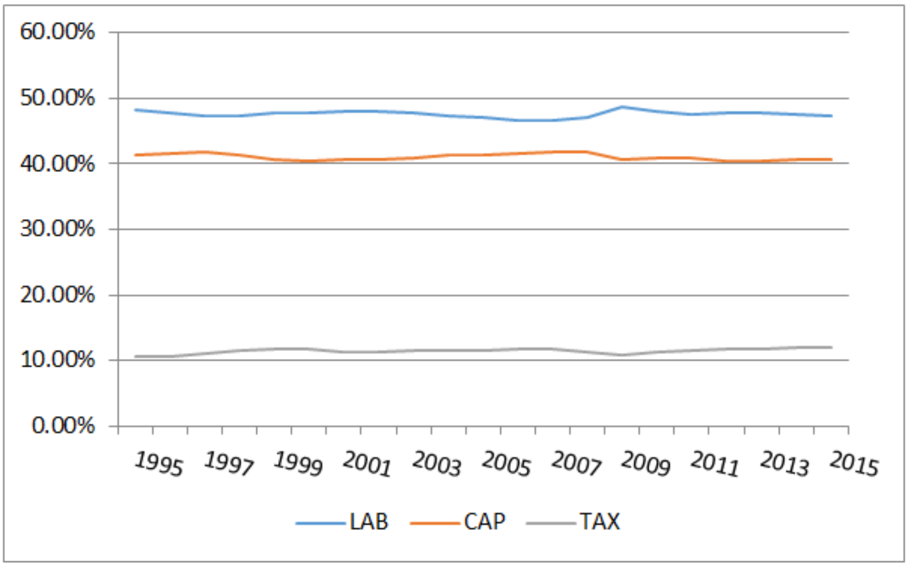


Figure 41. Functional income distribution EU 28 (1995-2015).

Given that now TAX is included, we cannot assume that α_{cap}=1-α_{lab}. Because of this, scenarios after 2015 must be estimated for both labor and capital shares.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.2.3.4. Energy-economy feedback

Most energy-economy-environment models consider economic growth to be independent from biophysical limits. In the MEDEAS framework, economy cannot trespass the boundaries set by nature. The Economy module is subject, at least, to an indirect and a direct feedback from the whole system. The indirect feedback is provided by the impacts of the emissions, as described in section 2.5. As the direct feedback for the economy module comes from the energy module, it is worth to focus here in this relationship, a key point of the model.

Once the production required to satisfy demand by sector is calculated as described in previous sections, the final energy required to satisfy demand is obtained by the Eqs. 18-19.

$$\hat{\mathrm{I}}_e = \hat{\mathrm{E}}\hat{x}^{-1} = \begin{pmatrix} \frac{E_{ij}}{x_i} & 0 \\ 0 & \frac{E_{nn}}{x_n} \end{pmatrix} = \begin{pmatrix} I_{e,ij} & 0 \\ 0 & I_{e,nn} \end{pmatrix}, \quad \mathrm{i} \in 1\ldots35; \mathrm{j} \in 1\ldots5 \qquad (18)$$

$$E = \hat{\mathrm{I}}_e x = \hat{\mathrm{I}}_e * L * D \qquad (19)$$

Let ê be the diagonal matrix of energy coefficients and Ê the diagonal matrix of total final energy demand (FED) by industrial sector (i) and final energy source (j). The energy coefficients stand for the energy intensities by sector and final energy source. World final energy consumption (FEC) by sector and energy source is collected from WIOD environmental accounts (Genty et al., 2012) and balanced with the International Energy Agency accounts. By pre-multiplying production by the energy coefficients (intensities), the model estimates the final energy required to satisfy demand. At this point, the energy demand of the economic system has to be compared with the energy available to supply it. Thus, FED required satisfying economy demand by sector and final energy source is compared with the final energy supply (FES) by source (Figure 42).

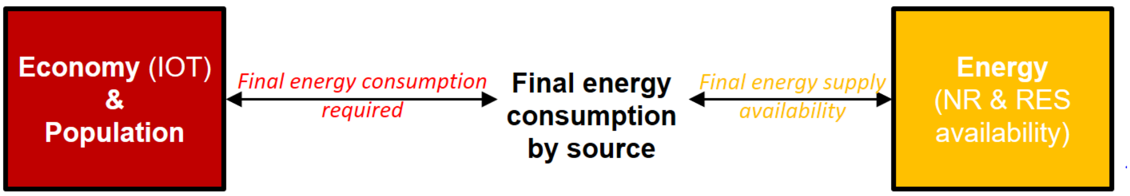


Figure 42. Energy-Economy feedback in MEDEAS.

Then, scarcity on one source can force the industrial sectors relying on this source to demand substitutive final energy types in the proportion established by the supply-demand gap. A shortage coefficient for each final energy source is calculated as a ratio between the FES and FED. In this

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

model version, we consider that the scarcest final energy source is the one that conditions the sectorial production process, following the approach of "limitant factor" applied in (Capellán-Pérez et al., 2015; de Castro, 2009). This shortage coefficient equals 1 when final energy consumption (FEC) satisfies demand, i.e. there is no supply restriction. In the case that energy demand is higher than energy supply, energy consumption matches the energy supply and the shortage coefficient is lower than 1, reducing the proportion of energy demanded which is actually consumed by each sector.

For each time period (Eqs. 20-23):

$$shortage\ coefficient_j = \frac{FES_j}{FED_j} \qquad (20)$$

If shortage coefficientj
- = 1: no energy constraints
- <1: energy constraints of fuel j

$$ShC = MIN(shortage\ coefficient_j) \qquad (22)$$

$$FEC_{i,j} = ShC \cdot FED_{i,j} \qquad (23)$$

Subscript i stands for the usual 35 industrial sectors plus household's final energy consumption and subscript j for the different final energy sources considered in MEDEAS. Finally, the energy limits transfer to the economy throughout an inverse Input-Output Analysis (IOA). Taking the inverse of energy intensity ($\hat{I}_e{}^{-1}{}_{ij}$) and the final energy actually consumed (E'_{ij}), feasible production is obtained (X'_i). Then, a set of feasible productions according to each final energy source is collected (Eqs. 24-25). The model is programmed to choose the minimum feasible production, as the scarcest final energy source is what limits the most, being consistent with the complementarity approach above mentioned.

$$\hat{I}_e{}^{-1}{}_{ij} * E'_{ij} = X'_i \qquad (24)$$

$$X' = Min\ (X'_i) \qquad (25)$$

Finally, the inverse process followed (from FD to X) takes places (from X' to FD') as described in the following equations (Eqs. 26-27):

$$X' = AX + FD' \qquad (26)$$

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

$$FD' = X(I - A) \quad (27)$$

In the model, this feedback is present not only at this level, but also for all relevant variables, which include 'not covered' as an addendum. For each variable included, the not-covered variables quantify the gap between the value of that variable with and without the feedback. Hence, when the energy demand is lower than the energy supply, not-covered variables equal 0. Contrarily, when there is energy scarcity, not-covered variables need to gather the quantities that should not be added in the subsequent periods. If they were not included, the feedback would only apply in the year when it appears, not responding dynamically in later years.

In the current version of MEDEAS, economy module is feedbacked by the energy availability (as well as indirectly by climate change impacts and EROI), obtaining a more realistic approach in the energy-economy-environment modelling. Without feedback between energy and economy, energy demand shall grow exogenously not taking into consideration availability of resources (Capellán-Pérez et al., 2016; Höök and Tang, 2013; Wang et al., 2017). The underlying assumption here is that this availability of resources matters, and that the functioning of the real economy depends on it. Thus, these models tend to look for an optimum energy mix regardless its supply availability –even though they usually take into consideration efficiency gains. Conversely, the energy-economy feedback provides a result that is not often taken into consideration in other IAMs.

As highlighted before, economic structure matters in MEDEAS. Each industrial sector has a different sensitiveness to final energy consumption by source. These are collected in Table 31 and, in Interregional Input-Output, for domestic production oriented to satisfy domestic demand are calculated as $\hat{I}_{ek}\ L_{rr}$L: diagonal matrix of energy intensities by sources 'k' times Leontief Matrix (upper-left quadrant). This represents the amount of final energy required to satisfy changes in final demand in monetary terms. For instance, we can see how sensitive is the consumption of fuels by sector 1 (Agriculture, Forestry, Hunting and Fisheries) to changes in demand. If demand of sector 1 rises in 1 million US$, there will be needed 1.26 EJ of electricity in order to satisfy it. Or how much fuel must be demanded by transport sectors (24 and 25, inland and water transport) in order to satisfy an additional US$ of demand. Sector 24 (inland transport) would require 26.14 EJ of fuels and sector 25 (water transport) 27.52EJ.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Table 31. Sectoral final energy sensitiveness by sources (EJ/million 1995 US$). Source: own elaboration.

Sectors	Electricity	Gas	Heat	Liquids	Solids
1	1.260	0.728	0.162	3.922	0.750
2	1.991	5.393	0.310	2.298	1.851
3	1.252	0.944	0.251	2.333	1.735
4	1.445	0.775	0.339	1.564	1.078
5	1.026	0.657	0.216	1.806	0.877
6	1.587	0.875	0.339	2.328	2.394
7	1.900	1.052	0.433	1.609	2.528
8	1.471	3.206	0.938	9.343	1.243
9	2.375	2.233	0.896	2.571	1.736
10	2.742	1.789	0.461	2.976	3.303
11	2.945	2.656	0.265	3.247	10.007
12	3.584	2.056	0.401	1.599	4.292
13	1.324	0.772	0.183	1.288	1.195
14	0.901	0.527	0.116	1.047	0.701
15	1.288	0.780	0.198	1.367	1.116
16	1.834	1.395	0.362	2.896	2.177
17	3.996	3.934	0.367	1.394	3.471
18	0.905	0.674	0.119	1.810	1.374
19	0.767	0.458	0.102	1.353	0.396
20	0.571	0.391	0.104	1.578	0.299
21	0.841	0.468	0.092	1.649	0.307
22	1.326	0.794	0.137	1.913	0.908
23	0.878	2.078	0.096	7.718	0.391
24	0.377	0.320	0.081	26.139	0.227
25	0.459	0.452	0.116	27.520	0.300
26	0.876	0.581	0.171	5.126	0.355
27	0.562	0.425	0.068	1.043	0.229
28	0.389	0.211	0.050	0.740	0.158
29	0.455	0.203	0.073	0.389	0.189
30	0.492	0.317	0.066	1.134	0.252
31	0.842	1.039	0.089	1.430	0.340
32	0.965	0.388	0.102	1.226	0.293
33	0.736	0.419	0.106	1.317	0.335
34	0.881	0.515	0.144	1.724	0.415
35	0.000	0.000	0.000	0.000	0.000

Finally, it is worth a brief comment on the evolution of energy intensities, described in detail in section 2.2.4. The historical data observed shows that even though sectoral energy intensities are slightly declining, they have remained more or less stable over time. However, different changes

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

may occur due to energy efficiency gains and change of energy technology in a sector. For the moment, energy intensities evolve following their trends but further developments could estimate the parameters to introduce the mentioned dynamics.

MEDEAS-World does not use trade, since all the energy consumed was produced at the same regional level. Thus, net energy final consumption could not trespass the biophysical boundary imposed by energy availability in the same region (the entire world). However, for the MEDEAS-Europe model it is not that simple. Boundaries can be artificially trespassed thanks to international trade, i.e. EU28 is able to consume more energy than it produces. Actually, this is the current situation for Europe and one of the main vulnerabilities in the context of world energy depletion. Hence, in order to take into account global limits on energy consumption, different scenarios can be applied. They are summarized in Table 32.

Table 32. Energy-economy feedback under different scenarios. Source: own elaboration.

Scenarios	Features
No limits	EU28 can import energy limitless.
Current shares	EU28 can import energy at current levels.
Fixed share	EU28 can import energy with a user-fixed level.
World scarcity->EU28 scarcity	MEDEAS-World scenarios impose scarcity to EU28.

In the 'No limits' scenario, there is no restriction for EU28. Thus, EU28 is allowed to import as much energy as it needs to consume, even if that means consuming 100% of the world's energy for each type. By contrast, the three other scenarios impose boundaries to energy consumption. 'Current shares' implies that, for each final energy source, EU28 can import no more than the current proportion of EU28 consumption over the world supply. 'Fixed share' lets the user to fix that proportion at will, regardless of current levels. Finally, there is the option to link MEDEAS-World results to MEDEAS-Europe. In this option, when energy scarcity appears at the world level, EU28 automatically starts to demand less energy in a determinate proportion. Even though that may sound like the most appropriate option, there might be no reason to assume that Europe is going to suffer scarcity even when the rest of the world is facing scarcity. Rather, EU28 could keep on consuming a higher proportion of world's energy as it can be stated in the 'No limits' and 'Fixed shares' scenarios. How the energy consumption is distributed amongst regions is also a measure of equality and has deep implications on the issue of a fair transition.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.2.4. Modelling of final energy intensities

In the world model, a method for calculating the final energy demanded to avoid double counting was developed. In the European model, due to the available data and trade exchanges, this method cannot be used.

Therefore, in the case of the European Union, we will calculate the energy consumption by final source, as it is explained below:

1. First, we need to compare the data calculated for the world (without double counting) for liquids, gases and solids with the original data taken from WIOD.
2. Through this sectoral and annual comparison of both values, we calculate a percentage that represents the variation.
3. The next step will be to calculate the average percentage for each sector over time.
4. Once we have these percentages calculated, we apply them to each sector for liquids, solids and gases, and so we calculate the energies in final source for the European Union without double counting.

After calculating the energy consumption for liquids, gases, solids, heat and electricity for the European Union we calculate the energy intensities following the same methodology as we did for the world, taking into account the data calculated previously.

The following figure shows an example of final energy intensities in some sectors for electricity (Figure 43).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

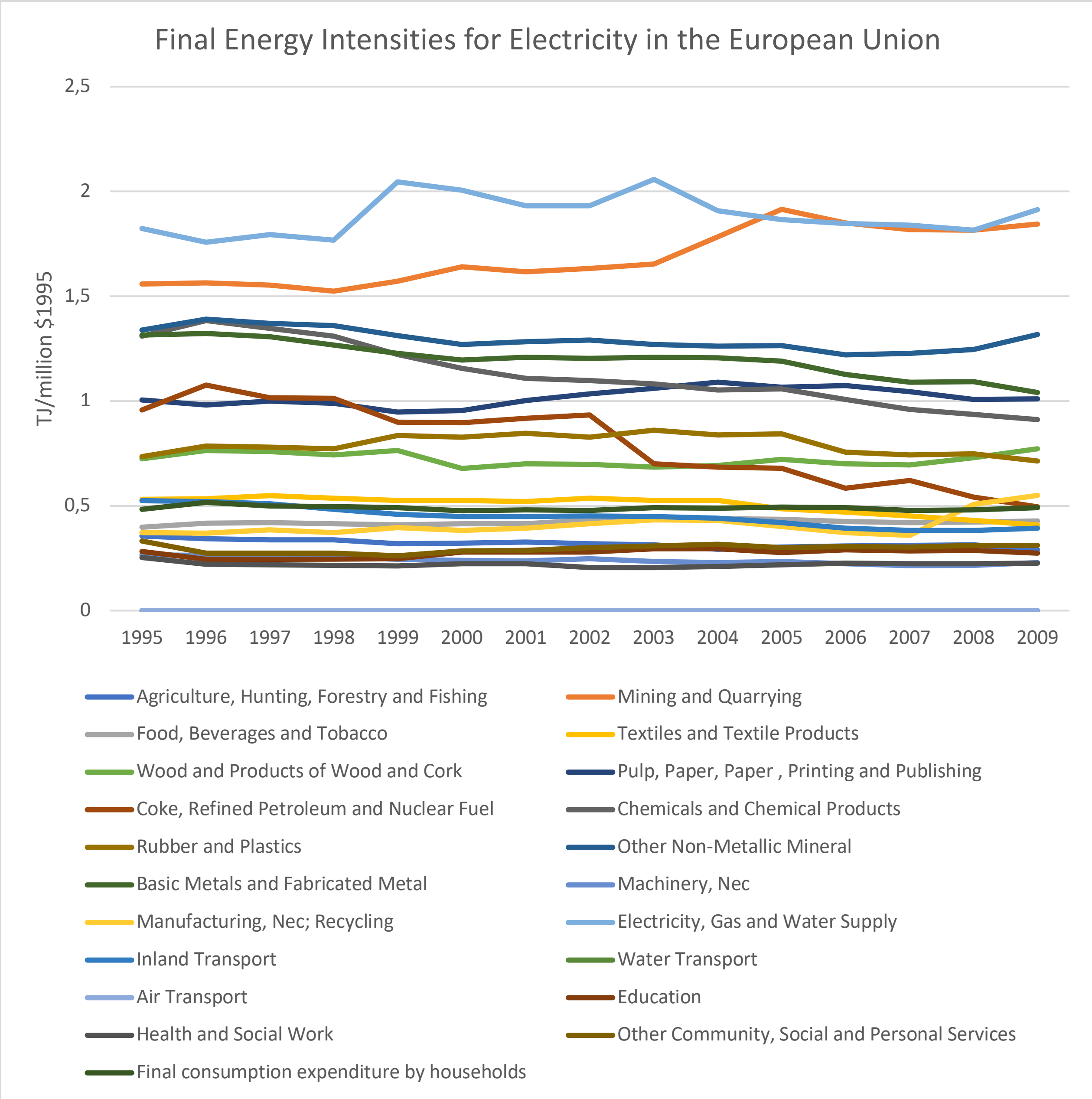


Figure 43. Historical evolution of electricity intensity by sector

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.3. Energy and infrastructures module

This part of the deliverable documents the estimation of energy demand (section 2.3.1), the energy supply (section 2.3.2), the energy resources availability in MEDEAS-EU (non-renewable resources in section 2.3.3. and renewable-resources in section (section 2.3.4**Error! Reference source not found.**), and the modelling of transport (section2.3.5). Primary energy in the model refers to the direct equivalent method.[2]

2.3.1. Estimation of energy demands

Methodology used for the estimation of energy demands in the MEDEAS-EU model is similar to the one employed for estimations in the MEDEAS-World model. Here, we include just a summary of main aspects. Deliverable 4.1 contains more detailed information.

2.3.1.1. Historic final demand

The WIOD database at the European level is the main source used to estimate the historic final energy data by fuel in order to match with the economic structure of the model. MEDEAS-EU aggregates the final energy sources in five categories: solids, liquids, gases, heat and electricity. The aggregation is performed using the WIOD database sources (Dietzenbacher et al., 2013; Timmer et al., 2012), which ultimately was built from the IEA database (IEA, 2016).

For the estimation of the 5 MEDEAS-EU categories of final fuels, the energy variable "Energy use, emission relevant" from WIOD energy data has been used with corrections, i.e., subtraction of energy associated to electricity/heat generation in order to avoid double counting.

[2] There are three alternative methods predominantly used to report primary energy. While the accounting of combustible sources, including all the fossil energy forms and biomass, is unambiguous and identical across the different methods, they feature different conventions on how to calculate primary energy supplied by non-combustible energy sources, i.e., nuclear energy and all renewable energy sources, except biomass. The direct equivalent method counts one unit of secondary energy provided from non-combustible sources as one unit of primary energy, that is, 1 kWh of (useful) electricity or heat is accounted for as 1 kWh = 3.6 MJ of primary energy. For more information see Annex II of (IPCC, 2011).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.3.1.2. Adjustment of energy demands to account for all non-commercial heat

In Deliverable 4.1 (section 2.3.1.3), the need for adjusting the demands of fuels to account for all non-commercial heat was justified in order to promote policies of substitution of non-renewable fuels by renewables sources in the heat sector.

The approach of MEDEAS-EU consisted on applying the global and static results from (IEA, 2014) which concluded that for the year 2011:

- More than 40% of primary energy supply of natural gas is used for heat production in industry and buildings.
- Around 20% each of world primary supply of coal and oil are also used for heating.
- Out of the 54 EJ of primary bioenergy supply in 2011, more than 80% were used for heat production in buildings, and a smaller amount (15% of the total) was used in industry.

A sectorial approach was thus not possible given the lack of available data. Thus, the total final energy demands for heat, solids, gas and liquids were modified accordingly assuming that the share of non-commercial heat in relation to the TPES of each source is maintained constant in the future (although this parameter can be modified by the user).

2.3.2. Energy supply in MEDEAS-EU

In MEDEAS-EU primary total energy demand is covered with different primary energy sources (see Table 33.).

Table 33. Sources of energy supply in MEDEAS-EU. Natural gas refers to both conventional and unconventional. Oil refers to both conventional and unconventional.

MEDEAS final energy category	NRE / RES	Energy source modelled in MEDEAS
Solids	NRE	Coal
		Peat
		Charcoal
		Waste
	RES	Primary solid biofuels (modern)
		Primary solid biofuels (traditional biomass)
Liquids	NRE	Conventional oil
		Unconventional oil
	RES	Biofuels (different generations and technologies)
Gases	NRE	Conventional gas
		Unconventional gas
	RES	Biogas
Electricity	NRE	Natural gas
		Oil
		Coal
		Uranium
	RES	Hydro
		Geothermal
		Solid bioenergy
		Oceanic
		Wind onshore
		Wind offshore
		Solar PV
		Solar CSP
Heat	NRE	Coal
		Natural gas
		Oil
		Waste
	RES	Geothermal
		Solar
		Solid biomass
		Biogas

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Although in practical terms heat can be demanded at different temperature levels (IEA, 2014),3 for the sake of simplicity, in this model version all heat demand and supply is aggregated.

[3] Heat-temperature ranges are typically defined as low (<100 degrees Celsius [°C]), medium (100°C to 400°C) and high (>400°C). Temperature levels are important to define the suitability of different supply technologies to meet specific heat requirements in the various end-use sectors (IEA, 2014).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.3.3. Non-renewable energy resources availability

MEDEAS-EU considers the following non-renewable primary energy resources:

- Conventional oil: refers to crude oil and NGLs.
- Unconventional oil: includes heavy and extra-heavy oil, natural bitumen (oil sand and tar
- sands) and oil shales, and biofuels.
- Conventional gas.
- Unconventional gas: includes shale gas, tight gas, coal-bed methane (CBM) and hydrates.
- Coal: includes anthracite, bituminous, sub-bituminous, black, brown and lignite coal.
- Uranium.

As explained with more detail in the section 2.8 of deliverable 4.1., we assume that the technologies which claim that they could increase the fissile material by 50 to 100 times, like fast breeders and the so-called fourth generation reactors, will not be available in the next decades. Nuclear fusion is not considered since the ITER and DEMO projects estimate that the first commercial fusion power will not be available before 2040 (http://www.iter.org). This would prevent this technology from substantially contributing to the energy mix in the timeline of MEDEAS.

2.3.3.1. Modelling of primary non-renewable energy resources in MEDEAS-EU

The availability of non-renewable energy resources in MEDEAS-EU depends on two constraints:

- Stock (available resource in the ground), ie., energy (Joules),
- Flow (extraction rate of this resource), ie., power = energy/time (Watts).

Figure 44. 44 illustrates the depletion over time of a non-renewable resource stock (cumulative extraction, grey dashed line) through flows (depletion curve, black solid line) in the absence of non-geologic restrictions (Kerschner and Capellán-Pérez, 2017). The maximum flow rate is reached much earlier than the full depletion of the stock, at half the time assuming that the extraction rate follows a logistic curve.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

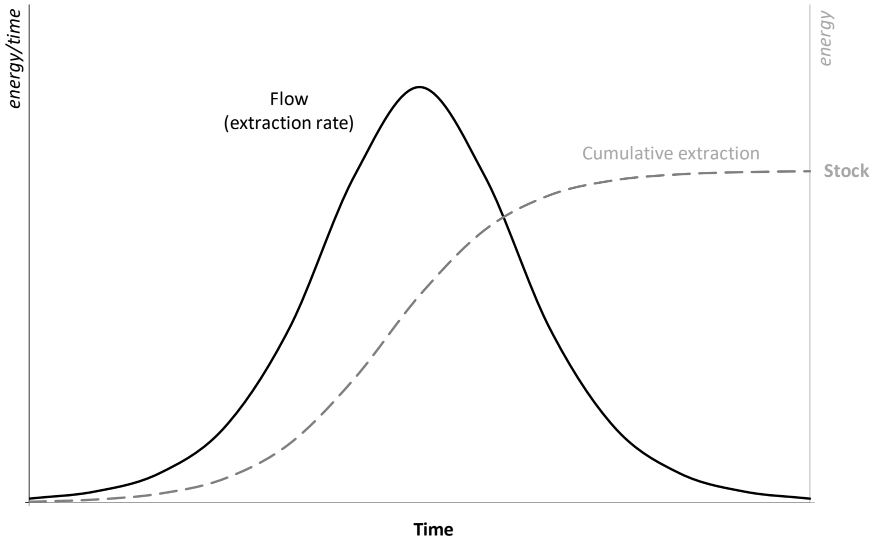


Figure 44. Simplified representation of the depletion of a non-renewable resource in the absence of non-geologic constraints. Stocks and flows of energy relative to time.

The available stock of a resource is usually measured in terms of ultimately recoverable resources (URR), or remaining RURR (RURR) if referenced to a given year. The RURR in a given time t is defined as the difference between the URR and cumulative extraction in time t (Eq. 28).

$$RURR_t = URR - cumulative\_extraction_t \tag{28}$$

In order to estimate the future availability of fossil fuels, we have reviewed the studies providing depletion curves for non-renewable energy resources taking into account both stocks and flow limits. These studies provide depletion curves as a function of time based by estimating the likely extraction rate of wells and mines. Although at global level there are many studies(e.g. (Aleklett et al., 2010; ASPO, 2009; EWG, 2013, 2008, 2007, 2006; Höök et al., 2010; Laherrère, 2010, 2006; Maggio and Cacciola, 2012; Mohr, 2012; Mohr et al., 2015; Mohr and Evans, 2011, 2009; Patzek and Croft, 2010; Zittel, 2012)), analyses focusing specifically on EU are scarce. For this reason, in the standard version of MEDEAS-EU the three cases from Mohr et al 2015 were built from the original dataset for the EU-28. However, any user can introduce any other curve and run a simulation. These curves should not be interpreted as projections of the extraction of a given fuel, but instead they represent curves of maximum possible extraction given the geological constraints (ie., assuming no demand or investment constraints).

The depletion curves of non-renewable energies reviewed in the literature represent extraction levels compatible with geological constraints as a function of time. Thus, to be incorporated as

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

inputs in the model, these depletion curves must be transformed, since demand is endogenously modelled for each resource. We assume that, while the maximum extraction rate (as given by the depletion curve) is not reached, the extraction of each resource matches the demand. Actual extraction will therefore be the minimum between the demand and the maximum extraction rate (Figure 45. 45a). To do this, the depletion curves have been converted into maximum production curves as a function of remaining resources (Mediavilla et al., 2013). In these curves, as long as the remaining resources are large, extraction is only constrained by the maximum extraction level. However, with cumulated extraction, there is a level of remaining resources that makes physical limits binding and maximum extraction rates are gradually reduced. The model uses a stock of resources (the RURR) and it studies how this stock is depleted depending on production, which is in turn determined by demand and maximum extraction (Figure 45. 45b).

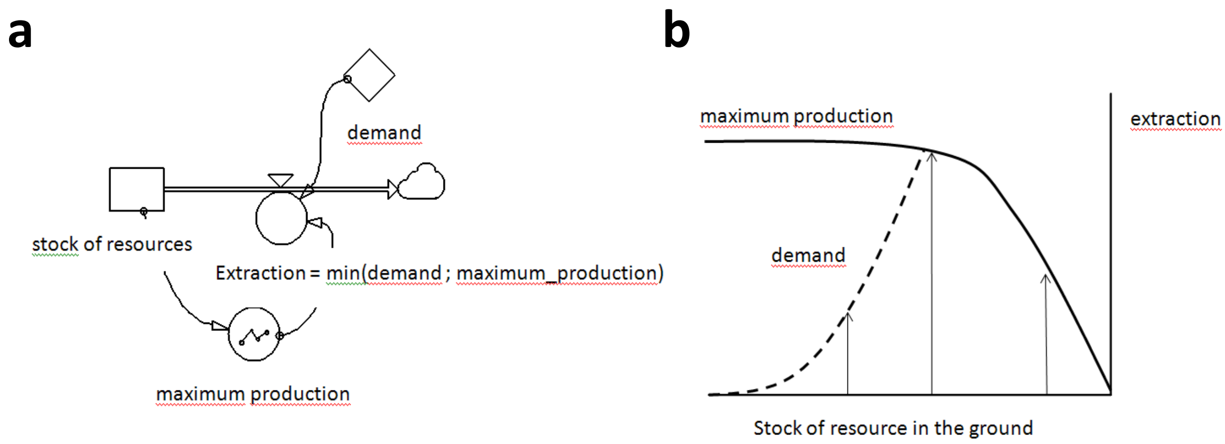


Figure 45. Integration of depletion curves in the model. (a) SD model. (b) A curve of maximum extraction (solid) compared with the demand (dashed).

Each study follows its own assumptions to derive the depletion curves of each fuel, and these should be carefully assessed before applying a depletion curve in the model by the users. The following subsections review the depletion curves of non-renewable energy resources by fuel found in the literature together with a brief discussion: oil (section 2.3.3.2.2), natural gas (2.3.3.2.3), coal (section 2.3.3.2.1) and uranium (section 2.3.3.2.1). MEDEAS allows selecting a diversity of depletion curves for each fuel (as well as considering a customized one or assuming the unconstrained extraction of the fuel).

The maximum extraction curve does not allow capturing the flow constraints when the peak rate of a fuel has not been reached. For this reason, unconventional oil & gas extraction is subject to an

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

additional constraint that limits the maximum annual growth extraction rate to avoid unrealistic growth extraction rates (see section 2.3.3.2).

2.3.3.2. Depletion curves by fuel

Studies elaborating depletion curves of non-renewable energy resources focusing on the EU are scarce in the literature. MEDEAS-EU incorporates the 3 availability cases (Low, BG and High) considered by (Mohr et al., 2015), reporting data at country level. Data at EU-28 level have been obtained as an addition of the individual countries. The consistency of Mohr's analysis at regional EU level has been assured checking with BP 2017 data (BP, 2017).

Comment on the nomenclature of Mohr' scenarios: we refer to Low-EU, BG-EU and High-EU given that the regional ranking of availability in the study does not always correspond to the global ranking (e.g. the Low-EU for unconventional oil does not correspond with the Low-global for that resource). Also, a higher URR does not always imply a higher rate of power extraction.

2.3.3.2.1. Coal

Coal production during the 20th century amounted to over 10 EJ/yr (with a dramatic decline during WWII), however since the early 1990s the production has declined declining dramatically reaching values of around 7.5 EJ/yr (see Figure 45). Mohr projections consider that the future production might increase slightly (Low and BG) or even double in the case of the High scenario to reach around 15 EJ/yr (Figure 46).

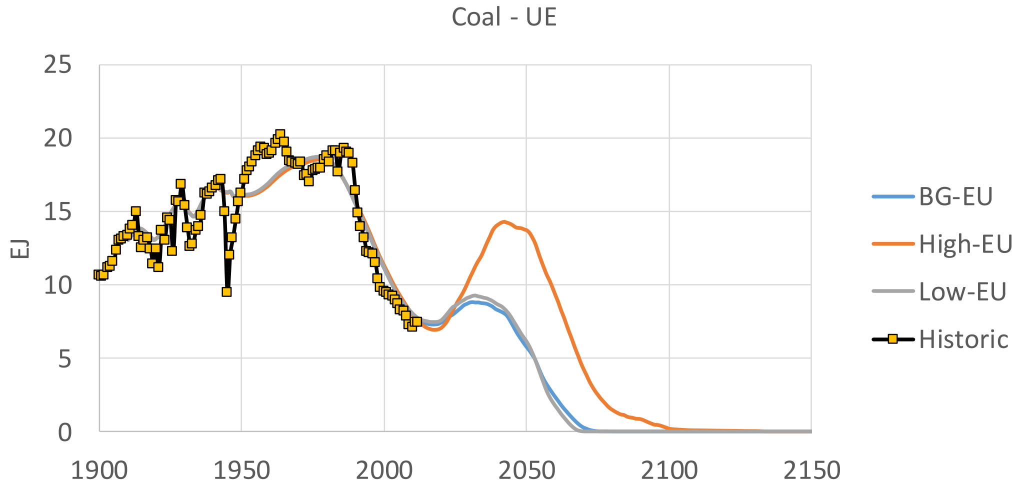


Figure 46. Coal historical extraction in UE-28 and 3 future availability cases (low, BG and high).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.3.3.2.2. Oil

Conventional oil dominates past extraction of oil in UE-28, with a peak between the end of 1980s and end of 1990s at almost 8 EJ. Current production has fallen dramatically, mainly to geological depletion in areas of high extraction (e.g. North Sea, UK and Norway (Capellán-Pérez, 2016)). Future extraction is only considered to be able to be roughly maintained at current levels in the most optimistic scenario (High-EU), which is well below the current consumption levels of liquids, i.e. > 22 EJ in 2015 (IEA balances) (Figure 47).

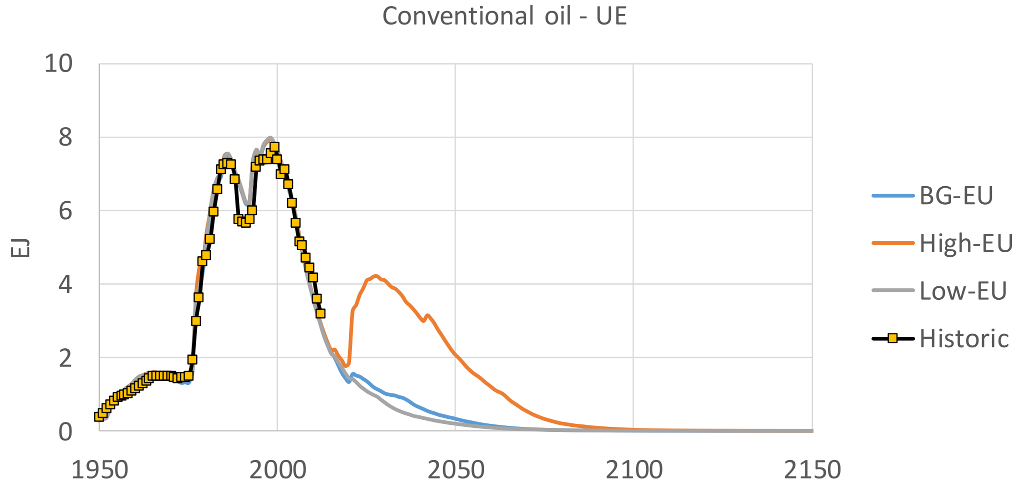


Figure 47. Conventional oil historical extraction in UE-28 and 3 future availability cases (low, BG and high).

Similarly, unconventional oil could only play a significant role under the “high” scenario and reaching a potential annual output of around 8 EJ, i.e. similar level to the maximum of conventional oil in the region (Figure 48).

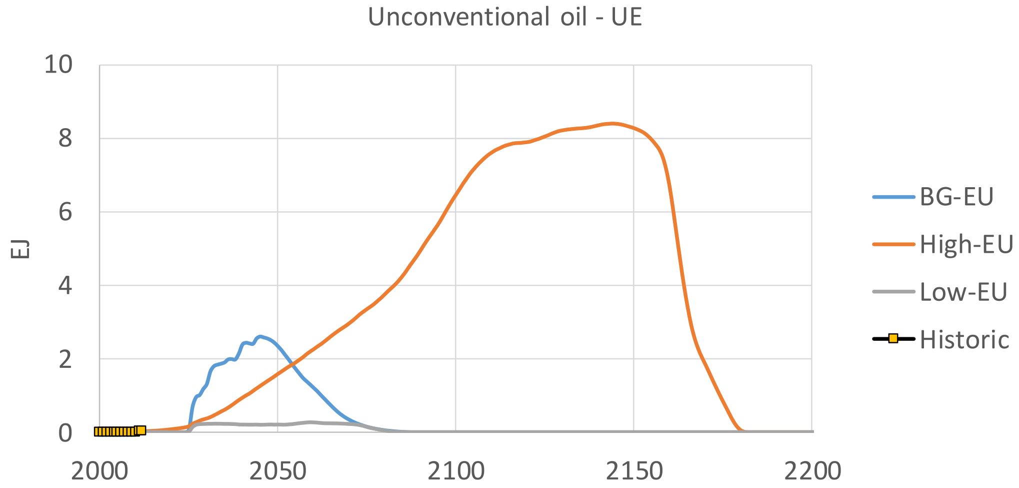


Figure 48. Unconventional oil historical extraction in UE-28 and 3 future availability cases (low, BG and high).

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691287

2.3.3.2.3. Gas

Mohr projections show a great agreement for the future availability of natural gas in EU, finding that in all cases extraction will tend to decrease in the next decades (Figure 49).

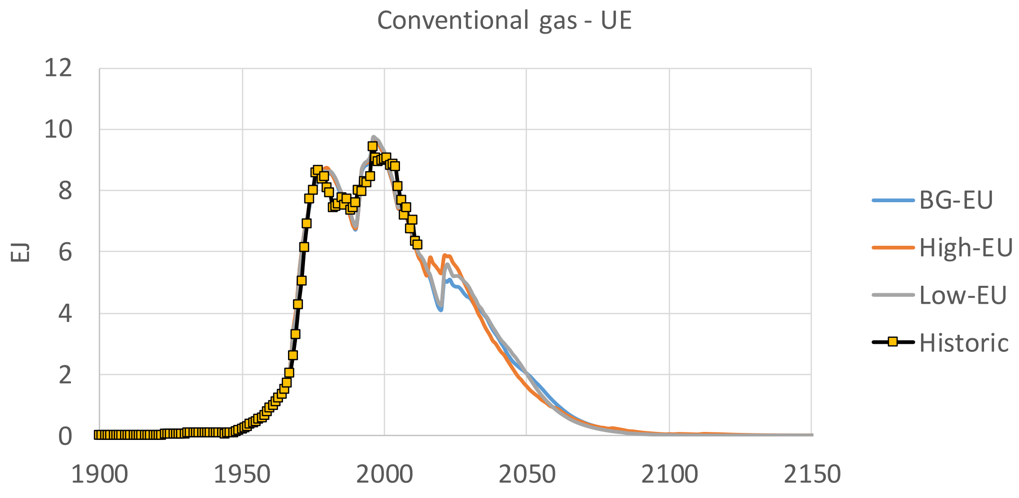


Figure 49. Conventional gas historical extraction in UE-28 and 3 future availability cases (low, BG and high).

There is great uncertainty in relation to the future geological availability of unconventional gas resources in the EU, maximum projections ranging from a mere 1 EJ/year for the low scenario and 7 EJ for the High. In any case, these numbers are to be compared with the current consumption of natural gas in the region, which amounts around 15 EJ/yr (Figure 50).

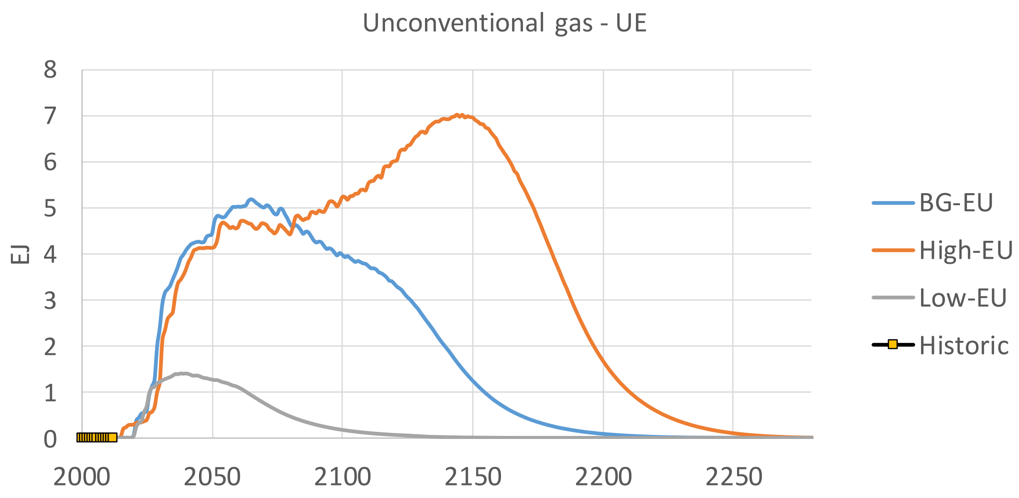


Figure 50. Unconventional oil historical extraction in UE-28 and 3 future availability cases (low, BG and high).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.3.3.2.4. Uranium

Extraction of uranium has strongly declined in the last 2 decades in the EU, falling from over 2,000 tons of metal extracted in 1995 to less than 300 in 2015 (BGS, 2017). No studies for the potential extraction of uranium at EU-level were found in the literature. Thus, given past trends and as a first approximation, it is assumed that in the next decades the UE will only be able to domestically extract the 2010-2015 average, the rest will have to be imported from the rest of the world (Figure 51).

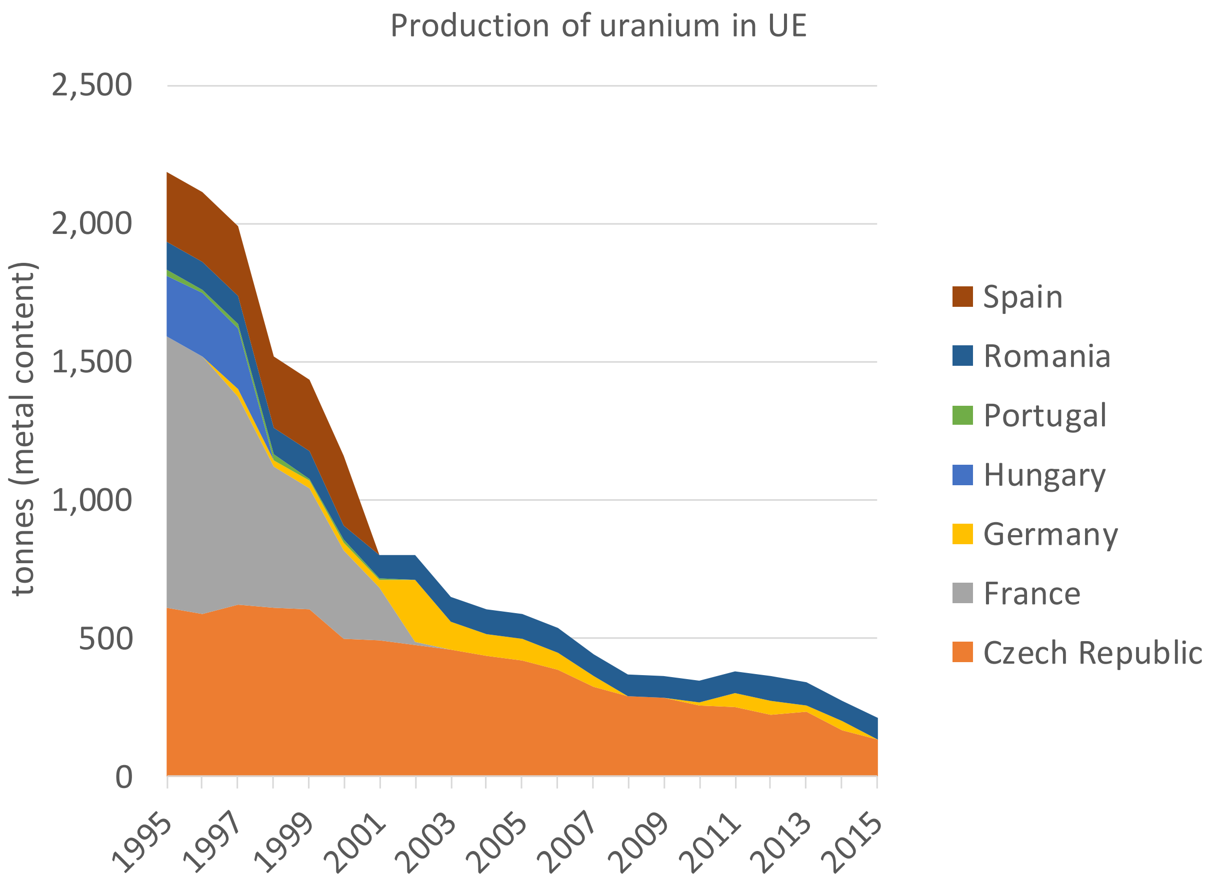


Figure 51. Historic production of uranium in UE (1995-2015).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.3.3.2.5. Depletion curves available in MEDEAS-EU

All the afore-mentioned curves are available as maximum extraction curves in MEDEAS-EU. Table 34 summarizes them.

However, we recall that these curves represent maximum extraction levels due to geological constraints, and "above-ground" factors (i.e. social, political, economic, cultural, etc.) might limit their actual constraints. In particular, the expansion of the extraction of unconventional oil from USA to other regions of the globe is highly disputable (Murray, 2016). Also, the extraction of unconventional gas implies a number environmental impacts (e.g. (Darrah et al., 2014; Howarth, 2015)). For these reasons, the by-default cases considered in MEDEAS-EU are "BG" for conventional fuels (coal, conventional oil and conventional gas) and "Lo" for unconventional fuels (unconv gas and unconv oil). The by-default cases considered in MEDEAS-EU are highlighted in grey in the Table 34.

Table 34. URR for each fossil fuel resource and case (low, best guess and high) for EU-28 from (Mohr et al., 2015). The by-default cases considered in MEDEAS-EU are highlighted in grey. Source: own work from (Mohr et al., 2015).

Fossil fuels (EJ)	BG-EU	Low-EU	High-EU
Coal	2,309.2	2,314.1	2,588.7
Conv oil	304.5	300.0	411.5
Unconv oil	77.5	14.2	722.7
Conv gas	538.0	542.0	540.8
Unconv gas	487.8	70.7	881.5

These depletion curves are subsequently transformed to curves of maximum extraction following the methodology afore-mentioned. Below we show the example of the curves built for unconventional gas (Figure 52).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

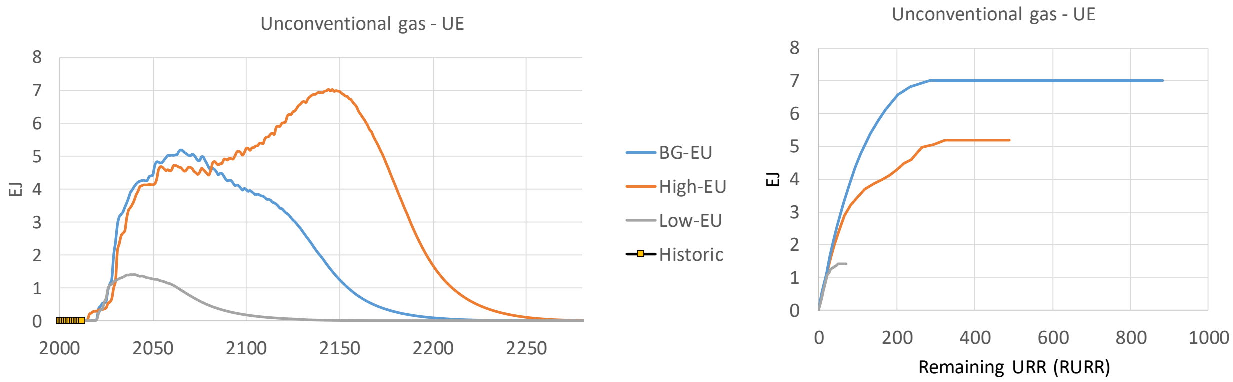


Figure 52. Domestic EU unconventional gas availability: (a) depletion curve as a function of time from the original reference; (b) curves of maximum extraction in function of the RURR as implemented in the model. The y-axis represents the maximum achievable extraction rate (EJ/year) in function of the RURR (EJ). As extraction increases and the RURR fall below the point where the maximum extraction can be achieved, the extraction is forced to decline following the estimations of the studies selected (panel (a)).

The same constraints to the (growth) extraction of unconventional fuels applied in D4.1 are also considered for the EU case.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.3.3.3. Waste to energy

Industry and municipal waste (renewable and non-renewable) are aggregated in the same category. In the period 1995-2014, the TPES has almost increased 4-fold reaching around 1 EJ by 2014 (+5.7% annual growth) (IEA, 2016). However, from a sustainable and social point of view, waste-to-energy is the worse option in terms of residues management. This issue has been recognized by the EU legislation which establishes a hierarchy of waste management options where the priority is given to prevention and reduction, and once the residues are generated, to its reuse and recycling (Koroneos and Nanaki, 2012). Thus, the application of sustainability policies in MEDEAS-EU translate into the reduction of the potential of waste. Current final use share and efficiencies of waste-to-energy are assumed constant given its past evolution (IEA, 2016).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.3.4. Renewable energy sources (RES) availability

Renewable energy is usually considered as a huge abundant source of energy; therefore, the technological limits are assumed to be unreachable for decades, and the alarm is supposed to be on the economic, political or ecological constraints (de Castro et al., 2011; IPCC, 2011; Kerschner and O'Neill, 2016). However, the large-scale deployment of renewable alternatives faces serious challenges in their integration within the electricity mix as a consequence of certain particular characteristics of these energy sources. In particular, their intermittency, seasonality and uneven spatial distribution, requiring storage (Lenzen, 2010; Smil, 2008, p. 362; Trainer, 2007); also, their lower energy density (de Castro et al., 2014, 2013, 2011; Smil, 2008); in many cases, their lower EROI than fossil resources (Prieto and Hall, 2013); their dependence on more or less scarce minerals and materials for the construction of power plants and related infrastructures (de Castro et al., 2013; García-Olivares et al., 2012); and finally, their associated environmental impacts (Abbasi and Abbasi, 2012; Danielsen et al., 2009; Keith et al., 2004; Miller et al., 2011). All together, these issues significantly reduce their sustainable potential (Capellán-Pérez et al., 2014; de Castro et al., 2014, 2013, 2011; Smil, 2008; Trainer, 2007).

In this section, we attempt to provide preliminary estimates for the techno-sustainable potentials of renewable energy sources considered in MEDEAS-EU. However, we highlight that this is a parameter fully customizable by the users of the model.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.3.4.1. Biomass-based

2.3.4.1.1. Solid bioenergy

In MEDEAS-EU, it has been assumed that potential is endogenous to the model, depending on the stock of exploitable forest from the Land module, according to the next equation (Eq. 29)

$$\text{km}^3 \text{ of wood x wood energy density } (\text{EJ/m}^3) \qquad (29)$$

The user can also decide the extraction rate, i.e. sustainable exploitation vs overexploitation.

2.3.4.1.2. Liquid biofuels

Potential is endogenously defined, depending on the "available land" in the Land module (section 2.6).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.3.4.2. RES for heat (excluding bioenergy)

2.3.4.2.1. Solar thermal

In MEDEAS-W this potential was estimated exogenously and introduced directly in EJ (Deliverable 4.1.). However, in MEDEAS-EU the potential of solar thermal is modelled endogenously, as done for PV in urban areas (available rooftop not assigned to PV, user selection by scenario).

Following data from (SHC, 2016), and taking into account the following relationship to estimate the power density (ρ_e, W_e/m^2), it is possible to endogenize the potential of solar thermal depending on the irradiance (I) of the considered region (see also (Capellán-Pérez et al., 2017b), according to the next equation (Eq. 30)

$$\rho_e = 700 \cdot \frac{W}{m^2} \cdot Cp \cdot Losses = I \cdot f_1 \cdot Losses \qquad (30)$$

Where,

700 W/m^2: nominal capacity of solar heat collectors;

f1: efficiency of the solar panel collector

C_p: capacity factor

Losses: energy losses in storage and pipelines

In this way, the potential is dependent on (1) the extent of urban areas; (2) the deployment of PV in urban areas and (3) the irradiance of the considered region.

2.3.4.2.2. Geothermal

The global geothermal technical potential for heat has been estimated by (Steffansson, 2005) at 41.6 EJ/yr with a range between 9.5 and 312.2 EJ/yr.

Considering the break-up for OECD-Europe from (IPCC, 2011), and since the ratio UE vs world for both the lower and upper value of the range is similar (i.e. 0.5/9.5~16/312.2~5%), the potential (primary energy) of geothermal for direct uses is = 41.6*5%= 0.23 TWh.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.3.4.3. RES for electricity generation (excluding bioenergy)

2.3.4.3.1. Hydroelectricity (without storage)

Global current production is estimated about 4,100 TWh (REN21, 2017), which is 47% of the potential considered in MEDEAS-World (1 TWe) (MEDEAS, 2017a).

Current production in UE (2015) has been estimated about 390 TWe (Eurostat, 2018). Given the high historical development of this technology in Europe, the capacity to increase the installed capacity in relation to the potential is lower comparing to the rest of the world (REN21, 2017). IEA, in the Blue Map Scenario (http://www.iea.org/publications/freepublications/publication/hydropower_essentials.pdf) until 2050 projects an increase in hydropower capacity in relation to current levels of +20% for UE vs +50% for the whole world. Thus, it can be assumed that the increasing potential for the EU is 2.5 times lower than the worldwide potential (aprox. 100 %), that is, an average of 25 %, with a range between 487.5TWh or 0.055TWh.

2.3.4.3.2. Pumped hydro storage

To calculate the PHS potential, it has been applied the 25 % rule of total hydro potential (Gimeno-Gutiérrez and Lacal-Arántegui, 2015; MEDEAS, 2017a). That is, PHS potential = 0.055*0.25 TWe.

2.3.4.3.3. Energy from Geothermal sources

Potential in the EU is proportional to the ratio of its terrestrial surface (excluding permanent ice) in relation to the world. The EU represents 3.3% of the world total: potential EU = 0.6*3.3% = 0.02 TWe.

2.3.4.3.4. Marine energy

Energy from marine sources is generated by using novel technologies, so there is a lack of accurate estimations for the EU. However, it has been considered that sea waves on coasts and tidal resources are limited due to physical dissipation (MEDEAS, 2017a). Therefore, it is expected that this resource will not contribute significantly in the near future energy mix in Europe.

Arbitrarily, it has been estimated as Marine energy = 20*current generation (IRENA db, 2017), i.e. 0.0011 TWe.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.3.4.3.5. Wind onshore

In the European continent (including non-EU areas), approximately 14.2 % of total wind areas are suitable for wind onshore energy generation, compared to the 9.2 % worldwide (Archer and Jacobson, 2005). Using the same proportion for the EU (3.28 % of global onshore area*14.2/9), about 5.2 % of the EU would be suitable for onshore wind energy generation respect to the world. However, most of the potential wind areas mapped for Europe are placed within the EU (Archer and Jacobson, 2005), so it can be assumed that the 1,491,000 km^2 suitable for onshore wind power generation are located within the EU. Since all the territories suitable for onshore wind power generation on ice-free areas account for 12.2 Gm^2, then about 12.2 % of suitable winds would circulate in the EU territories. Thus, the onshore wind potential would be in a range between 0.052-0.122 TWe, with a best guest around 0.1 TWe (10 % of total).

2.3.4.3.6. Wind offshore

The EU continental shelf represents 20% of worldwide continental self (assuming that North Atlantic continental shelf entirely becomes to the EU). Thus, about 20 % of total offshore wind power generation potential could be assumed for the EU. More precisely, if EU suitable wind offshore areas within the continental shelf was 3.66 Gm^2 (low relief area + 50 % of medium relief area) and worldwide equivalent was 8.34 Gm^2 (worldwide continental shelf, excluding Antarctic and Artic Oceans, and using remoteness criteria), then almost 44 % of total suitable offshore wind power generation areas belonged to the EU. Therefore, between 20-44 % of total potential for offshore wind power generation would be inside the EU borders, with a best guest of 0.1 TWe (about 0.25 TWe) (bluehabitat.org, 2017).

2.3.4.3.7. PV urban in MEDEAS

In MEDEAS-W version delivered in the project (MEDEAS-W 1.1), as a first approximation, all the PV modules were assumed to be located on land. In the current version of the model the possibility to locate solar in urban areas (mainly rooftops) has been included.

Methodology

PV in urban areas have some particularities in relation to power plants on land: notably a worse performance given that the panels have to adapt to an existing infrastructure (Capellán-Pérez et al., 2017a). However, for the sake of simplicity and as a first approximation, PV in urban areas has not been modelled as an additional electric renewable ("RES elec") technology. Instead, the user can select for each scenario the share of the total PV installed in urban areas in relation to the total PV installed, as well as the

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

share of rooftops for PV in relation to other uses (solar thermal, green roofs, daylighting, etc.)[4]. The installed power on urban areas is constrained by the available potential, which may eventually limit the actual installed PV power on urban areas. The available potential is estimated following the methodology presented in (Capellán-Pérez et al., 2017a), which found that in current conditions, a plausible maximum range dedicated to PV systems would be in the order of 2–3% of urban areas, according to the next equation (Eq. 30).

$$potential\ PV\ urban(t) = urban\ area \cdot \rho_e(t) \tag{30}$$

The net global solar power density (ρ_e) of solar PV in urban land is estimated as follows (Eq. 31):

$$\rho_e(t) = I \cdot f_1(t) \cdot f_2 \cdot f_3 \tag{31}$$

I represents the annual global average solar irradiance for (168 W_e/m^2) and the factors f1, f2 and f3 account for the losses related to the cell efficiency conversion (user defined), the average performance ratio over the plant's life cycle (0.67) and the land-occupation ratio defined for urban lands as formulated (Eq. 32):

$$f_3 = 2.5\% \cdot share\ of\ rooftops\ available\ for\ PV\ \cdot \tag{32}$$

Given to the fact that PV in urban areas is not modelled as a separate technology, the user can select the share of the total PV to be installed in urban areas during the simulation period (the rest will be on land). This share is however constrained by the total potential in urban areas (endogenous variable). The historical share of rooftop at global level is not currently known given that in many countries differentiation between rooftop PV and utility scale PV is not recorded (Khetarpal, 2016). As a first approximation, we consider the historic share for rooftop PV in the EU-27 estimated by (van de Ven et al., 2018): 61.3% (2005); 44.6% (2010) and 51.6% (2015).

With this approach, the performance of PV in urban areas and on land is the same: same f1, PR and EROI.

Results: PV on urban land at EU level

Considering the next assumptions:

[4] This parameter also allows constraining the geographical extent of the installation of solar PV in urban areas.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

- Global urban area of 300 Mha (middle from the 200-400 range given by (de Castro et al., 2013))
- Share of rooftops available for PV = 50%
- Cell efficiency increases from current 12% to 20% in 2050
- Built-up area from (FAO and IIASA, 2009): 142,000 km^2 (14.2 Mha)
- Solar irradiance: "scenario distributed generation over UE" average of country levels of France, Germany, Hungary, Poland, UK and Spain: 135 W_e/m^2.

The potential for PV on urban land at the European level is illustrated by the Figure 53.

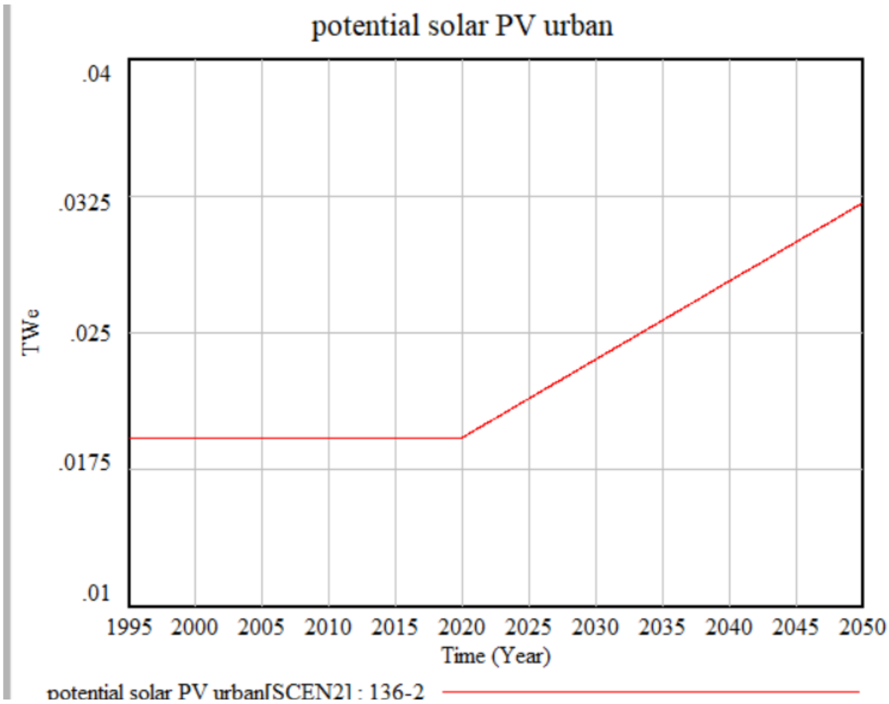


Figure 53. Potential of PV on urban land at European level

This result could be compared with other estimations in literature (e.g. (Šúri et al., 2007)).

2.3.4.3.8. Solar on land (CSP and PV)

The potential of solar on land for both CSP and PV is endogenous as a function of the available land (see Land module). Thus, depending on the competing uses of land in each scenario, the potential will vary. We apply the approach used for solar PV in urban areas, but replacing "urban areas" for "Land availability" and considering f3 corresponds with the region Temperate1 in (Capellán-Pérez et al., 2017a), i.e. 0.23).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.3.5. Transport

The Transport module in MEDEAS-Europe is very similar to the transport module of MEDEAS-World (see details in Deliverable 4.1). It is based on five views that treat *Energy demand for transportation*, *Households transportation*, *Inland commercial transportation*, *Total number of vehicles* and *Batteries for alternative transportation*.

As in MEDEAS-World, modelling of the transport sectors is based on two main dynamics: a general enhancement of liquid-based vehicles due to improvements in motor efficiency (which is relatively low since vehicle market is already covered by fuel economy standards (IEA/OECD, 2014)) and a shift from one type of vehicle to another with a different energy source. The model separates commercial transportation (Inland, Air and Water Transport sectors) and households transport activity. For Inland Transport and Households transportation, the vehicle shift is considered as well as the general efficiency improvement, in Air and Water transportation only the general improvement is studied.

The changes of vehicles considered are from conventional liquids-based vehicles to battery electric, plug and non-plug-in hybrids and natural gas vehicles for all types of vehicles. Biofuels and LPG are considered liquid fuels and are not included for vehicle change. One of the policies that might lead to important energy saving and has been introduced in the model, is the shift from four wheelers to two and three wheels vehicles, which is combined with the electrification of two wheelers. Changes in mobility patterns that require profound social transformations, such as shift to public transportation, non-motorized transport or very light electric vehicles (electric bikes and three wheelers) for the moment, are not included in the model. Cars using hydrogen, synthetic fuel and similar alternatives are not introduced in the model as they are still in a developmental stage.

Household vehicles are organized into six types: liquid, electric, hybrid and gas four wheelers and liquid and electric two wheelers. Inland Transport vehicles are classified into the following types: liquid, hybrid and gas heavy vehicles (trucks); liquid, hybrid, electric and gas light cargo vehicles; liquid, electric, hybrid and gas buses; electric and liquids trains. Classification and the data came from EU2017 (EC, 2017). Statistical data about alternative vehicles has been obtained from (IEA/OECD, 2017), and energy for vehicles from TERM2016 (EEA, 2016).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.3.5.1. Households intensity variation

The methodology used to calculate energy savings due to vehicle change is the same used in MEDEAS-World model. Households intensities are the relation between their economic demand and the energy of each type consumed. The change of these intensities is related to the changes of types of vehicles using the following equations (Eqs. 33-35), (that where described in section 2.14.7.1 of Deliverable 4.1)

$$\frac{dIH_{liq}}{dt} = A_1 \frac{d}{dt}\%H_{liq4w} + A_1 \cdot sr_{hyb} \cdot \frac{d}{dt}\%H_{hyb4w} + A_2 \cdot \frac{d}{dt}\%H_{liq2w} \quad (33)$$

$$\frac{dIH_{elec}}{dt} = A_1 \cdot sr_{elec4w} \frac{d}{dt}\%H_{elec4w} + A_2 \cdot sr_{elec2w} \cdot \frac{d}{dt}\%H_{liq2w} \quad (34)$$

$$\frac{dIH_{gas}}{dt} = A_1 \cdot sr_{gas4w} \frac{d}{dt}\%H_{gas4w} \quad (35)$$

Being $\%H_{liq4w}, \%H_{hyb4w}, \%H_{liq2w}$ the percentages of liquid four wheelers, hybrid four wheelers and liquid two wheelers, $\frac{dIH_{liq}}{dt}, \frac{dIH_{elec}}{dt}, \frac{dIH_{gas}}{dt}$,the derivatives of the intensities of Households Transportation to each type of fuel and $rs_{hyb,}sr_{elec2w}, sr_{elec4w}, rs_{gas4w,}$ the ratios between the efficiencies of each vehicle compared to the one of average four wheelers of liquid fuels. Parameters A_1 and A_2 are estimated using the values of the initial calibrating year (default 2015).

For the intensity of Inland Transportation sector, a similar approach is used, and changes in the intensities are related to the changes in percent of vehicles using the following equations (Eqs. 36-38):

$$\frac{dI_{liq\ inland\ t}}{dt} = CX_{HV} \cdot \frac{d}{dt}\%HV_{liq} + CX_{LV} \cdot \frac{d}{dt}\%LV_{liq} + CX_{bus} \cdot \frac{d}{dt}\%bus_{liq} + CX_{train} \cdot \frac{d}{dt}\%train_{liq} \quad (36)$$

$$\frac{dI_{elec\ inland\ t}}{dt} = CX_{LV} \cdot sr_{elec\ LV} \cdot \frac{d}{dt}\%LV_{elec} + CX_{bus} \cdot sr_{elec\ bus} \cdot \frac{d}{dt}\%bus_{elec} + CX_{train} \cdot sr_{elec\ train} \cdot \frac{d}{dt}\%train_{elec} \quad (37)$$

$$\frac{dI_{gas\ inland\ t}}{dt} = CX_{HV} \cdot sr_{gas\ HV} \cdot \frac{d}{dt}\%HV_{gas} + CX_{LV} \cdot sr_{gas\ LV} \cdot \frac{d}{dt}\%LV_{gas} + +CX_{bus} \cdot sr_{gas\ bus} \cdot \frac{d}{dt}\%bus_{gas} \quad (38)$$

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Where $\%HV_{liq}$, $\%HV_{hyb}$, $\%HV_{gas}$ stand for the percent of heavy vehicles of different fuels, $\%LV_{liq}$ $\%LV_{elec}$, $\%LV_{hyb}$, $\%LV_{gas}$ for light cargo vehicles, $\%bus_{liq}$, $\%bus_{elec}$, $\% \, bus_{hyb}$, $\%bus_{gas}$ for buses of different types $\%train_{liq}$, $\%train_{elec}$ of and trains all relative to each group of vehicle. Constants $CX_{vehicle}$ are calculated using the initial values of vehicles, for each vehicle.

Similar saving ratios as the ones described for Households Transportation are used. A summary is shown in Table 35, and a detailed discussion of these values can be found in in section 2.14.7.3 of Deliverable 4.1.

Table 35. Saving ratios estimated for different vehicles and fuels compared to liquid-based equivalent vehicles.

	Electric	Hybrid	Gas
Light four wheelers	0.33	0.6	1
Heavy vehicles and buses	0.50	0.6	1
Two wheelers	0.21	-	-
Trains	0.60	-	-

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.3.5.2. Transport Policies

The implementation of transport policies in MEDEAS-Europe is based on the growth of the percent's of vehicles. The value of the variables *P percent elec Hveh, P percent hyb Hveh, P percent gas Hveh, P percent 2w elec* determines the value of each percentage in the final year of the policy (*T fin Hveh*). The percent is relative to each type of vehicle (two or four wheelers). Additionally, the variable *P share 2wheelers*, determines the percent of two wheelers. For the vehicles of Inland Transport sector similar variables are used: *P percent HV hyb, P percent HV gas, P percent LV elec,* etc.

The stock of electric, plug-in hybrids and natural gas-powered vehicles is still very low compared to the global number of vehicles. The 200.000 electric vehicles sold in Europe in 2016 are an important achievement (helped by the estate incentives of France, Germany and Norway), but this number still pales compared to the 14.6 million new registrations of all cars. MEDEAS-Europe considers an BAU scenario for the growth of alternative vehicles with the same percent of vehicles in the final year of the policy as those considered for the World and described in Deliverable 4.1. The BAU scenario is based on a linear growth that continues the observed increment of these vehicles in last years. The only difference is stablished in the electric 2 wheelers, which are very common in Asia but are almost non-existent in Europe, and in electric railways, more common in Europe than the average Worlds number.

The prospects for alternative vehicles are highly uncertain, as the breakthrough to fully commercial models has yet to come and consumers would have to adjust to the characteristics of the new vehicles. Therefore, a more optimistic scenario about the growth of alternative vehicles must have a high component of speculative thinking. Scenario 2 has been defined multiplying the objectives of BAU scenario, in some cases one order of magnitude. Still the final percentage of alternative vehicles is small due to the delays of the stock of vehicles. For a detailed description of the choice of the parameters of the BAU scenario, please, refer to Deliverable 4.1.

The batteries needed for the electric and hybrid vehicles of all types have been calculated using the ratios described in section 2.14.7.4.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Table 36. Objectives of stocks of alternative vehicles in the final year of the policy expressed in terms of the percent of vehicles relative to each class for BAU and Scenario 2.

Type of vehicle	Percent in year T fin (2050 default) BAU	Percent in year T fin (2050 default) Scenario 2
Electric households 4 wheeler	0.64	6.4
Hybrid households 4 wheeler	1.08	10.8
Gas household vehicle 4 wheeler	14.89	30
Electric 2 wheeler	0	10
Percent 2 wheelers	33.25	33.25
Hybrid heavy vehicles	0.045	0.45
Gas heavy vehicles	0.045	0.45
Electric light cargo vehicles	0.074	0.74
Hybrid light cargbo vehicles	0.036	0.36
Natural gas light cargo vehicles	1.597	15.97
Electric bus	0	6
Hybrid bus	0	10
Natural gas bus	0	30
Electric train	90	90

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.4. Materials module

In the materials module, MEDEAS-EU follows a similar structure to MEDEAS-W (deliverable 4.1.). Thus, the same set of minerals is considered: Aluminium (Al), Cadmium (Cd), Chromium (Cr), Copper (Cu), Galium (Ga), Indium (In), Iron (Fe), Lithium (Li), Magnesium (Mg), Manganese (Mn), Molybdenum (Mo), Nickel (Ni), Lead (Pb), Silver (Ag), Tin (Sn), Tellurium (Te), Titanium (Ti), Vanadium (V), and Zinc (Zn).

However, the difficulty to find consistent and homogenous data at EU-level for the variables used in MEDEAS-W, and other additional variables required to model trade (e.g. past production and consumption, reserves and resources, recycling rates, etc.) compelled to adapt the modelling. In particular, the databases shown in table X have been reviewed.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Table 37. Mineral databases reviewed for the MEDEAS-EU model.

Database	Data provided	Area/Countries	Minerals	Data period
USGS. USA Geological Survey	There are only data available for **mineral production.** They can be downloaded in MSExcel format. Data files are released each year, so, in order to have a long historical data series files must be grouped together.	Data are aggregated in Europe and Central Eurasia. Another option could be to aggregate all countries which are included in EU-28 (there are not data for all of them)	We have data for the following minerals: aluminum, copper, iron and steel, lead, manganese ore, nickel, silver, tin, titanium and zinc.	1995-2013 Different years in each file
BGS. British Geological Survey	There are data available for **mineral production, exports and imports**. They can be downloaded in an MSExcel file, but also in PDF.	We do not have data for every country in EU-28. It could be because not in every country exists production of every mineral.	We have data for all minerals needed, but we can only download data for one mineral each time.	1970-2015 Disadvantage: data can be downloaded for a maximum of ten years each time.
Euromines. European Association of Mining Industries, Metal Ores & Industrial Minerals	There is only data available for **mineral production**. Data is not available in MSExcel format; they are only displayed in the screen.	We do not have data for every country in EU-28.	We have data for the following minerals: Aluminum, Antimony, Bauxite, Copper, Gold, Iron, Lead, Manganese, Nickel, Platinum, Silver, Titanium, Tungsten and Zinc.	1999-2015
Minerals4EU	We have data for **mineral production, imports and exports, resources and reserves**. Data are not available in Excel format. They are displayed in the screen.	We have data for all the countries in the EU-28. In order to gather all data, it is necessary to do it country by country.	We have data for all minerals except aluminum, gallium and titanium.	2004-2013

The review of databases revealed that there is no database that includes all the dimensions required for modelling minerals in MEDEAS-W. For example, just 1 out of 4 databases include

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

information for the whole dataset of minerals included in MEDEAS (BGS), but this database lacks information related to the level of reserves and resources at EU-level. In fact, as reported by Minerals4EU, the reserve and resource available data at EU member state level belong to different reporting systems (e.g. JORC, PERC or NI 43-101, or to a national system restricted to an individual country or group of countries). Because of these variations in reporting methodology, it is inappropriate to aggregate the resource and reserve data presented to determine national or European totals because the figures are not directly comparable.

Thus, the modelling of materials in MEDEAS-EU has to be adapted to data availability, and consists mainly of:

- Modelling of future demand of minerals for the main RES technologies for the generation of electricity (CSP, PV, wind), grids (high power, HVDCs) and EV batteries, with the method already explained within the section 2.4.1.1 of deliverable 4.1.,
- Recycling levels of minerals in EU correspond with the World average (section 2.4.3 of deliverable 4.1)
- Comparison of the cumulated demand of each mineral in EU with the world level of current reserves and resources (information coming from MEDEAS-W boundary simulation).
- Comparison of the annual demand of each mineral in EU with the current EU production level.

EROI levels per technology are calculated exactly the same as in the case of MEDEAS-W.

Table 38 shows the current (2015) level of production of each mineral in UE (BGS, 2017).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Table 38. EU domestic current (2015) production level for each mineral considered in MEDEAS. Source : own elaboration from (BGS, 2017).

	Production 2015 (million tons)
Aluminium	2,214,674
Cadmium	1,783
Chromium	946,188
Copper	855,512
Galium	11
Indium	91
Iron	33,140,406
Lithium	17,120
Magnesium	0
Manganese	143,762
Molybdenum	0
Nickel	46,553
Lead	217,986
Silver	2,081,676
Tin	42
Tellurium	33
Titanium	0
Vanadium	0
Zinc	697,291
Uranium	211

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.5. GHG emissions module

As a first approximation, in MEDEAS-W (Deliverable 4.1) all the GHG emissions were calculated as the sum of CO_2 and CH_4 (in terms of CO_2 equivalents). In the European model, the emissions due to the six main greenhouse gases included in the Kyoto Protocol (i.e., CO_2, CH_4, N_2O, SF_6, PFC, HFC) are calculated.

To transform the effects of different emissions to a common scale — often called 'CO_2 equivalent emissions'—the emissions (E_i) associated to a certain i component can be multiplied to the adopted normalized metric (M_i), as follows (Eq. 39):

$$CO_2 - eq_i = M_i \cdot E_i \quad (39)$$

One well-known M_i is the Global Warming Potential (GWP), defined as the time-integrated Radiative Forcing (RF) due to a pulse emission of a given component, relative to a pulse emission of an equal mass of CO_2. The GWP was presented in the First IPCC Assessment (IPCC, 1990), and the GWP value of each gas depends on the chosen time horizon, usually 20 years and 100 years are the most used values.

A time horizon of 100 years was later adopted as a metric to implement the multi-gas approach embedded in the United Nations Framework Convention on Climate Change (UNFCCC) and made operational in the 1997 Kyoto Protocol. In this module we have used both the 20-year time horizon and the 100-year time horizon, so using the variable "GWP time frame" we can choose which of the 2 different time intervals will be used for the calculation.

Total emission, expressed on CO_2-equivalent, are the sum of the contribution of each gas, so the GWP data of each gas and for each time horizon are necessary (Eq. 40).

$$Total\ CO_2 - eq\ emissions = CO_2\ emissions + GWP_{CH_4} \cdot CH_4\ emissions + GWP_{N_2O} \cdot N_2O emissions + GWP_{SF_6} \cdot SF_6\ emissions + GWP_{PFCs} \cdot PFCs\ emissions + GWP_{HFCs} \cdot HFCs\ emissions \quad (40)$$

According to the data of the IPCC fifth assessment report (IPCC, 2013), the GWP data for the gases studied and for the different time horizons chosen are shown in the Table 39.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Table 39. Global warming potentials (GWP) for the 20 years and the 100 years horizons (without carbon feedback factors). Source: (IPCC, 2013).

GAS	GWP 20 years	GWP 100 years
CH_4	84	28
N_2O	264	265
PFCs	4,880	6,630
SF6	17,500	23,500
HFC-134a	3,710	1,300
HFC-23	10,800	12,400
HFC-32	2,430	677
HFC-125	6,090	3170
HFC-143a	6,940	4,800
HFC-152a	506	138
HFC-227ea	5,360	3,350
HFC-245ca	2,510	716
HFC-4310mee	4,310	1,650

CO_2 emissions

CO_2 emissions are those calculated endogenously as the sum of those due to the combustion of fossil fuels, soil management, the land use change and the combustion of biofuels.

CH_4 emissions

In the case of CH4 emissions, the same methodology used in MEDEAS-W has been used. Thus, total CH_4 emissions is the sum of the RCPs data (Representative Concentration Pathways; RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5) (Clarke et al., 2007; Fujino et al., 2006; Grübler, 2007; Hijioka et al., 2008; Smith and Wigley, 2006; van Vuuren et al., 2007; Wise et al., 2009), excepting the corresponding part of the emissions generated by power plants, energy conversion, extraction and distribution, with the data obtained endogenously due to the emissions generated in the extraction of the different fossil fuels.

Rest of GHGs emissions (N_2O, SF_6, PFCs (CF_4), HFCs)

For the historical data on gas emissions in EU-28, the emission data of the JRC-EDGAR database (EC-JRC and PBL, 2011) are used, and the data for the EU-28 countries are added.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Whereas, the EU-28/World emission ratios of historical emissions have been used and have been maintained for the different RCPs up to the year 2100 for the evolution of the data since 2015, according to the IIASA RCP database (http: //www.iiasa. ac.at/web-apps/tnt/RcpDb) (Clarke et al., 2007; Fujino et al., 2006; Grübler, 2007; Hijioka et al., 2008; Smith and Wigley, 2006; van Vuuren et al., 2007; Wise et al., 2009).

The following graphs (Figures 54-58) represent the emissions of the different GHGs for each PCR until the year 2100, before the conversion to CO_2 equivalent.

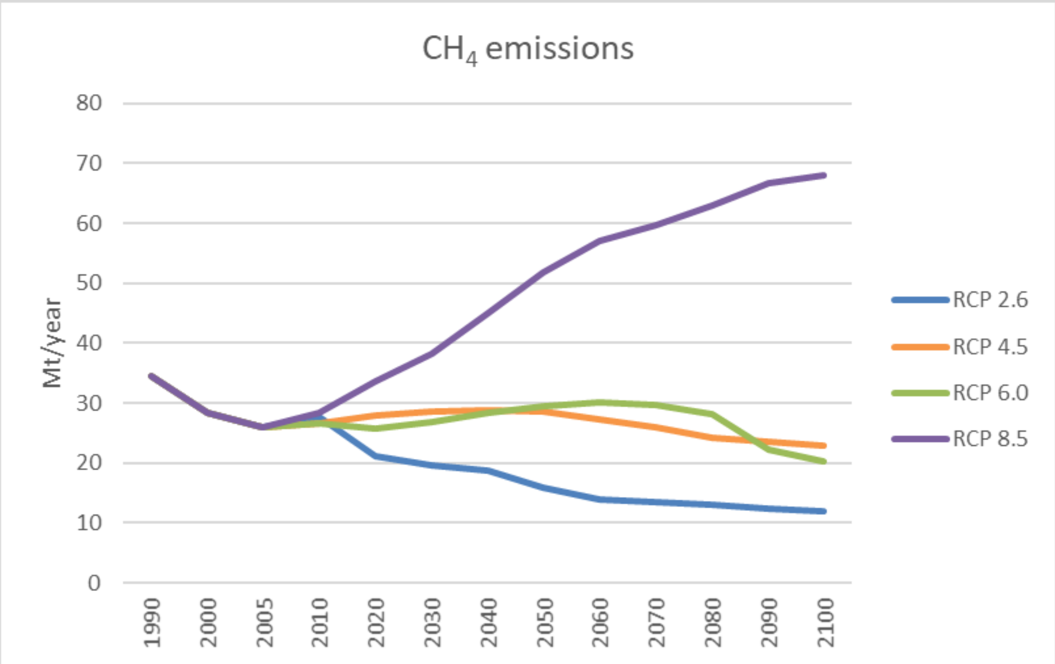


Figure 54. CH_4 emissions (1990 - 2100) for each RCP.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

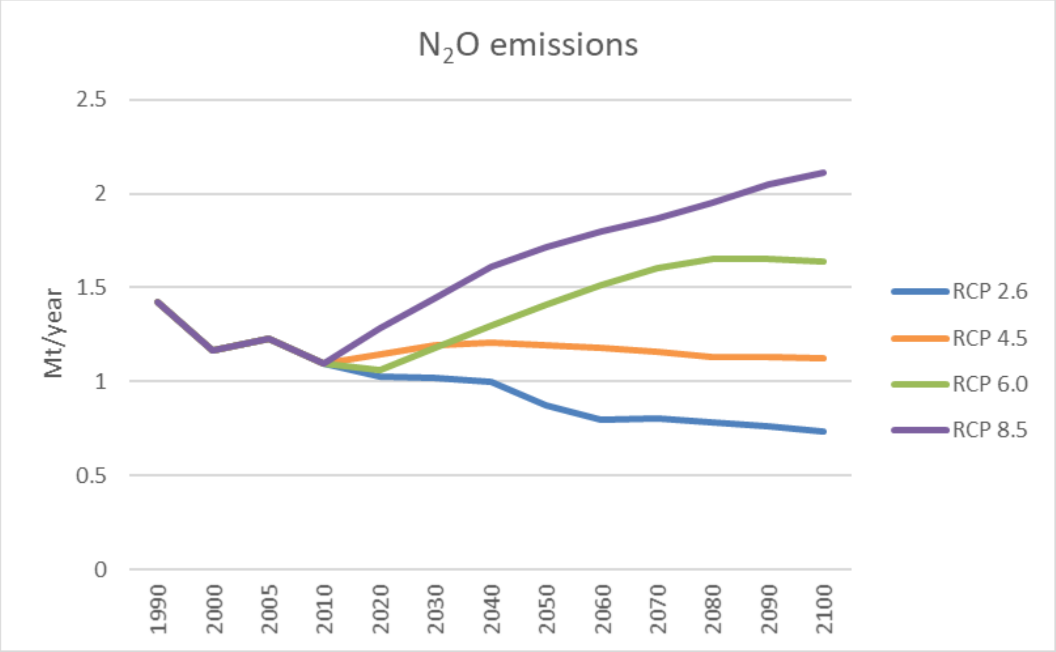


Figure 55. N_2O emissions (1990 - 2100) for each RCP.

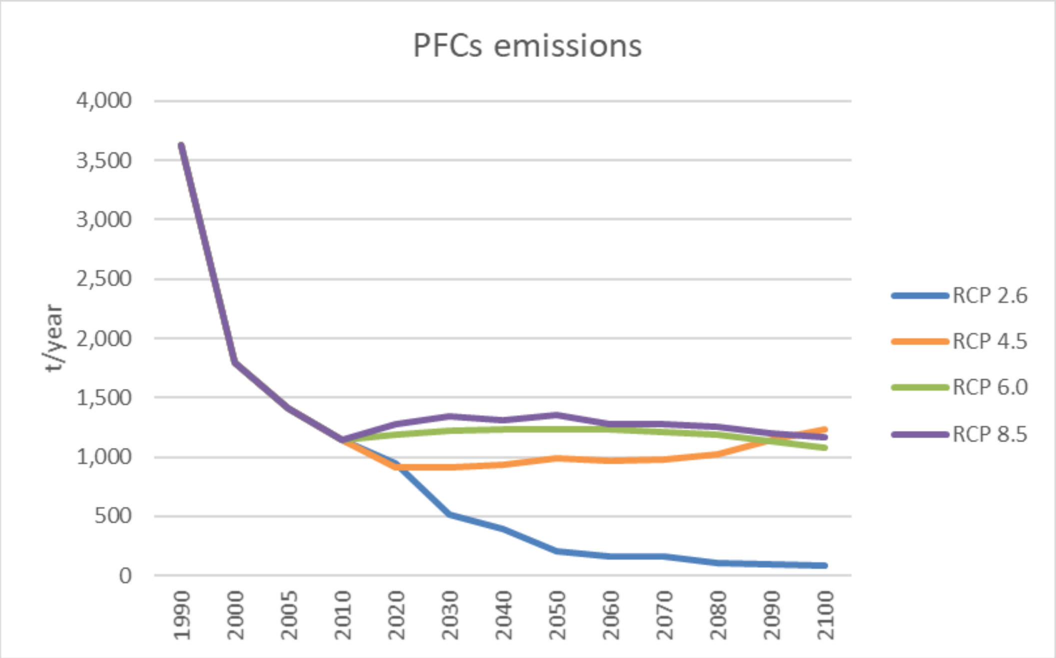


Figure 56. PFCs (CF_4) emissions (1990 - 2100) for each RCP.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

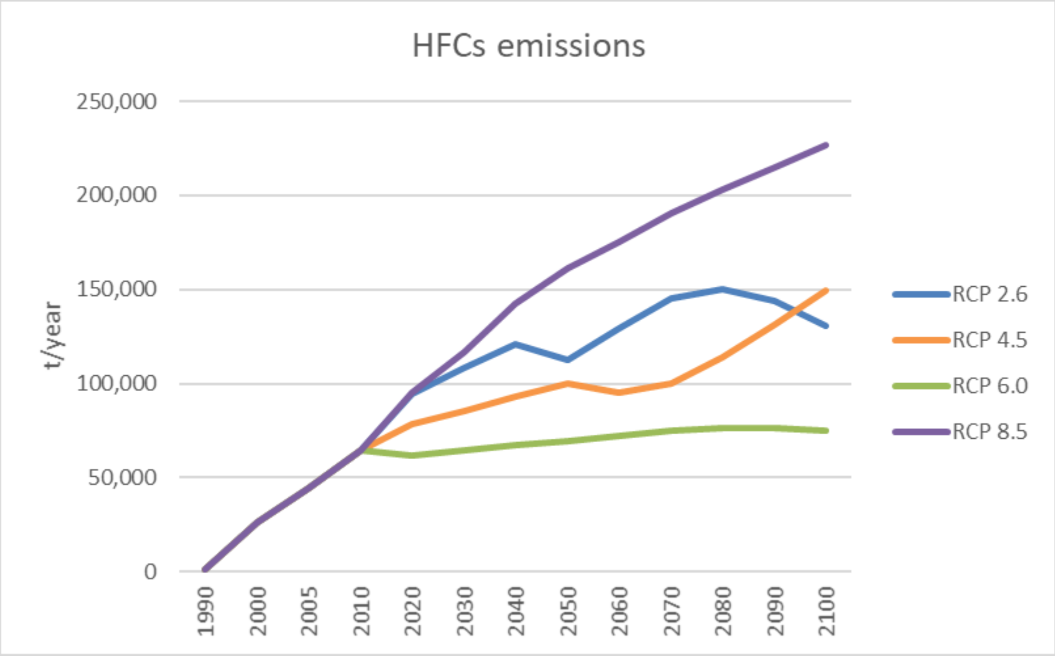


Figure 57. HFCs emissions (1990 - 2100) for each RCP.

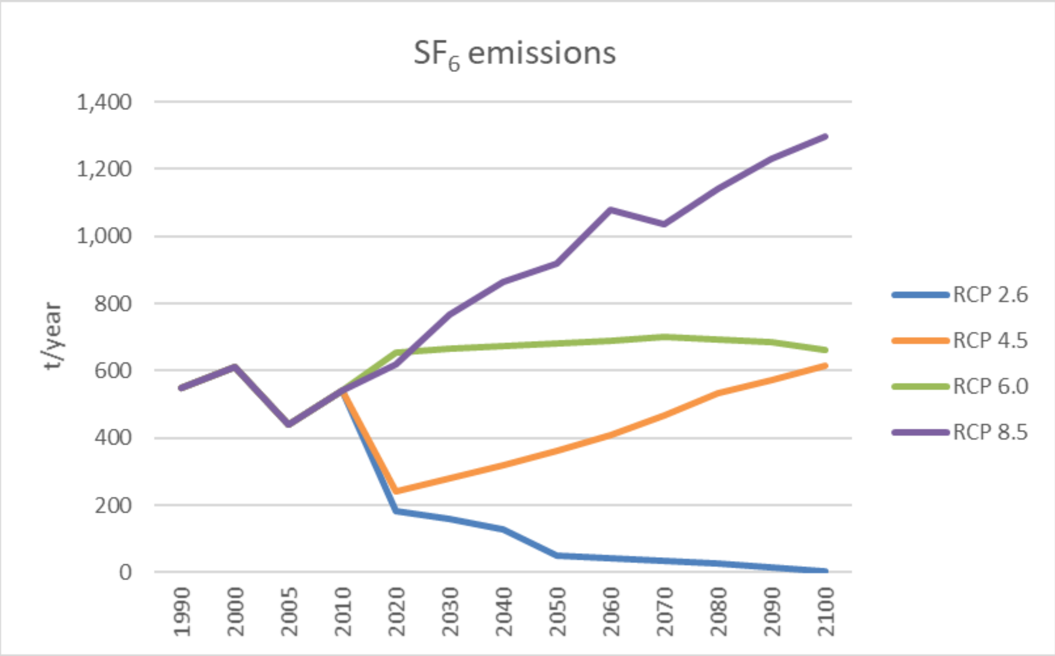


Figure 58. SF_6 emissions (1990 - 2100) for each RCP.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.6. Land-use module

The representation of land use and land cover dynamics is highly complex given that they depend on a diversity of natural and human factors. Forthcoming climate change increases the challenge. In this sense, relatively few integrated assessment models include this dimensions, such as GCAM (Kyle et al., 2011) or IMAGE (Elke Stehfest et al., 2014).

Given the scope of the project, a stylized representation of land-use in EU has been included in the model. It does not attempt to comprehensively model the biophysical-human interrelations and represent all the land use and land cover types. Instead, its main objective is to allow to endogenize some variables which in previous versions of the model had to be assumed exogenous although they are ultimately land-dependent. These variables are:

- Built-up land,
- Potential for biomass (including the explicit consideration of the demand of biomass for non-energy uses),
- Potential for solar energy (both on land –PV and CSP) and rooftop –PV and solar thermal-).

This approach has the advantage that it takes into account that most land uses are mutually exclusive. Most data for the construction of this module has been taken from FAOSTAT (http://www.fao.org/faostat/en/).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.6.1. Current situation

In terms of land-use, the land dedicated to agriculture (including arable land, permanent crops and permanent pastures, FAOSTATS definitions) has been decreasing in the last 25 years at an annual average rate of -0.2% and the forest area (including primary, planted and other naturally regenerated) has increased at +0.8%/yr. Other land, which accounts for the rest of land (i.e. built-up and related land, barren land, other wood land, etc.) has increased at >1% reaching over 18% of the total land area (total land area excluding area under inland water bodies) of the EU (FAOSTAT, 2017).

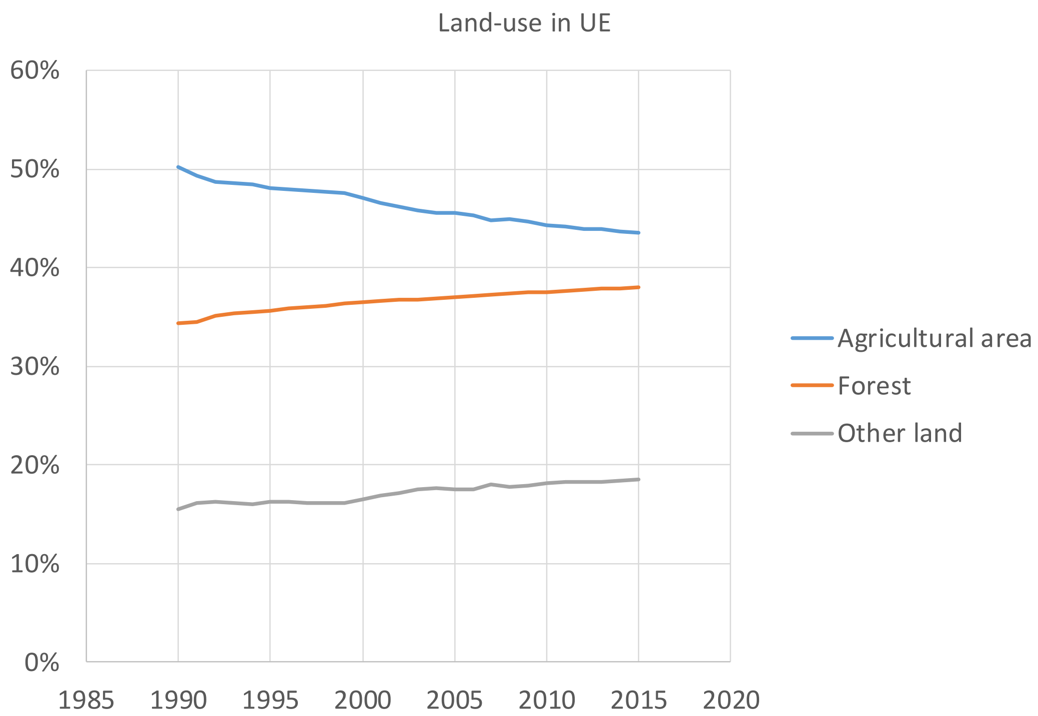


Figure 59. Historical evolution of land-use shares (1990-2015) for agricultural area, forest and other land.

However, it must be highlighted that the UE is a net food importer, with net imports having gone up significantly in the past decade. Thus, the decreasing trend in agricultural land does not represent rather an increase in external food dependence (i.e. loss of food sovereignty) which has more than compensated for the yield productivity improvements.

Virtual land exports have declined to 14 Mha in 2007/2008, while virtual land imports have gone up to almost 49 Mha (+15%). In the period 2007/2008 the virtual net import of land has amounted to almost 35 Mha (Von Witzke and Noleppa, 2010). Thus, the EU is using approximately one third of her own usable arable area outside its own territory. The currently occupied arable land in third

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

countries is almost equivalent to the entire territory of Germany; and the increase of virtual land trade between 1999/2000 and 2007/2008 amounts to 9.6 million hectares, which is larger than the land area of Hungary, for instance. A major cause of the substantial growth in virtual land import is the increased use of soybeans and related products. They account for an increase of about 3.7 Mha. Additional substantial contributions have resulted from coarse grains (plus 2.7 million hectares), wheat (plus 1.6 million hectares) and corn (plus 1.5 million hectares). Palm fruits have contributed an additional 1.0 Mha to the increase in net imports of virtual land. Other oilseeds, oleaginous fruits and vegetables have acted to slightly reduce net imports. In fact, the EU is now tied with China as the world's largest net importer in terms of value. As a consequence, the EU has become a large importer of virtual agricultural land, driving reductions in natural habitats such as tropical rain forests and increasing greenhouse gas emissions from converting forests and grass-lands into cropland (Von Witzke and Noleppa, 2010) (Figure 60).

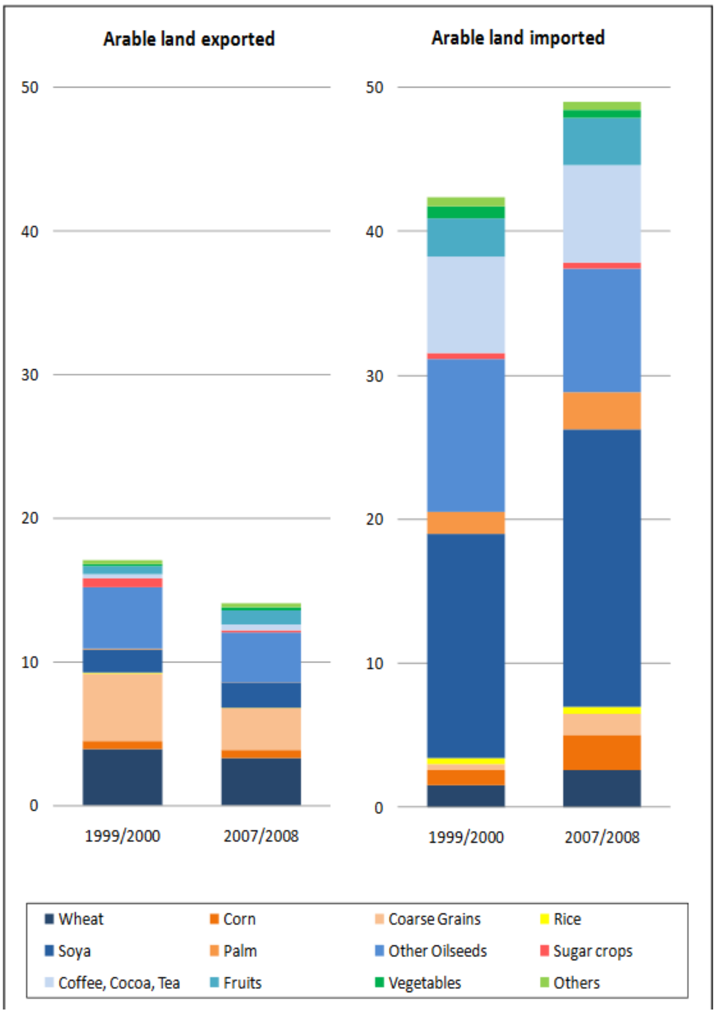


Figure 60. EU arable land virtually traded (in Mha).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

In relation to domestic forests in the EU, most of the forest area corresponds to naturally regenerated forest, with an area roughly constant in the last decades of ~100 Mha. Planted forests have been increasing steadily at a rate of +1.4%/yr reaching ~55 Mha in 2015. Primary forests represent a mere 3% of total forest area, i.e. ~1% of the total land area of the UE. It is remarkable that the surface occupied by primary forests is smaller than the artificial surfaces (including urban and associated areas), ~9.5 Mha (Figure 61).

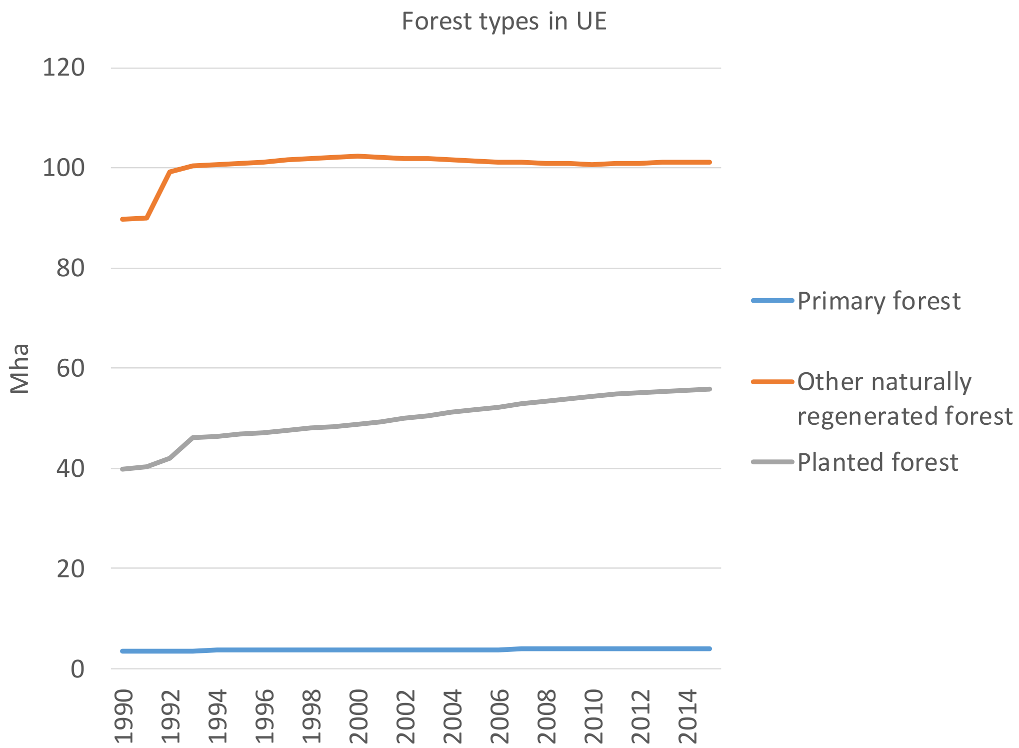


Figure 61. Historical evolution of area covered of forest by type in EU (1990-2015).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.6.2. Overview of the modelling approach to build the Land Module in MEDEAS-EU

Figure 62 shows a simplified representation of the Land Module in MEDEAS-EU. The boxes represent the stocks modelled, depicting different types of land-use and cover (most categories correspond with FAO nomenclature given that this database has been the main source of data for the construction of the module):

- Primary forest: naturally regenerated forest of native species, where there are no clearly visible indications of human activities and the ecological processes are not significantly disturbed (FAO, 2014).
- Forest available: represents the rest of forests in FAO database, i.e. ”Planted forest“ (forest predominantly composed of trees established through planting and/or deliberate seeding) and “Other naturally regenerated forest” (forest predominantly composed of trees established through natural regeneration where there are clearly visible indications of human activities) (FAO, 2014).

- Agricultural land: includes both categories “Arable land and Permanent crops” and “Permanent pastures”:
    - Arable land represents the land under temporary agricultural crops (multiple-cropped areas are counted only once), temporary meadows for mowing or pasture, land under market and kitchen gardens and land temporarily fallow (less than five years). The abandoned land resulting from shifting cultivation is not included in this category. Data for “Arable land” are not meant to indicate the amount of land that is potentially cultivable.
    - Permanent crops is the land cultivated with long-term crops which do not have to be replanted for several years (such as cocoa and coffee); land under trees and shrubs producing flowers, such as roses and jasmine; and nurseries (except those for forest trees, which should be classified under "forest"). Permanent meadows and pastures are excluded from land under permanent crops.
    - Permanent meadows and pastures is the land used permanently (five years or more) to grow herbaceous forage crops, either cultivated or growing wild (wild prairie or grazing land).

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691287

- Urban land: corresponds with FAO's "Artificial surfaces (including urban and associated areas)", including areas that have an artificial cover as a result of human activities such as construction (cities, towns, transportation), extraction (open mines and quarries) or waste disposal.
- Available land: this category has been built specifically for the Land Module of MEDEAS framework following the approach used in (Capellán-Pérez et al., 2017a), and represents the terrestrial land that is currently neither being used by the primary sector (arable land, permanent crops, permanent meadows and pastures and productive forest area) nor built-up.
- Land for solar and hydro RES: represents the land occupied by solar facilities and hydropower plants
- Marginal land occupied by biofuels: represents the marginal lands occupied by biofuels,
- Agricultural land for BioE: represents the agricultural land used to grow biofuels.

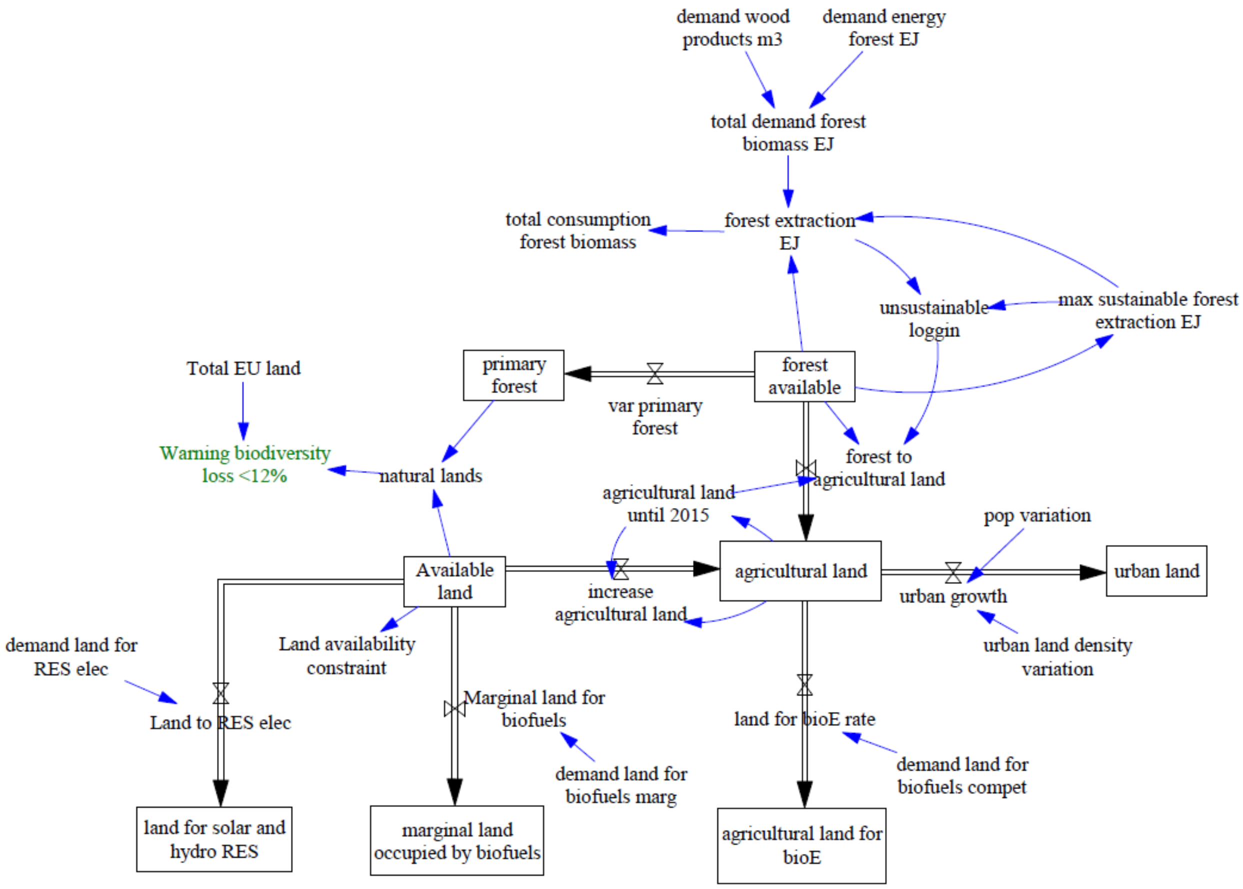


Figure 62. Overview of the Land Module in MEDEAS-EU.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

The Land Module functions as follows: It takes the demand of different types of final energy (e.g. electricity, liquids, heat) generated by the Economy module (see section 2.2.3.1.) as inputs. Depending on the assumptions and policy targets of each scenario, there will be a demand for renewable energy resources which are dependent on land: bioenergy (from forests and grown as crops) and renewable energies for the generation of electricity, such as PV, CSP and Hydro. Solar thermal and rooftop PV are related to the urban surface and policy targets in terms of urban land density variation. Non-energetic uses of wood are also taken into account. These demands are confronted with the land availability (forest, agricultural land, available land), which may ultimately constrain the actual extraction of bioenergy resource/installation of power centrals. A “warning” indicator of “Biodiversity loss” is formulated, considering the ratio of natural areas vs the total land, which gives a qualitative idea of the potential danger of biodiversity loss of the scenario simulated.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691287

2.6.3. Methodology

In this subsection the rationale and assumptions considered for the modelling of Land in MEDEAS-EU are described.

2.6.3.1. Primary forests

Given past trends (slow annual growth in the period 1992-2015) and for the sake of simplicity, primary forest area is considered to remain constant in the standard version of MEDEAS. However, the user can consider the continuation of past trends or introduce a customized value.

2.6.3.2. Forest available

Solid bioenergy to be extracted from forests in the model is dependent on the area of forest available, as well as from a scenario-dependent parameter of “unsustainable logging”. This parameter allows for a higher extraction of wood but at the cost of degrading the stock of forests which ultimately causes deforestation. This degradation process is assumed to increase the availability of land for agriculture, which is an optimistic assumption given that in some cases degraded forests may also end up being marginal or barren lands.

However, in the standard version of the model the total area for forest is assumed to remain constant, assuming unlikely that the area dedicated to forest in the UE will decrease in future decades since it goes against historical trends and allows to capture CO2, preserve biodiversity, etc. (excepting in the cases of potential collapse/rapid degradation scenarios).

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691287

2.6.3.3. Agricultural land

This is a key stock of the model given that in recent decades land for agriculture has been the main use of land at EU-level (although with a decreasing trend: 49% in 1992 vs 44% in 2015 FAOSTAT). The requirements of land for agriculture depend on many parameters, some technical such as productivity yields, and other socio-cultural such as diets. In this context, 2 key factors must be taken into account:

(1) As aforementioned, the EU is a net food importer, and net imports have gone up significantly in the past years (Von Witzke and Noleppa, 2010).

(2) It seems unlikely that this deficit may be covered by yields increases. Recent studies have found strong evidence of yield plateaus in some of the world's most intensive cropping systems, among them some of the most important EU producers. Specifically, a linear, upper plateau historic trend was found for Denmark, France, Germany, Italy, the Netherlands and the UK for both wheat and maize. A hypothesis that can explain the occurrence of yield plateaus is that average farm yields approach a biophysical yield ceiling for the crop in question, which is determined by its yield potential in the regions where the crop is produced (Grassini et al., 2013). Moreover, yield increases are critically dependent on the use of inputs such as fertilizers (natural gas) and water, which may be scarcer in the future.

Hence, given that a substantial amount of EU consumed food depends on imports and the adverse impacts on biodiversity on virtual land imports of UE in the rest of the world, we assume as a reasonable future target that the UE will roughly maintain the current area dedicated to agriculture. Moreover, this is also consistent with the fact that demand for food in next decades is assumed to increase substantially at a global level (together with population increase). This implies a global increase in the competition for land. This target might even be seen as conservative given that future climate impacts affecting current yields are not considered in the Land module of MEDEAS-EU.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.6.3.4. Urban land

The future evolution of urban land is commonly related with the evolution of population and economic growth. For example, in IMAGE, urban built-up areas increase per grid cell in the scenario period as a function of GDP and population and depend on a country- and scenario-specific urban density curve (Elke Stehfest et al., 2014). In the AIM model, a similar approach is taken: the spatial distribution is created by assuming that urban grid cells are increased in proportion to the increase in population and GDP in each country; the urbanization rate is also used as explanatory variable (Masui et al., 2011). However, these approaches lack to capture the fact that different types of urbanization exist, although operational indicators of urban sprawl are complex to be set e.g. (Hasse and Lathrop, 2003).

In MEDEAS-EU, given that resolution at grid level is not available, a simpler approach had to be taken. Firstly, given that built-up areas mostly expand into very productive agricultural areas (Elke Stehfest et al., 2014), we assume that built-up surface is subtracted from the agricultural area, thus, leading to additional demand for agricultural area in the “available land” stock. Secondly, a lineal model was built to estimate the urban land surface considering the variation of population and the variation of urban land density (i.e. urban m^2/population of the country) considering data from 1992 to 2015 for the UE at aggregated level from FAOSTAT and (World Bank database, 2018):

$$Urban\ land = a \cdot Pop + b \cdot Urban\ land\ density + c \qquad (41)$$

Table 40 reports the main outputs and validation tests of the regression performed (R^2 = 0.999952; F (2,21) = 220267.6; p < 0.1), which show that the model is significant.

Table 40. Regression model for urban land in MEDEAS-EU

	Coefficient	Standard deviation	t	p-value
c	-9.61332	0.416904	-23.06	2.14e-16***
b	0.0478639	0.000263219	181.8	4.60e-35***
a	1.99746e-8	9.118335e-10	21.78	6.96e-16***

*** p-value < 0,1

The evolution of population is scenario dependent, while the future urban land density is a parameter, which can be selected by the user and is considered also scenario-dependent, since it is a parameter highly dependent on urbanism legislation, cultural practices, etc. A mapping of countries with different ratios of urban land per capita (data from FAOSTAT and World Bank) was

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691287

performed (see Figure 63). This way, the user can select for each scenario the assumed urban land per capita in the year 2050. Note the influence of urbanization rates and urbanism policies, e.g. China and Singapore have very similar urban land per capita ratios although very different GDPpc ratios.

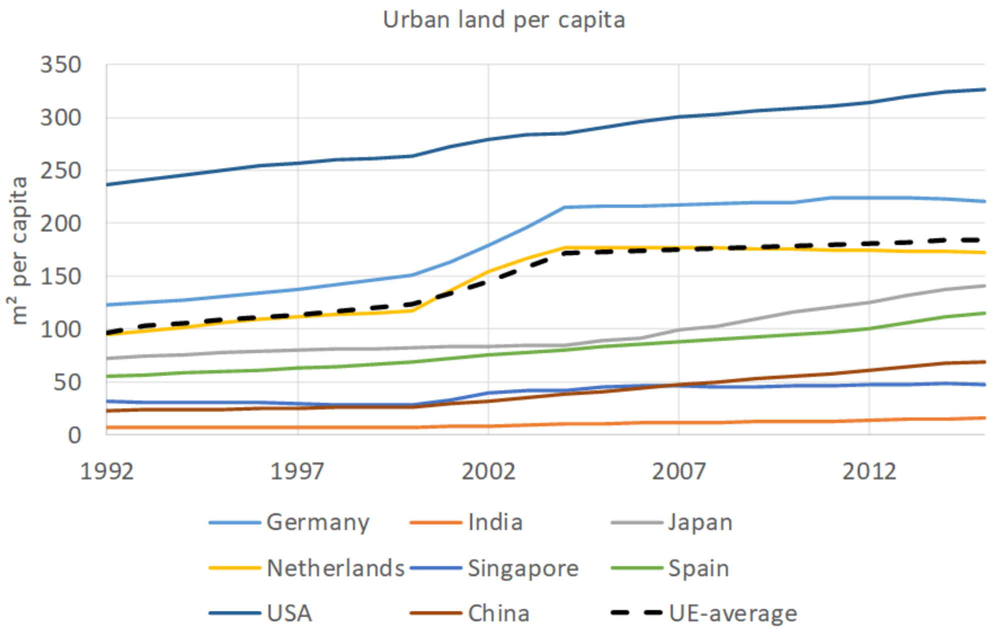


Figure 63. Urban land per capita.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.6.3.5. Available land for human uses

The "land availability" at UE level is defined adapting the methodology applied in (Capellán-Pérez et al., 2017a) and includes the terrestrial land that is currently neither being used by the primary sector (arable land, permanent crops, permanent meadows and pastures and productive forest), land nor built-up and permanent snow and glaciers. This stock includes the land required for additional human uses (i.e. balance of agricultural land, installation of plants for generation of electricity from renewable energy sources, biofuel plantations, etc.).

Figure 64 shows the historical evolution of the main land categories in EU, based on (FAO, 2017).

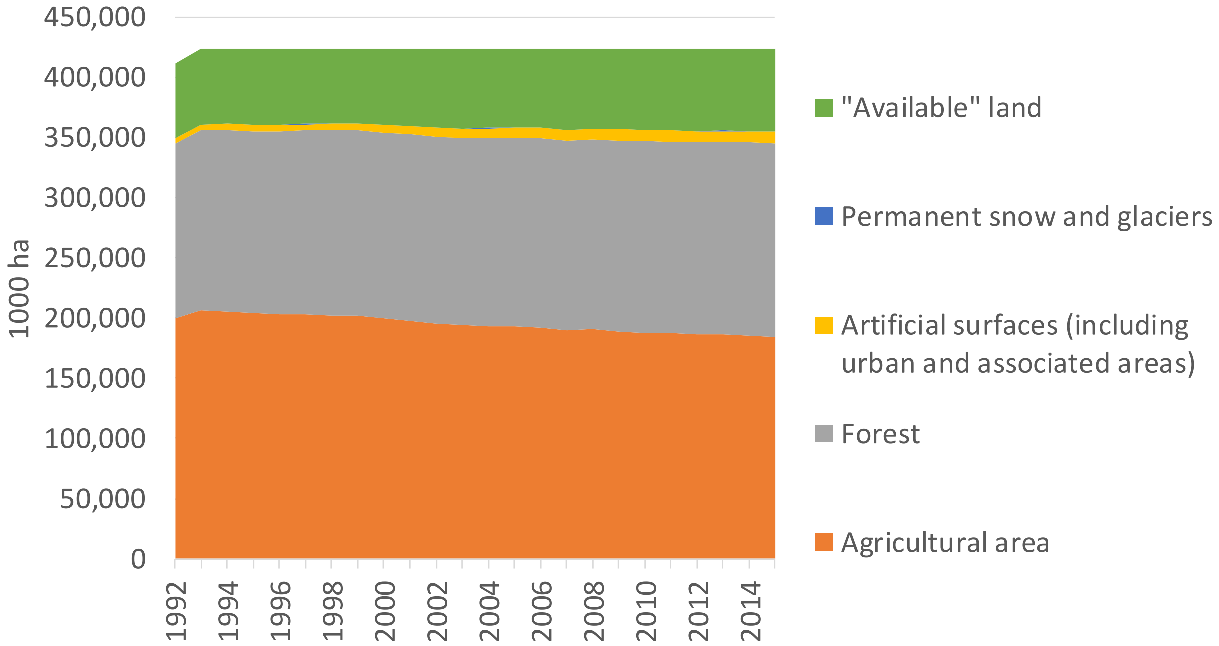


Figure 64. Historical evolution of the main stocks of land considered in the Land Module of MEDEAS-EU (1992-2015).

This definition of land availability must be taken as a first conservative approximation, since many other factors would in fact reduce the land availability: orography (e.g. mountains), yield productivity (e.g. barren lands for biofuels), protected areas (e.g. the EU-27 has an average of around 27% of its surface protected), locations with suboptimal resource, etc. (see also (Deng et al., 2015)).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.6.3.5. Natural land and biodiversity warning

Natural lands in MEDEAS are defined as the primary forests and the “available land”. We interpret the ratio of natural lands vs the total land as an indicator of biodiversity loss, given that natural lands can be understood as an insurance that ensures the resilience and stability generated by biodiversity. We apply here the value of 12% of the territory as considered in the Brundtland Report and for the calculation of the standard ecological footprint (Wackernagel et al., 2002; WCED, 1987). This value is a conservative lower bound, which has been strongly criticized as being unable to a assure an effective protection of biodiversity (Vačkář, 2012). For example, the UNEP and IUCN give 17% as a reference value (Juffe-Bignoli et al., 2014), while Soulé and Sanjayan (Soulé and Sanjayan, 1998) argued for a minimum share of 25-50%.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691287

2.7. Social and environmental impacts

2.7.1. Context and MEDEAS approach

The main aim of this module in MEDEAS framework is to translate the behavior of each model scenario into a set of variables that provide information about its social dimension. This is a complex and delicate task, since, in fact, social dimensions such as education, health, culture, life expectancy, etc. depend on more dimensions that the ones modelled in MEDEAS, which mainly evolves through energetic and monetary variables. Thus, the computation of indicators such as HDI is in principle further the scope of the project.

The followed approach consists on reporting outputs which can be obtained from the current version of the model. MEDEAS does not report “a” variable to measure well-being. We consider that well-being is a multidimensional feature which cannot be reduced to a single variable (UN, 1990). Instead, we illustrate the social evolution of each scenario assessing a set of variables. We complete the information with the reporting of key environmental impacts indicators given that well-being is intrinsically linked to a healthy environment (Daily, 1997; Levin et al., 2009; Schneider and Morton, 1981). How energy forces and infrastructures interrelate with institutions and ideations of political power are beyond the scope of the project (Boyer, 2014). The construction of this set of indicators was assisted by the D2.2 Task e (MEDEAS, 2016).

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691287

2.7.2. Social and environmental indicators

As explained with more detail in Deliverable 4.1., in the MEDEAS framework we identify as social and environmental indicators the following variables, also included in MEDEAS-EU model:

- Total Final and by final fuel Consumption per capita
- Total Primary and by fuel Consumption per capita
- Electricity consumption per capita
- Total water use per capita
- Potential HDI level given energy use
- Consumption of RES per capita
- Share of RES in total final consumption
- Annual penetration of RES in the total final and primary energy consumption
- GDP per capita
- Jobs associated to RES technologies
- EROIst of the system
- GHG emissions per capita
- Atmospheric GHG concentration levels
- Temperature increase over pre-industrial levels

The following indicators from the Sustainable Development Goal Indicators (UN, 2015) are available in MEDEAS:

- 7.3.1 Energy intensity measured in terms of primary energy and gross domestic product (GDP)
- 8.1.1 Annual growth rate of real GDP per capita
- 9.4.1. CO_2 emission per unit of value added

Two new variables are included in the MEDEAS-EU model, therefore, biodiversity and energy footprint, and methodology for water uses have slightly changed. Biodiversity has been explained with more detail in section 2.6.3.5. In the next sections, we will explain the methodology used for energy footprint and water uses in the MEDEAS-EU model.

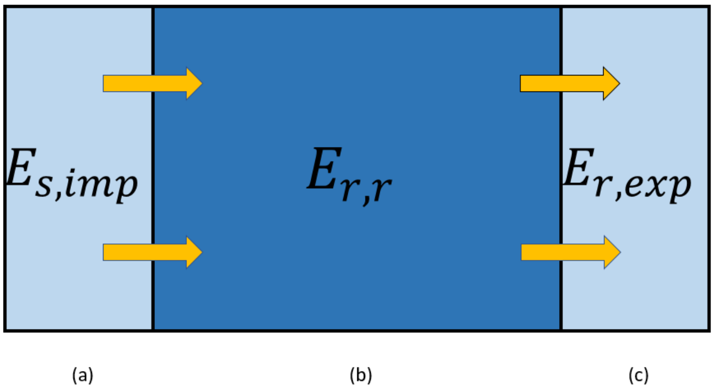
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.7.3. Energy footprint

Energy footprint is an indicator which measures the energy used in a territory to produce the output required to satisfy its demand. Because part of one country's demand is produced outside its borders, trade is a fundamental variable. This way, the energy required to produce abroad the products that Europe imports must be incorporated to the European energy footprint. Conversely, the energy consumed during the production process of exports to the rest of the world, do not have to be incorporated following the abovementioned definition. Thus, we can define energy footprint in a certain region 'r' and taking foreign countries as 's' as (Eq.42):

$$EF_r = E_{r,r} + E_{s,imp} - E_{r,exp} \quad (42)$$

Being EF_r the energy footprint in region 'r', first subscript in the other variables represents region where output is produced and the second what demand it is destined to satisfy: domestic demand ('r'), imports ('imp') and exports ('exp'). Energy flows in this framework can be expressed as in Figure 65. Energy required to produce exports is 'exported' within the products exported and energy required to produce (abroad) imports is 'imported' within the products imported.



$E_{r,r}$= Energy consumed in region r to produce output required to satisfy domestic demand.

$E_{s,imp}$= Energy embedded in imports required to satisfy domestic demand.

$E_{r,exp}$= Energy embedded in exports required to satisfy foreign demand.

Figure 65. Energy flows in MEDEAS-Europe from the Energy Footprint point of view.

Energy footprint can be a measure of environmental load displacement (Cole, 2004; Peng et al., 2016), the process through which developed countries 'displace' dirtier production to the least developed countries. The main methodologies found in the literature to estimate energy footprint

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

are life-cycle analysis (Castellani et al., 2018; Kaldellis and Apostolou, 2017) and structural decomposition analysis, or SDA, based on Input-Output Analysis (Kaltenegger et al., 2018; Lan et al., 2016). Even though most of the SDA studies include international trade, only a few do it employing a multi-regional input-output (MRIO) framework (Kagawa and Inamura, 2004; Lan et al., 2016). In MEDEAS-Europe, it has been integrated System Dynamics and Input-Output Analysis employing a MRIO approach.

The methodology applied in MEDEAS-Europe consists on the decomposition of multi-regional Leontief Matrix into four - as explained in section 2.2.3.2. Following this approach, Leontief Matrix is divided in this different figures: LA_{rr} is the region r's production sensitivity to final demand of region r products (upper-left quadrant); LA_{rs} is the region r's production sensitivity to region s intermediate demand of imports (upper-right quadrant); LA_{sr} is the region s's production sensitivity to region r intermediate demand of imports (lower-left quadrant); LA_{ss} is region s's production sensitivity to final demand of region r products (lower-right quadrant). Taking these definitions into account, we can express the variables in Eq.42 as (Eq. 43-45):

$$E_{r,r} = LA_{rr} * I_r \quad (43)$$

$$E_{s,imp} = LA_{sr} * I_s \quad (44)$$

$$E_{r,exp} = LA_{rs} * I_r \quad (45)$$

And, thus the energy footprint is obtained as follows (Eq. 46):

$$EF_r = LA_{rr} * I_r + LA_{sr} * I_s - LA_{rs} * I_r \quad (46)$$

This way, MEDEAS-Europe estimates for each year the energy carriers of EU28 demand, by incorporating energy embedded in imports ($E_{s,imp}$) and subtracting energy embedded in exports ($E_{r,exp}$).

Finally, we can estimate the energy coverage rate as the proportion of energy really 'enjoyed' by the EU28 economy (domestic plus embedded in imports less embedded in exports) over total energy consumed in EU28. In terms of Figure 1, (a)+(b) is the total energy 'enjoyed' by the EU28 economy, (b)+(c) the total energy consumed in the EU28 and (a)-(c) the energy balance of trade. Hence, the energy coverage rate is the proportion between them or, more formally (Eq. 47):

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

$$ECR_r = \frac{E_{r,r}}{EC_r} + \frac{E_{s,imp} - E_{r,exp}}{EC_r} - 1 \quad (47)$$

Where ECR_r is the energy coverage rate in region r and EC_r the total energy consumed in the same region. That is, ECR_r is a representation of the amount of energy available for EU28 consumption over the amount of energy consumed in the region. In other words, a positive ECR_r reflects the proportion of energy enjoyed over energy consumed (because it is being imported embedded in products demanded from abroad). Conversely, if it is negative, it means that the region is enjoying a proportion under its energy consumed (because it is being exported embedded in products demanded abroad). Given the description of energy footprint in Eq.42 we can rearrange Eq. 47 as:

$$ECR_r = \frac{EF_r}{EC_r} - 1 \quad (48)$$

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.7.4. Water use

This part of the module allows calculating water consumption in MEDEAS Europe by type (blue, green and grey) by economic sector and for households. The aggregated values allow calculating the total water consumption and social indicators such as the total water consumption per capita.

2.7.4.1. Water data

Data used in this module is taken from the environmental accounts within the WIOD database (Genty et al., 2012) (Release 2013, http://www.wiod.org/database/eas13 see also (Arto et al., 2016)). This database compiles data of water consumption for each sector, and also for households, disaggregated by country and type of water. Data is available for years 1995 to 2009.

Then, the first task was to aggregate all countries needed in order to have water consumption data for the EU-28. According to these data, the Figure 66 represents the EU-28 consumption of water by type for the 1995-2009 period.

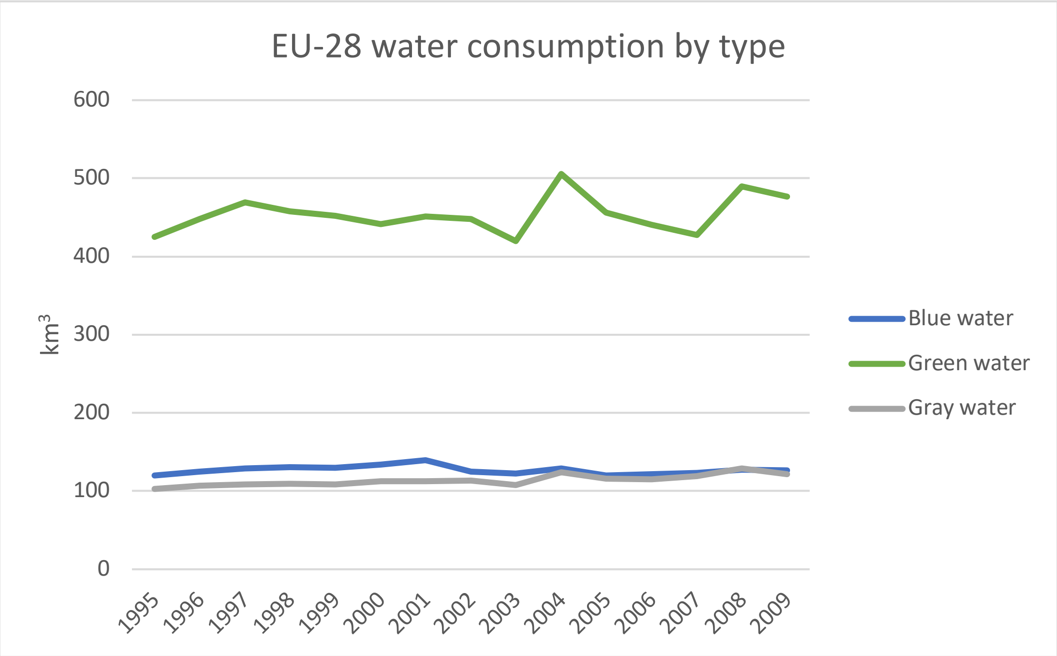


Figure 66. EU-28 water consumption (1995-2009) by type from WIOD database.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

2.7.4.2. Water potential

Two water potentials at EU-28 level are considered: the total water resource and the share of it which is accessible for human use. First, we have used the Internal Renewable Water Resources (IRWR) from AQUASTAT,[5] which is a metric of the long-term average annual flow of rivers and recharge of aquifers generated from endogenous precipitation (double counting of surface water and groundwater resources is avoided by deducting the overlap from the sum of the surface water and groundwater resources): 1,505 km^3.

The share available for human use was obtained combining the IRWR for UE-28 with the share of total renewable (blue) water supply accessible to humans from the OECD (75%) from Table 10.1 from (UNESCO, 2009): 1,130 km^3.

[5] http://www.fao.org/nr/water/aquastat/water_res/index.stm

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

3. Tested scenarios and results

3.1. Scenarios

The objective of this deliverable is to present the European version of the MEDEAS model. In order to illustrate some of the capabilities and diversity of features included in the model, this section reports the outputs from two experimental simulations. It is important to recall that the model includes thousands of variables and it is very flexible in the design of its scenarios. This section does not pretend to be comprehensive and exhaustive, but only to illustrate some experimental results. Section 3.1.1. describes the tested scenarios, section 3.1.2. the implementation in the model and, finally, section 3.2. reports the obtained results.

3.1.1. Tested scenarios

MEDEAS-EU model, as any simulation tool, needs assumptions about the socio-economic context evolution of both the EU and the rest of the World as external inputs, such as expected economic growth, population evolution or technological progress.

Running models can be a cumbersome task when the models have several parameters, assumptions and policies that can be varied at the same time. In order to establish those inputs in a coherent and sensible way, scenario methodology is usually applied. The current standard set of scenarios in climate change research is the Shared Socioeconomic Pathways (SSPs). The SSPs are a set of five qualitative descriptions of future changes in demographics, human development, economy and lifestyle, policies and institutions, technology, and environment and natural resources. The narratives are intended as a description of plausible future conditions at the level of large world regions that can serve as a basis for integrated scenarios of emissions and land use, as well as climate impact, adaptation and vulnerability analyses (MEDEAS, 2017b; O'Neill et al., 2017).

In this report, we apply the SSP2 scenario from the climate change modelling community in the MEDEAS-EU framework, which constitutes a scenario similar to a BAU (continuation of current trends). We follow the approach of "adaptive scenarios" presented in Task 3.3.c (MEDEAS, 2017c); i.e. the inclusion of biophysical feedbacks and constraints modifies the exogenous assumptions of the scenario. We call that scenario SSP2-baseline.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Subsequently, we apply a set of policies to try to mitigate GHG emissions to safe levels. We refer to this scenario as SSP2-OLT (optimum level transition, D3.3 (MEDEAS, 2017b)).

3.1.2. Implementation of the scenarios in MEDEAS-EU

For the implementation of SSP2-Baseline and SSP2-OLT in MEDEAS-EU, the exogenous drivers of population evolution and expected GDP growth for Europe from IIASA D3.3 (MEDEAS, 2017b) have been used (see Figure 67).

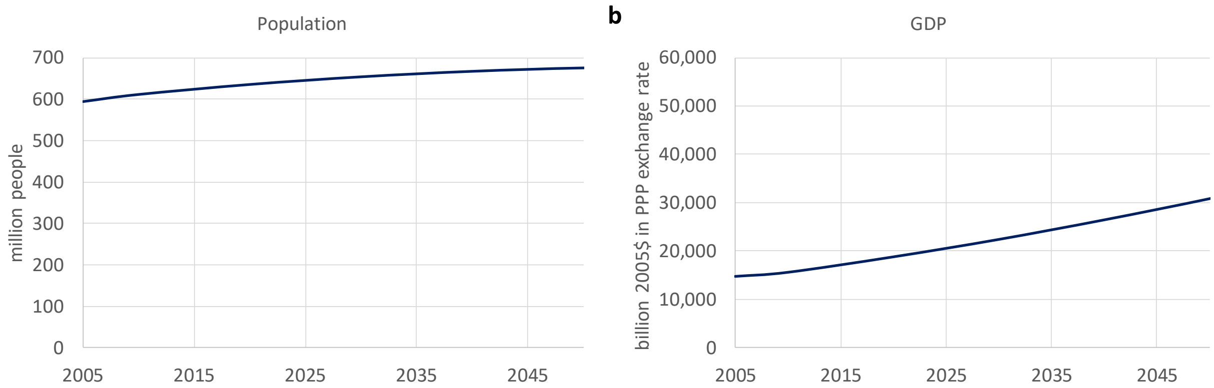


Figure 67. Population growth and GDP quantification of the SSP2 from D3.3.

We shall recall that in MEDEAS, GDP is an endogenous variable, so in the spirit of "Adaptive scenarios" Task 3.3.c (MEDEAS, 2017c), the exogenous GDP trend will be achieved only in the case that there are not constraints that limit it.

For the rest of assumptions to run the SSP2-Baseline, we have interpreted the narrative and adjusted the parameters of the model to it. We recall that this narrative is basically a BAU, i.e. an extrapolation of current trends.

For the SSP2-OLT, after literature review, we have implemented a set of policies starting in 2020 with the aim of directing the energy system towards a low carbon and sustainable future, which includes:

- Higher deployment of RES for electricity, biofuels and heat,
- Preference to technologies which save land (e.g. rooftop PV),
- (Slight) increase in nuclear power,
- Higher electrification (and shift to hybrid modes) of transport,
- Higher recycling rates of minerals,

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

- Reducing the share of oil in electricity and heat consumption,
- Increase the final energy efficiencies at both economic sector and technology-levels.

Thus, the SSP2-OLT could be classified as a "Green Growth" scenario.

Both scenarios share the same characteristics in terms of required GDPpc required, population evolution and fossil fuel and uranium endowments, among others. As explained before, the simulation of a scenario within MEDEAS-EU requires the global context to be taken into account, i.e. the SSP2-Baseline for EU is affected by the evolution of some key variables of this same scenario at global level (the same applies for SSP2-OLT); see D4.1 for more details on these results. For example, climate change impacts, and imports from RoW, which are constrained by total global production per primary commodity.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

3.2. Experimental results

This section reports the main results of MEDEAS-EU 1.0 model up to 2050 with the scenarios described in the previous section (SSP2-Baseline and SSP2-OLT). Population grows following the exogenous path imposed.

The generation of energy from RES increases steadily from current ~10 EJ/yr for both scenarios, almost doubling in the case of the OLT by 2050 (Figure 68a). The consumption of non-renewable energies (oil, coal, gas and uranium) is roughly maintained at current levels in the period 2015-2025, starting to steadily decrease thereafter (Figure 68b). As a result, the share of renewables in the energy mix increases to almost reach 50% in OLT. Figure 68 shows the exponential increase trend in the penetration share of renewables in the energy mix (Figure 68c).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

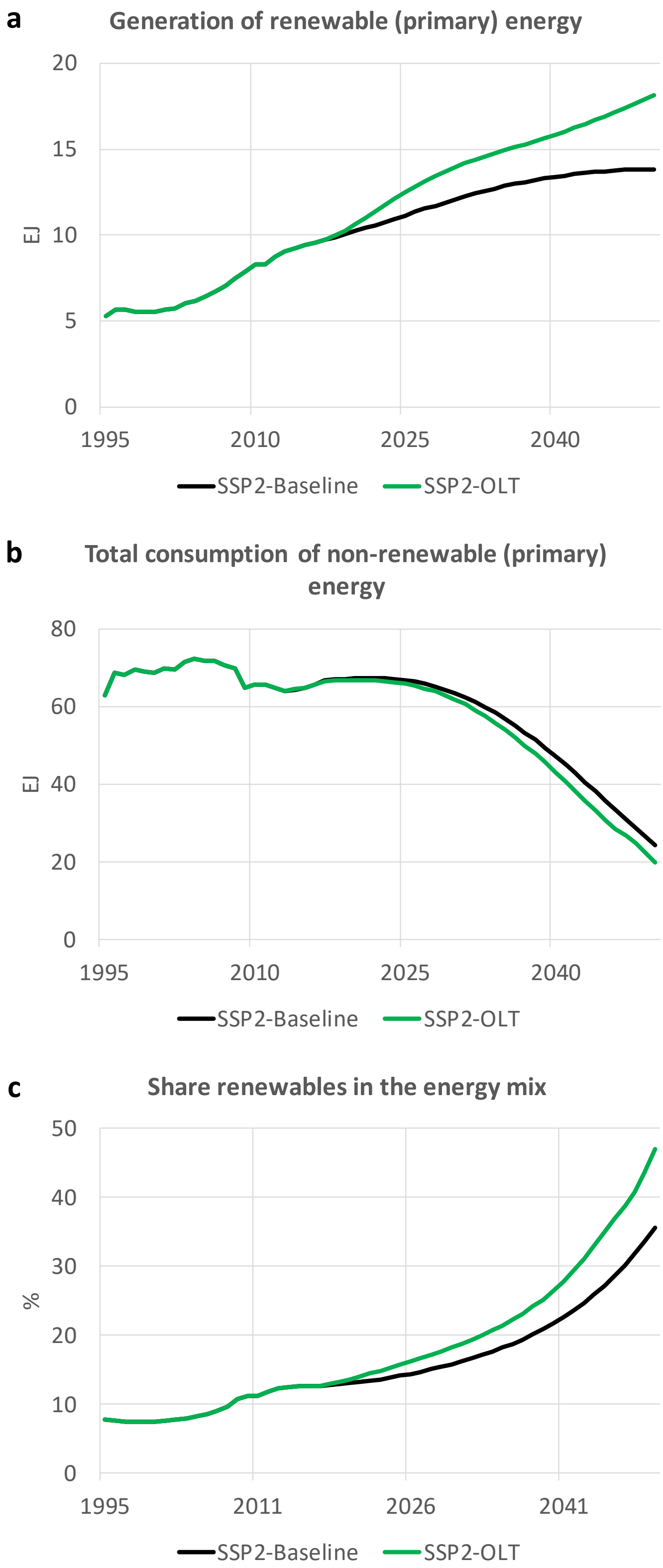


Figure 68. Primary energy mix: (a) generation of renewables; (b) non-renewables (oil, gas, coal and uranium) and (c) share of renewables in the energy mix.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

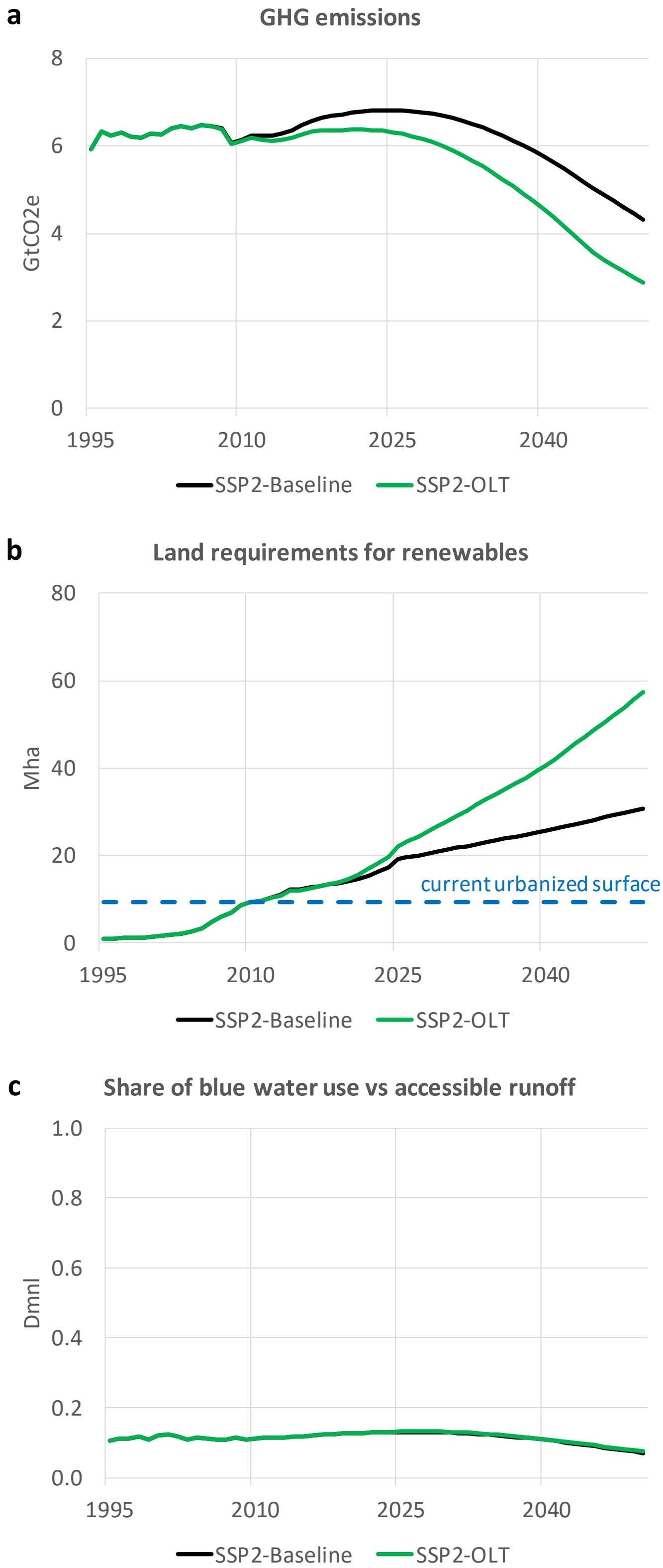


Figure 69. Environmental impacts: (a) GHG emissions; (b) Land requirements for renewables and (c) share of blue water use vs. accessible runoff.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

This transition process to renewable energies implies significant environmental impacts: GHG emissions follow a similar pathway than the consumption of non-renewable energies. In the Baseline scenario, there is a slight increase in GHG emissions until 2030 followed by a decline, while in the case of the OLT scenario there is a stabilization from current levels followed by a decline from 2025 (Figure 69a). Land requirements for renewables (from biofuel crops, solar on land, hydro and wind) nowadays roughly occupy the same area than artificial surfaces in the EU. The expansion of renewables in both scenarios drive the increase in the use of land for energy purposes, 30 Mha in Baseline and almost 60 Mha in the OLT (figure 69b). These surfaces are significant and represent 7 and 14% in relation to the total terrestrial area of the UE. In the case of OLT, the natural areas represent less than 12% of the total terrestrial area before 2035, thus representing a potential danger for biodiversity preservation in the EU. Also, water consumption increases although remaining all the simulation period < 20% of the estimated accessible runoff (figure 69c).

In terms of minerals required for the deployment of alternative technologies in UE (i.e. electric batteries and technologies for electricity generation solar PV, CSP, wind onshore and wind offshore), Table 41 shows the demand (of mined minerals) in 2050 of each mineral considered in MEDEAS framework as a share of the EU current level of extraction. Those minerals with a demand higher than 10% in any of the scenarios are aluminum, copper, gallium, indium, lithium, manganese, tin and tellurium. Table 41 also shows that there is a trade-off in the OLT scenario between higher demand of minerals (due to higher level of deployment of alternative technologies) and higher recycling rates, which in some cases cause that the demand of mined mineral in this scenario to be lower than for the Baseline scenario (e.g. aluminum, copper, manganese, nickel, etc.).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Table 41. Demand of mined mineral in 2050 of each mineral as a share of the EU current level of extraction. – a represents minerals which are currently not mined in the UE.

	Demand of mined mineral in 2050 as a share of EU-2015 extraction	
Mineral	SSP2-Baseline	SSP2-OLT
Aluminium (Al)	10%	4%
Cadmium (Cd)	1.3%	4%
Chromium (Cr)	<1%	<1%
Copper (Cu)	24%	11%
Gallium (Ga)	11%	35%
Indium (In)	19%	64%
Iron (Fe)	2%	<1%
Lithium (Li)	53%	80%
Magnesium (Mg)	- [a]	- [a]
Manganese (Mn)	x2.5	95%
Molybdenum (Mo)	- [a]	- [a]
Nickel (Ni)	5%	1%
Lead (Pb)	<1%	<1%
Silver (Ag)	<1%	<1%
Tin (Sn)	X32	x7
Tellurium (Te)	55%	x1.8
Titanium (Ti)	- [a]	- [a]
Vanadium (V)	- [a]	- [a]
Zinc (Zn)	<1%	<1%

In terms of the efficiency of the system, Figure 70a shows that the EROI of the system declines for both scenarios from current levels ~10:1 to < 8:1 by 2050. This level represents a mid-way between the minimum EROI levels identified in the literature to sustain a complex society typical from the advanced industrial economies of the North hemisphere (Brandt, 2017; Hall et al., 2009). The decline in the OLT scenario is steeper due to the larger penetration of renewables in the energy mix of this scenario. It is noteworthy that the EROI levels of the EU system are higher than those obtained for global level and reported in D4.1. This is related to the different energy mix in both cases: the renewable electricity mix in EU is dominated by wind (~60% by 2050) which is a

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

technology of relatively high EROI, while in the global scenario the renewable electricity mix was dominated by solar technologies (>60% by 2050), which are characterized by lower EROI levels.

Figure 70b shows the evolution of the total final energy intensity (all sectors and households aggregated). Scenario OLT achieves higher efficiency levels by 2050, however this trend is somewhat compensated by a higher EROI of the system. The cumulated efficiency gains in terms of final energy in the period 2009-2050 are of -25% and -28%, respectively.

However, Figure 70c shows that in terms of physical energy intensity, i.e. taking into account the ratio between the primary energy actually consumed and the net energy used by the society, the efficiency of the system does not improve for any of the simulated scenarios.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

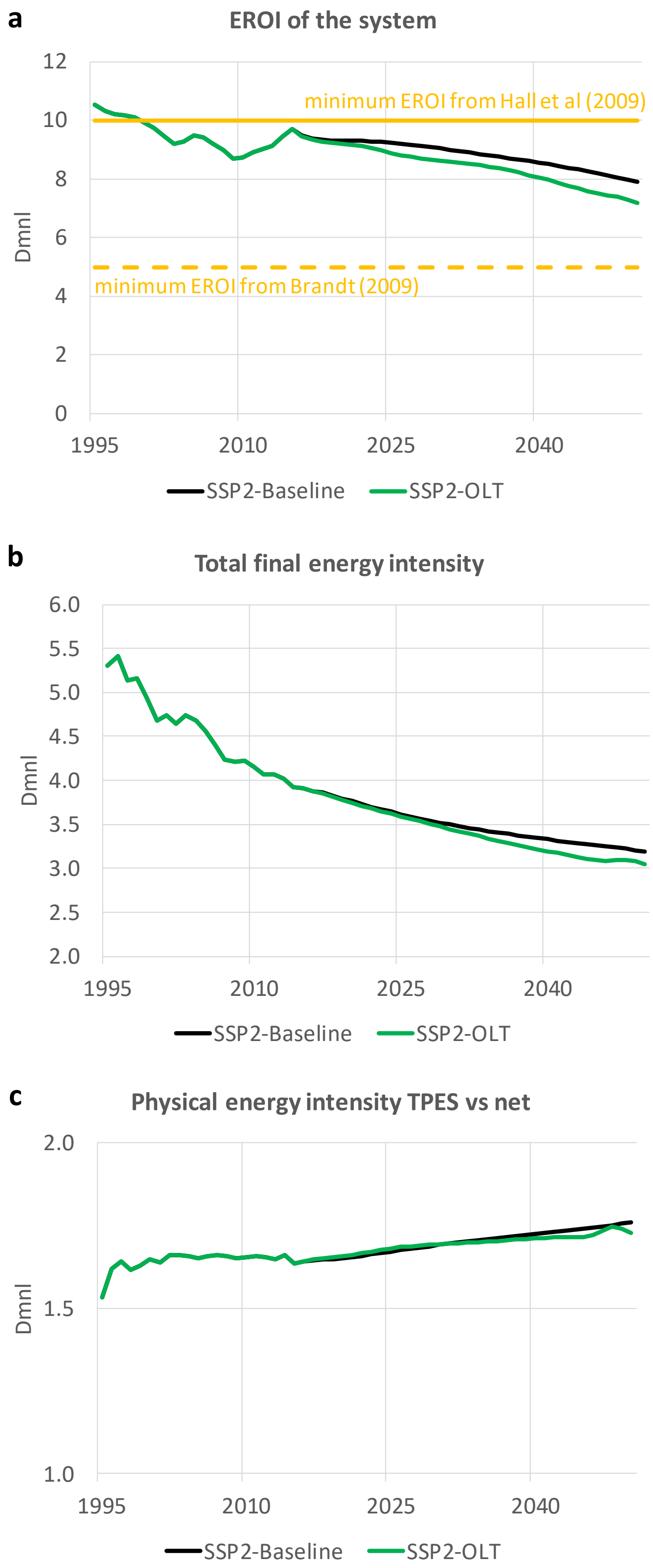


Figure 70. Efficiency of the system: (a) EROI of the system; (b) Total final energy intensity and (c) Physical energy intensity TPES vs net.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

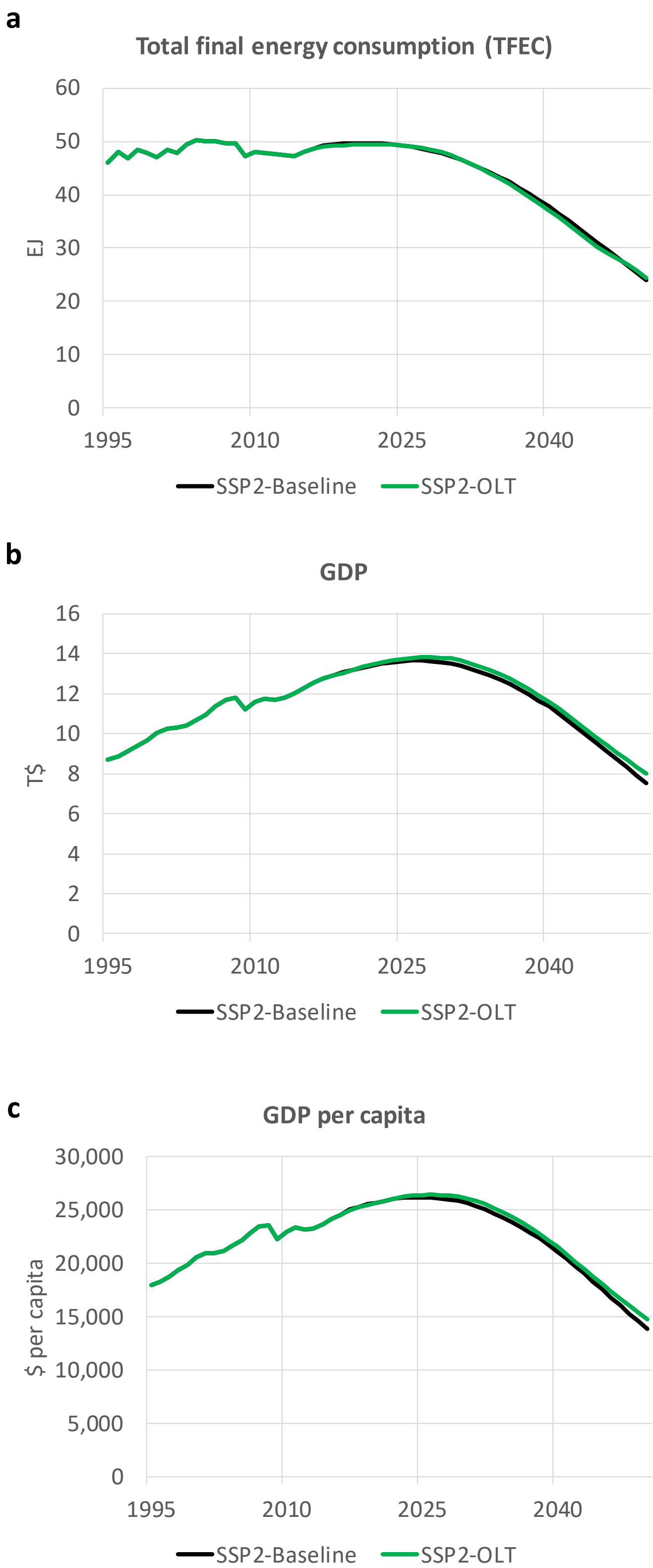


Figure 71. Aggregated variables: (a) Total Final Energy Consumption, (b) GDP and (c) GDP per capita.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

In terms of aggregated energy and monetary variables, both the Total Final Energy Consumption (TFEC) and Gross Domestic Product (GDP) show a similar trend in the simulated period for both scenarios (Figures 71a, 71b y 71c): roughly maintaining current levels up to 2025-2030, and a declining thereafter. This is mainly due to the strong climate change impacts coming from the MEDEAS-W in both scenarios, reaching 5-6% by 2050. Thus, in this case, EU policies for the transition to a low carbon system are hindered by the non-mitigation of GHG at global level. The integration of IOT modelling allows to compute the total final energy footprint (TFEF), which is currently around +15% of the TFEC; this difference decreases in both scenarios in a way that by 2050 the TFEC is almost equivalent to the TFEF.

In the performed simulations, trade of UE from RoW has not been constrained. However, as shown in Figure 72, the share of imports of non-renewable energies of EU from the RoW as a share of the global non-renewable energy extraction remains in both scenarios at around historical levels of ~10%.

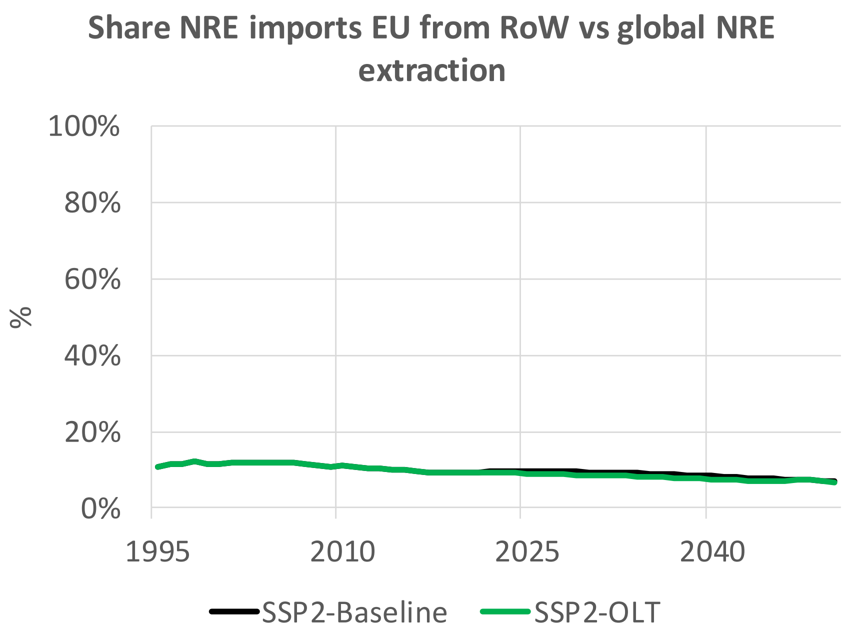


Figure 72. Share of non-renewable energy imports of EU from RoW as a share of the global non-renewable energy extraction.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

4. Limitations and further developments of MEDEAS-EU model

As any model, MEDEAS-EU presents a number of limitations. Most of them are shared with MEDEAS-World model.

4.1. Structure of the model

By submodules, we identify the most significant potential developments:

Economy module

- The main data source (WIOD database) provides a limited number of observations (15 years from 1995 to 2008). For the update of the global version as well as development of MEDEAS-EU and country level new data sources may be used instead,
- Consistent endogenous integration of technological change in the economic submodule (dynamic evolution of technical coefficients of A matrix, energy intensities evolution, etc.),
- Dynamic evolution of technical coefficients of A matrix: in the current version the A matrix remains constant with the 2009 values while the pathways simulated by the model imply in fact structural changes in the economic structure.
- Consideration of rebound effect,
- Consideration of employment,
- Consideration of taxes. The current modelling structure may allow to separately taxing (1) households and (2) firms (Gross Operating Surplus), which would subsequently affect public investment,

Energy and infrastructures module

- Expand the modelling of energy infrastructures to all energy generation and distribution technologies,
- Computation of the EROIst (and allocation mechanism) to all energy sources,
- Estimation of EROIst, EROIpou and EROIext of the whole system

Interaction of Energy and Economy

- Integration of primary energy intensities,

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

- More realistic allocation of energy scarcity between economic sectors (investigate different allocation rules beyond the proportional method implemented in this model version),
- Improve the modelling of the interaction between energy supply and demand in cases of energy scarcity for a more realistic, dynamic approach (e.g. replacement of final fuels),
- Improve the method to feed-back the EROI of the energy system to the economic submodule.

The improvement of the representation of the energy and economic interaction may allow to explore the possibility to reach a steady-state economic level based on a constant level of RES sustainable exploitation.

Materials

- Consider estimates at EU levels of the future availability of minerals.
- Improve the representation of minerals supply constraints, and eventually feed-back to the energy and infrastructure submodule.
- Include the dependence of energy requirements as a function of decreasing ore for those minerals where this is a relevant fraction of the full LCA.

GHG module

- Pursue the investigation related to the design and implementation of the damage function, given the high uncertainties related to the climate change impacts,
- Implications of different levels of adaptation (Füssel, 2010; Watkiss et al., 2015),
- Explore integration of climate change feedbacks through the economy module of MEDEAS (e.g. climate impacts as loss of productive capacity),

Social and environmental impacts indicators

- Estimate jobs of NRE to be able to compare the net gain/loss of jobs after the energy transition.
- Implement a relationship between inequality indicators (e.g. ratio labour vs capital share) and other inequality indicators such as Gini. The relationship between inequality and climate change impacts might also be investigated (Neher and Miola, 2015).

The current version of MEDEAS focus on solely 1 of the 9 planetary boundaries identified in the literature: climate change. Further versions of the model would substantially benefit through the

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

implementation of aspects of the other dimensions: novel entities, stratospheric ozone depletion, atmospheric aerosol loading, ocean acidification, biogeochemical flows (phosphorus and nitrogen), freshwater use and land-system change (Rockström et al., 2009; Steffen et al., 2015). However, the limitations to include these dimensions are considerable given the uncertainties and complexities involved.

Given that neither climate change impacts nor potential energy scarcities play a role in most energy-economy-environment models in the literature, most models operate within a "growth paradigm". However, this is not the case in MEDEAS framework, where biophysical constraints have the potential to restrain economic production significantly. Thus, further work must be focus on the consistent integration of feedbacks that may start to operate in situations of continued GDP reductions (e.g. affecting investments, demand, etc.). These feedbacks will likely be very different depending on the societal approach to deal with this situation, e.g. maintain of the "growth paradigm" or shift to alternative "no-growth" approaches (Capellán-Pérez et al., 2015). Non-linear effects such as the so-called "Seneca effect" (i.e. when the decline is faster than growth) might also be expected.[6]

[6] http://cassandralegacy.blogspot.rs/2011/08/seneca-effect-origins-of-collapse.html.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

4.2. Policies

The current MEDEAS model has a set of policies to explore alternative scenarios. However, most of these are technological options, and non-technological alternatives focusing on the shift of individual and collective preferences and lifestyle changes are scarce (as most models in the literature (van Sluisveld et al., 2016)). Hence, further versions of MEDEAS may include:

- Alternative diets with lower carbon and energy footprint –and potentially healthier- (Green et al., 2015),
- Higher education, which could lead to reduced energy intensity in production (MEDEAS, 2016, p. 2),
- Reduction in working hours per person (MEDEAS, 2016),
- Demand management policies (mobility, etc.),
- Agroecological farming (reduce fossil fuel inputs, peak potassium, peak phosphorus) (García-Olivares, 2015).
- A more sophisticated modelling of the non-energy use demand would allow to implement more targeted substitution policies (Daioglou et al., 2014; García-Olivares, 2015).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

5. Conclusions

MEDEAS-Europe simulation model is the main result of the deliverable 4.2 of the MEDEAS project. It is an integrated energy-economy-environment assessment model that has been developed with the systems dynamics methodology and initially programmed with the Vensim software. However, it will be later translated to Python, in order to provide a model in open-source software. This model requires as input some of the results of the simulation of the MEDEAS-World model. Thus, it is required to design and run in parallel two compatible storylines at global and European level in order to obtain consistent results in MEDEAS-Europe. MEDEAS-Europe model is based on the global version of MEDEAS and consists of 7 modules: Economy, Energy, Infrastructures, Materials, Land Use, Social and Environmental Impacts Indicators and GHG Emissions. Among the main novelties of the MEDEAS framework with respect to other IAMs are the integration of input-output matrices, feedback between vaiables of the environmental, economic and energy modules and the estimation and feedback of the EROI. In particular, the adaptation to the regional European level includes the representation of trade (at both final goods/services and primary energy level) with the rest of the worls, as well as a simplified representation of the land-use system.

By default, the simulation model of MEDEAS-Europe is designed to be run in the 1995-2050 time window, being the year the unit of time, although internally the simulation has a lower sampling period. Conceptually, the MEDEAS-Europe model is structured in 7 modules:

- Economy and population: the economy of MEDEAS is modelled following a post-Keynesian approach assuming disequilibrium (i.e. non-clearing markets), demand-led growth and supply constraints. The economic structure is captured by the integration of IOA (35 industrial sectors and households).
- Energy: this module includes the renewable and non-renewable energy resources potentials and availability, taking into account biophysical and temporal constraints. In total, 5 final fuels are considered (electricity, heat, solids, gases and liquids) and a diversity of energy technologies are modelled. A net energy approach has been followed.
- Energy infrastructures represent the infrastructures of power plants to generate electricity and heat.
- GHG Emissions: this module projects the GHG emissions in the European Union generated by human activities.
- Materials: estimation of the materials required for the construction and O&M of the alternative energy infrastructures.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

- Land-use: it is a simple model oriented to obtain information to estimate the potential for biomass and the potential for solar energy.
- Social and environmental impacts: this module translates the "biophysical" results of the simulations into metrics related with social and environmental impacts. The objective of this module is to contextualize the implications for human societies in terms of well-being for each simulation.

These modules have been programmed in approximately 100 simulation windows and using more than 5,000 variables. The modules of economy and energy are the most extensive and reach the highest degree of disaggregation. The model consists of a modular and flexible structure, where each module can be expanded/simplified/replaced by another version or submodel, new modules can be added, etc.

The scope of the model covers all the challenges that were proposed in the project. Some of these relevant challenges are:

a) Use of information generated by the MEDEAS-World simulation model.
b) Integration of Input-Output Matrices (IOT) in the Economy module.
c) Modeling the commercial relations of Europe through the IOT.
d) EROI estimation and its feedback.
e) Socio-economic indicators model implementation.
f) Supply-demand closures model implementation. The energy shortage determines the feedback between the energy and the economic module.
g) The effects of climate change are feedback into energy consumption.
h) Two standard scenarios have been modelled and implemented. Three other scenarios have been programmed.

The experimental results presented in this report illustrate the potentiality of MEDEAS-Europe model. The flexible modelling approach allows to model different assumptions and hypothesis. The preliminary results show the great importance of global evolution of EU-28 future: without a global coordinated and fast action to mitigate GHG emissions, the EU-28 may have too little leeway to adapt to climate change impacts.

Despite the challenges encountered with the model, there are still many limitations and uncertainties. In particular, further developments should address the inclusion of more dynamics in the economy module. Concretely, it is important to make A matrix evolving under different scenarios, but endogenously as well. More dynamization would help to improve the model's

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

allocation between different energy fuels and technologies. Moreover, the modelling of the interaction between energy supply and demand in cases of energy scarcity should be improved. The portfolio of policies should be expanded to include more non-technological options. For these and other reasons detailed in the previous section, the interpretation of the results must be done with caution.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Acknowledgements

The authors gratefully acknowledge Iñaki Arto for assisting with the interpretation and use of the WIOD database and Steve Mohr for sharing his country-level dataset including the scenarios of potential future extraction of fossil fuels.

References

Abbasi, T., Abbasi, S.A., 2012. Is the Use of Renewable Energy Sources an Answer to the Problems of Global Warming and Pollution? Crit. Rev. Environ. Sci. Technol. 42, 99–154. doi:10.1080/10643389.2010.498754

Alcamo, J., Leemans, R., Kreileman, E., 1998. Global change scenarios of the 21st century: results from the IMAGE 2.1 model. Pergamon, Tarrytown, N.Y.

Aleklett, K., Höök, M., Jakobsson, K., Lardelli, M., Snowden, S., Söderbergh, B., 2010. The Peak of the Oil Age – Analyzing the world oil production Reference Scenario in World Energy Outlook 2008. Energy Policy 38, 1398–1414. doi:10.1016/j.enpol.2009.11.021

Archer, C.L., Jacobson, M.Z., 2005. Evaluation of global wind power. J. Geophys. Res. Atmos. 110.

Arto, I., Andreoni, V., Rueda-Cantuche, J.M., 2016. Global use of water resources: A multiregional analysis of water use, water footprint and water trade balance. Water Resour. Econ. 15, 1–14. doi:10.1016/j.wre.2016.04.002

ASPO, 2009. ASPO Newsletter n. 100.

BGS, 2017. World mineral statistics data [WWW Document]. URL https://www.bgs.ac.uk/mineralsuk/statistics/wms.cfc?method=searchWMS

bluehabitat.org, 2017. Continental shelf [WWW Document]. URL http://www.bluehabitats.org/?page_id=1660

Bouwman, A., Kram, T., Goldewijk, K.K., 2006. Integrated modelling of global environmental change: an overview of IMAGE 2.4. Netherlands Environmental Assessment Agency, Bilthoven.

Boyer, D., 2014. Energopower: An Introduction. Anthropol. Q. 87, 309–333. doi:10.1353/anq.2014.0020

BP, 2017. BP statistical review of world energy.

Brandt, A.R., 2017. How Does Energy Resource Depletion Affect Prosperity? Mathematics of a Minimum Energy Return on Investment (EROI). Biophys. Econ. Resour. Qual. 2, 2.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

doi:10.1007/s41247-017-0019-y

Briens, F., 2015. Investigating Pathways to Post-Growth Economies Through Prospective Macroeconomic Modeling: Vision and Scenarios for France. Leeds.

Capellán-Pérez, I., 2016. Development and Application of Environmental Integrated Assessment Modelling towards Sustainability. University of the Basque Country, Bilbao, Spain.

Capellán-Pérez, I., Arto, I., M. Polanco-Martínez, J., González-Eguino, M., B. Neumann, M., 2016. Likelihood of climate change pathways under uncertainty on fossil fuel resource availability. Energy Environ. Sci. 9, 2482–2496. doi:10.1039/C6EE01008C

Capellán-Pérez, I., de Castro, C., Arto, I., 2017a. Assessing vulnerabilities and limits in the transition to renewable energies: Land requirements under 100% solar energy scenarios. Renew. Sustain. Energy Rev. 77, 760–782. doi:10.1016/j.rser.2017.03.137

Capellán-Pérez, I., de Castro, C., Mediavilla, M., Miguel, L.J., de Blas Sanz, I., Carpintero, Ó., Frechoso, F., Nieto, J., 2017b. World Limits Model (WoLiM) 1.5- Model Documentation. Technical Report. Energy, Economy and System Dynamics Group of the University of Valladolid, Spain.

Capellán-Pérez, I., Mediavilla, M., Castro, C. de, Carpintero, Ó., Miguel, L.J., 2015. More growth? An unfeasible option to overcome critical energy constraints and climate change. Sustain. Sci. 1–15. doi:10.1007/s11625-015-0299-3

Capellán-Pérez, I., Mediavilla, M., de Castro, C., Carpintero, Ó., Miguel, L.J., 2014. Fossil fuel depletion and socio-economic scenarios: An integrated approach. Energy 77, 641–666. doi:10.1016/j.energy.2014.09.063

Castellani, B., Rinaldi, S., Bonamente, E., Nicolini, A., Rossi, F., Cotana, F., 2018. Carbon and energy footprint of the hydrate-based biogas upgrading process integrated with CO2 valorization. Sci. Total Environ. 615, 404–411. doi:10.1016/j.scitotenv.2017.09.254

Christensen, P.P., 1989. Historical roots for ecological economics — Biophysical versus allocative approaches. Ecol. Econ. 1, 17–36. doi:10.1016/0921-8009(89)90022-0

Clarke, L., Edmonds, J., Jacoby, H., Pitcher, H., Reilly, J., Richels, R., 2007. Scenarios of greenhouse gas emissions and atmospheric concentrations, Sub-report 2.1A of Synthesis and Assessment

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Product 2.1. Washington D.C., USA.

Cole, M.A., 2004. US environmental load displacement: examining consumption, regulations and the role of NAFTA. Ecol. Econ. 48, 439–450. doi:10.1016/j.ecolecon.2003.10.016

Cordier, M., Uehara, T., Weih, J., Hamaide, B., 2017. An Input-output Economic Model Integrated Within a System Dynamics Ecological Model: Feedback Loop Methodology Applied to Fish Nursery Restoration. Ecol. Econ. 140, 46–57. doi:10.1016/j.ecolecon.2017.04.005

Daily, G.C., 1997. Nature's Services: Societal Dependence On Natural Ecosystems. Island Press, Washington DC, USA.

Daioglou, V., Faaij, A.P.C., Saygin, D., Patel, M.K., Wicke, B., Vuuren, D.P. van, 2014. Energy demand and emissions of the non-energy sector 7, 482–498. doi:10.1039/C3EE42667J

Danielsen, F., Beukema, H., Burgess, N.D., Parish, F., Brühl, C.A., Donald, P.F., Murdiyarso, D., Phalan, B., Reijnders, L., Struebig, M., Fitzherbert, E.B., 2009. Biofuel Plantations on Forested Lands: Double Jeopardy for Biodiversity and Climate. Conserv. Biol. 23, 348–358. doi:10.1111/j.1523-1739.2008.01096.x

Darrah, T.H., Vengosh, A., Jackson, R.B., Warner, N.R., Poreda, R.J., 2014. Noble gases identify the mechanisms of fugitive gas contamination in drinking-water wells overlying the Marcellus and Barnett Shales. Proc. Natl. Acad. Sci. 111, 14076–14081. doi:10.1073/pnas.1322107111

de Castro, C., 2009. Escenarios de Energía-Economía mundiales con modelos de dinámica de sistemas. University of Valladolid, Valladolid, Spain.

de Castro, C., Carpintero, Ó., Frechoso, F., Mediavilla, M., de Miguel, L.J., 2014. A top-down approach to assess physical and ecological limits of biofuels. Energy 64, 506–512. doi:10.1016/j.energy.2013.10.049

de Castro, C., Mediavilla, M., Miguel, L.J., Frechoso, F., 2013. Global solar electric potential: A review of their technical and sustainable limits. Renew. Sustain. Energy Rev. 28, 824–835. doi:10.1016/j.rser.2013.08.040

de Castro, C., Mediavilla, M., Miguel, L.J., Frechoso, F., 2011. Global wind power potential: Physical and technological limits. Energy Policy 39, 6677–6682. doi:10.1016/j.enpol.2011.06.027

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

De Haan, M., 2001. A Structural Decomposition Analysis of Pollution in the Netherlands. Econ. Syst. Res. 13, 181–196. doi:http://dx.doi.org/10.1080/09537320120052452

Deng, Y.Y., Haigh, M., Pouwels, W., Ramaekers, L., Brandsma, R., Schimschar, S., Grözinger, J., de Jager, D., 2015. Quantifying a realistic, worldwide wind and solar electricity supply. Glob. Environ. Chang. 31, 239–252. doi:10.1016/j.gloenvcha.2015.01.005

Dietzenbacher, E., Los, B., Stehrer, R., Timmer, M., de Vries, G., 2013. The Construction of World Input–Output Tables in the Wiod Project. Econ. Syst. Res. 25, 71–98. doi:10.1080/09535314.2012.761180

Dowlatabadi, H., 1998. Sensitivity of climate change mitigation estimates to assumptions about technical change. Energy Econ. 20, 473–493. doi:10.1016/S0140-9883(98)00009-7

EC, 2017. EU transport in figures - Statistical pocketbook 2017. Publication Office of the European Union, Luxembourg. doi:10.2832/041248

EC-JRC, PBL, 2011. Emission Database for Global Atmospheric Research (EDGAR), release version 4.2. [WWW Document]. URL http://edgar.jrc.ec.europa.eu

EEA, 2016. Transitions towards a more sustainable mobility system : TERM 2016 - Transport indicators tracking progress towards environmental targets in Europe. EEA Report No 34/2016, Copenhagen, Denmark.

Eurostat, 2018. Eurostat Database. European Commission, http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home/.

EWG, 2013. Fossil and Nuclear Fuels – the Supply Outlook (No. 2013/03/18 LBST). Energy Watch Group.

EWG, 2008. Crude Oil - The Supply Outlook. Energy Watch Group / Ludwig-Boelkow-Foundation.

EWG, 2007. Coal: Resources and Future Production (No. EWG-Paper No. 1/07).

EWG, 2006. Uranium Resources and Nuclear Energy (No. 1/2006), EWG-Series. Energy Watch Group.

FAO, 2017. FAOSTAT Agri-environmental indicators, Land Cover [WWW Document]. URL

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

http://www.fao.org/faostat/en/#data/LC

FAO, 2014. FAO statistical yearbook 2014. Bangkok, Thailand.

FAO, IIASA, 2009. Global Agro-ecological Zones. FAO Rome and IIASA Laxenburg, Italy and Austria.

FAOSTAT, 2017. FAOSTAT Agri-environmental indicators, Land Use [WWW Document]. URL http://www.fao.org/faostat/en/#data/RL

Farley, J., Daly, H.E., 2003. Ecological Economics: Principles and Applications, 1 edition. ed. Island Press, Washington.

Fujino, J., Nair, R., Kainuma, M., Masui, T., Matsuoka, Y., 2006. Multi-gas Mitigation Analysis on Stabilization Scenarios Using Aim Global Model. Energy J. doi:10.2307/23297089

Füssel, H.-M., 2010. Modeling impacts and adaptation in global IAMs. Wiley Interdiscip. Rev. Clim. Chang. 1, 288–303. doi:10.1002/wcc.40

García-Olivares, A., 2015. Substitutability of Electricity and Renewable Materials for Fossil Fuels in a Post-Carbon Economy. Energies 8, 13308–13343. doi:10.3390/en81212371

García-Olivares, A., Ballabrera-Poy, J., García-Ladona, E., Turiel, A., 2012. A global renewable mix with proven technologies and common materials. Energy Policy 41, 561–574. doi:10.1016/j.enpol.2011.11.018

Genty, A., Arto, I., Neuwahl, F., 2012. Final database of environmental satellite accounts: technical report on their compilation. WIOD Deliv. 4.6, Doc. downloadable http//www.wiod.org/publications/source_docs/Environmental_Sources.pdf.

Gimeno-Gutiérrez, M., Lacal-Arántegui, R., 2015. Assessment of the European potential for pumped hydropower energy storage based on two existing reservoirs. Renew. Energy 75, 856–868. doi:10.1016/j.renene.2014.10.068

Grassini, P., Eskridge, K.M., Cassman, K.G., 2013. Distinguishing between yield advances and yield plateaus in historical crop production trends. Nat. Commun. 4, 2918. doi:10.1038/ncomms3918

Green, R., Milner, J., Dangour, A.D., Haines, A., Chalabi, Z., Markandya, A., Spadaro, J., Wilkinson, P., 2015. The potential to reduce greenhouse gas emissions in the UK through healthy and realistic

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

dietary change. Clim. Change 129, 253–265. doi:10.1007/s10584-015-1329-y

Grübler, A., 2007. Scenarios of long-term socio-economic and environmental development under climate stabilization. Technol. Forecast. Soc. Change 74, 887–935. doi:10.1016/J.TECHFORE.2006.05.026

Hall, C.A.S., Balogh, S., Murphy, D.J.R., 2009. What is the Minimum EROI that a Sustainable Society Must Have? Energies 2, 25–47. doi:10.3390/en20100025

Hardt, L., O'Neill, D.W., 2017. Ecological Macroeconomic Models: Assessing Current Developments. Ecol. Econ. 134, 198–211. doi:10.1016/j.ecolecon.2016.12.027

Hassan, R., Chakrabort, C., Sultana, N., Mokhlesur Raman, M., 2016. Monetary Policy and Research Department Bangladesh Bank. Monet. Policy Res. Dep. Bangladesh Bank Working pa.

Hasse, J.E., Lathrop, R.G., 2003. Land resource impact indicators of urban sprawl. Appl. Geogr. 23, 159–175. doi:10.1016/J.APGEOG.2003.08.002

Hijioka, Y., Matsuoka, Y., Nishimoto, H., Masui, T., Kainuma, M., 2008. Global GHG emission scenarios under GHG concentration stabilization targets. J. Glob. Environ. Eng. 13, 97–108.

Ho, L.S., 2012. Globalization, exports, and effective exchange rate indices. J. Int. Money Financ. 31, 996–1007.

Höök, M., Tang, X., 2013. Depletion of fossil fuels and anthropogenic climate change—A review. Energy Policy, Special Section: Transition Pathways to a Low Carbon Economy 52, 797–809. doi:10.1016/j.enpol.2012.10.046

Höök, M., Zittel, W., Schindler, J., Aleklett, K., 2010. Global coal production outlooks based on a logistic model. Fuel 89, 3546–3558. doi:10.1016/j.fuel.2010.06.013

Howarth, R.W., 2015. Methane emissions and climatic warming risk from hydraulic fracturing and shale gas development: implications for policy. Energy Emiss. Control Technol. 3, 45–54.

IEA, 2016. IEA World Energy Statistics and Balances, World Energy Statistics and Balances (database). IEA/OECD, Paris (France).

IEA, 2014. Heating without global warming–market developments and policy considerations for

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

renewable heat. International Energy Agency, Paris.

IEA/OECD, 2017. Global EV Outlook 2017 : Two million and counting.

IEA/OECD, 2014. World Energy Outlook 2014. OECD / IEA, Paris.

IPCC, 2013. Climate change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Stocker, T.F., D. Qin, G. - K. Plattner, M. Tignor, S.K. Allen, J. Bosc hung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA,. doi:10.1017/CBO9781107415324

IPCC, 2011. Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge University Press, United Kingdom and New York (USA).

IPCC, 1990. Climate change: The IPCC First Assessment. Report prepared for Intergovernmental Panel on Climate Change by Working Group I. Cambridge University Press, Cambridge, Great Britain, New York, NY, USA and Melbourne, Australia.

IRENA db, 2017. IRENA Resource (Database). International Renewable Energy Agency, http://resourceirena.irena.org.

James, D.E., Jansen, H.M.A., Opschoor, J.B., 1978. Economic Approaches to Environmental Problems. Elsevier North Holland, Amsterdam.

Juffe-Bignoli, D., Burgess, N., Bingham, H., Belle, E., de Lima, M., Deguignet, M., Bertzky, B., Milam, A., Martinez-Lopez, J., Lewis, E., 2014. Protected planet report 2014. UNEP-WCMC Cambridge, UK.

Kagawa, S., Inamura, H., 2004. A Spatial Structural Decomposition Analysis of Chinese and Japanese Energy Demand: 1985–1990. Econ. Syst. Res. 16, 279–299. doi:10.1080/0953531042000239374

Kainuma, M., 2003. Climate policy assessment: Asia-Pacific integrated modeling. Springer, Tokyo.

Kaldellis, J.K., Apostolou, D., 2017. Life cycle energy and carbon footprint of offshore wind energy. Comparison with onshore counterpart. Renew. Energy 108, 72–84. doi:10.1016/j.renene.2017.02.039

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Kaltenegger, O., Löschel, A., Pothen, F., 2018. The Effect of Globalisation on Energy Footprints: Disentangling the Links of Global Value Chains. Energy Econ. doi:10.1016/j.eneco.2018.01.008

Keith, D.W., DeCarolis, J.F., Denkenberger, D.C., Lenschow, D.H., Malyshev, S.L., Pacala, S., Rasch, P.J., 2004. The influence of large-scale wind power on global climate. Proc. Natl. Acad. Sci. U. S. A. 101, 16115–16120. doi:10.1073/pnas.0406930101

Kemfert, C., 2005. Induced technological change in a multi-regional, multi-sectoral, integrated assessment model (WIAGEM): Impact assessment of climate policy strategies. Ecol. Econ. 54, 293–305. doi:10.1016/j.ecolecon.2004.12.031

Kerschner, C., Capellán-Pérez, I., 2017. Peak-Oil and Ecological Economics, in: Spash, C.L. (Ed.), Routdlege Handbook of Ecological Economics: Nature and Society. Abingdon, pp. 425–435.

Kerschner, C., O'Neill, D.W., 2016. Economic Growth and Sustainability, in: Kopnina, H., Shoreman-Ouimet, E. (Eds.), Sustainability. Key Issues, Key Issues in Environment and Sustainability. Routledge, p. 392.

Khetarpal, D., 2016. World Energy Resources: Solar 2016, World Energy Council. World Energy Council.

Koroneos, C.J., Nanaki, E.A., 2012. Integrated solid waste management and energy production - a life cycle assessment approach: the case study of the city of Thessaloniki. J. Clean. Prod. 27, 141–150. doi:10.1016/j.jclepro.2012.01.010

Kyle, P., Luckow, P., Calvin, K., Emanuel, W., Mayda, N., Yuyu Zhou, 2011. GCAM 3.0 Agriculture and Land Use: Data Sources and Methods.

Laherrère, J., 2010. Peak Oil y Seguridad Energética. Buenos Aires (Argentina).

Laherrère, J., 2006. Oil and gas, what future? Groningen, Netherlands.

Lan, J., Malik, A., Lenzen, M., McBain, D., Kanemoto, K., 2016. A structural decomposition analysis of global energy footprints. Appl. Energy 163, 436–451. doi:10.1016/j.apenergy.2015.10.178

Lavoie, M., 2014. Postkeynesian Economics: New Foundations. Edward Elgar, Chentelham.

Lenzen, M., 2010. Current State of Development of Electricity-Generating Technologies: A

Literature Review. Energies 3, 462–591. doi:10.3390/en3030462

Leontief, W., 1970. Environmental repercussions and the economic structure: An input-output approach. Rev. Econ. Stat. 52, 262.

Levin, S.A., Carpenter, S.R., Godfray, H.C.J., Kinzig, A.P., Loreau, M., Losos, J.B., Walker, B., Wilcove, D.S., 2009. The Princeton guide to ecology. Princeton University Press.

Maggio, G., Cacciola, G., 2012. When will oil, natural gas, and coal peak? Fuel 98, 111–123. doi:10.1016/j.fuel.2012.03.021

Masui, T., Hanaoka, T., Hikita, S., Kainuma, M., 2006. Assessment of CO2 Reductions and Economic Impacts Considering Energy-Saving Investments. Energy J. 27, 175–190.

Masui, T., Matsumoto, K., Hijioka, Y., Kinoshita, T., Nozawa, T., Ishiwatari, S., Kato, E., Shukla, P.R., Yamagata, Y., Kainuma, M., 2011. An emission pathway for stabilization at 6 Wm−2 radiative forcing. Clim. Change 109, 59–76. doi:10.1007/s10584-011-0150-5

Meadows, D.H., 1972. The Limits to Growth; A Report for the Club of Rome's Project on the Predicament of Mankind, 2 edition. ed. Universe Pub, New York.

MEDEAS, 2017a. Deliverable D4.1 (Deliverable MEDEAS project). GEEDS, University of Valladolid.

MEDEAS, 2017b. Deliverable D3.3 (Deliverable MEDEAS project). INSTM, IIASA, CSIC, CIRCE.

MEDEAS, 2017c. Deliverable D3.4 (Deliverable MEDEAS project). INSTM, MU, UVa.

MEDEAS, 2016. Deliverable D2.2 (Deliverable MEDEAS project). CIRCE, BSERC, MU, UVa, IIASA, ICM-CSIC & AEA.

Mediavilla, M., de Castro, C., Capellán, I., Javier Miguel, L., Arto, I., Frechoso, F., 2013. The transition towards renewable energies: Physical limits and temporal conditions. Energy Policy 52, 297–311. doi:10.1016/j.enpol.2012.09.033

Miller, L., Gans, F., Kleidon, A., 2011. Estimating maximum global land surface wind power extractability and associated climatic consequences. Earth Syst. Dynam 2, 1–12.

Miller, R.E., Blair, P.D., 2009. Input-Analysis. Foundations and Extensions. Cambridge University

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Press, Cambridge, UK.

Mohr, S.H., 2012. Fossil fuel future production, world and Australia focus. Sydney, 2-4 December 2012.

Mohr, S.H., Evans, G.M., 2011. Long term forecasting of natural gas production. Energy Policy 39, 5550–5560. doi:10.1016/j.enpol.2011.04.066

Mohr, S.H., Evans, G.M., 2009. Forecasting coal production until 2100. Fuel 88, 2059–2067. doi:10.1016/j.fuel.2009.01.032

Mohr, S.H., Wang, J., Ellem, G., Ward, J., Giurco, D., 2015. Projection of world fossil fuels by country. Fuel 141, 120–135. doi:10.1016/j.fuel.2014.10.030

Morita, T., Jiang, K., Masui, T., Matsuoka, Y., Rana, A., 2003. Long-term Scenarios based on AIM Model, in: Climate Policy Assessment. Springer, Tokyo, pp. 17–36.

Murray, J.W., 2016. Limitations of Oil Production to the IPCC Scenarios: The New Realities of US and Global Oil Production. Biophys. Econ. Resour. Qual. 1, 13.

Neher, F., Miola, A., 2015. The Role of Social Inequalities for the Vulnerability to Climate Related Extreme Weather Events. Joint Research Centre, Publications Office of the European Union, Luxembourg.

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W., 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Chang. 42, 169–180. doi:10.1016/j.gloenvcha.2015.01.004

OECD, 2005. Glossary of statistical terms [WWW Document]. http://stats.oecd.org/glossary/. URL http://stats.oecd.org/glossary/

Patzek, T.W., Croft, G.D., 2010. A global coal production forecast with multi-Hubbert cycle analysis. Energy 35, 3109–3122. doi:10.1016/j.energy.2010.02.009

Peng, S., Zhang, W., Sun, C., 2016. "Environmental load displacement" from the North to the South: A consumption-based perspective with a focus on China. Ecol. Econ. 128, 147–158. doi:10.1016/j.ecolecon.2016.04.020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Pollit, H., 2014. Technical Manual, Version 6.0.

Prieto, P.A., Hall, C.A.S., 2013. Spain's Photovoltaic Revolution: The Energy Return on Investment, 2013th ed. Springer.

REN21, 2017. Renewables 2017. Global Status Report. REN 21, Paris.

Rezai, A., Stagl, S., 2016. Ecological macroeconomics: introduction and review. Ecol. Econ. 121, 181–185.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., Wit, C.A. de, Hughes, T., Leeuw, S. van der, Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A., 2009. A safe operating space for humanity. Nature 461, 472–475. doi:10.1038/461472a

Schneider, S.H., Morton, L., 1981. The Primordial Bond Exploring Connections Between Man and Nature Through the Humanities and Sciences. Plenum Press. New York.

Scrieciu, S., Rezai, A., Mechler, R., 2013. On the economic foundations of green growth discourses: the case of climate change mitigation and macroeconomic dynamics in economic modeling. Wiley Interdiscip. Rev. Energy Environ. 2, 251–268. doi:10.1002/wene.57

SHC, 2016. Solar Heat Worldwide. Markets and Contribution to the Energy Supply 2014. Solar Heating & Cooling Programme IEA.

Smil, V., 2008. Energy in nature and society: general energetics of complex systems. MIT Press, Cambridge, Massachusetts, USA.

Smith, S.J., Wigley, T.M.L., 2006. Multi-Gas Forcing Stabilization with Minicam. Energy J. doi:10.2307/23297091

Soulé, M.E., Sanjayan, M.A., 1998. ECOLOGY: Conservation Targets: Do They Help? Science (80-.). 279, 2060–2061. doi:10.1126/science.279.5359.2060

Steffansson, V., 2005. World geothermal assessment, in: Proceedings World Geothermal Congress 2005. 24-29 April 2005, Antalya, Turkey.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sörlin, S., 2015. Planetary boundaries: Guiding human development on a changing planet. Science 347, 1259855.

Stehfest, E., van Vuuren, D., Bouwman, L., Kram, T., 2014. Integrated assessment of global environmental change with IMAGE 3.0: Model description and policy applications. Netherlands Environmental Assessment Agency (PBL).

Stehfest, E., van Vuuren, D., Kram, T., 2014. Integrated assessment of global environmental change with IMAGE 3.0: Model description and policy applications. Netherlands Environmental Assessment Agency (PBL).

Sterman, J., Fiddaman, T., Franck, T., Jones, A., McCauley, S., Rice, P., Sawin, E., Siegel, L., 2012. Climate interactive: the C-ROADS climate policy model. Sys.Dyn.Rev. 28, 295–305. doi:10.1002/sdr.1474

Stern, D.I., 1997. Limits to substitution and irreversibility in production and consumption: A neoclassical interpretation of ecological economics. Ecol. Econ. 21, 197–215. doi:10.1016/S0921-8009(96)00103-6

Šúri, M., Huld, T.A., Dunlop, E.D., Ossenbrink, H.A., 2007. Potential of solar electricity generation in the European Union member states and candidate countries. Sol. Energy 81, 1295–1305. doi:10.1016/j.solener.2006.12.007

Taylor, L., Rezai, A., Foley, D.K., 2016. An integrated approach to climate change, income distribution, employment and economic growth. Ecol. Econ. 121, 196–205.

Timmer, M., Erumban, A.A., Gouma, R., Los, B., Temurshoev, U., de Vries, G.J., Arto, I., Genty, V.A.A., Neuwahl, F., Francois, J., 2012. The world input-output database (WIOD): contents, sources and methods. Institue for International and Development Economics.

Trainer, F., 2007. Renewable energy cannot sustain a consumer society. Springer Science & Business Media.

Uehara, T., Nagase, Y., Wakeland, W., 2013. Integrating Economics and System Dynamics Approaches for Modeling an Ecological-Economic System. Syst. Sci. Fac. Publ. Present.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

UN, 2015. Report of the Inter-Agency and Expert Group on Sustainable Development Goal Indicators. United Nations. Economic and Social Council. Statistical Commission.

UN, 1990. Human development report. United Nations Dev. Program.

UNESCO, 2009. The United Nations World Water Development Report 3–Water in a Changing World. United Nations Educational Scientific and Cultural Organization, Paris.

Vačkář, D., 2012. Ecological Footprint, environmental performance and biodiversity: A cross-national comparison. Ecol. Indic., The State of the Art in Ecological Footprint: Theory and Applications 16, 40–46. doi:10.1016/j.ecolind.2011.08.008

van de Ven, D.-J., Capellán-Pérez, I., Arto, I., Cazcarro, I., De Castro, C., González-Eguino, M., 2018. The potential land use impact of solar energy. Forthcoming.

van Sluisveld, M.A.E., Martínez, S.H., Daioglou, V., van Vuuren, D.P., 2016. Exploring the implications of lifestyle change in 2°C mitigation scenarios using the IMAGE integrated assessment model. Technol. Forecast. Soc. Change 102, 309–319. doi:10.1016/j.techfore.2015.08.013

van Vuuren, D.P., den Elzen, M.G.J., Lucas, P.L., Eickhout, B., Strengers, B.J., van Ruijven, B., Wonink, S., van Houdt, R., 2007. Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. Clim. Change 81, 119–159. doi:10.1007/s10584-006-9172-9

Von Witzke, H., Noleppa, S., 2010. EU agricultural production and trade: Can more efficiency prevent increasing “land-grabbing” outside of Europe? Berlin, Germany.

Wackernagel, M., Schulz, N.B., Deumling, D., Linares, A.C., Jenkins, M., Kapos, V., Monfreda, C., Loh, J., Myers, N., Norgaard, R., Randers, J., 2002. Tracking the ecological overshoot of the human economy. Proc. Natl. Acad. Sci. 99, 9266–9271. doi:10.1073/pnas.142033699

Wang, J., Feng, L., Tang, X., Bentley, Y., Höök, M., 2017. The implications of fossil fuel supply constraints on climate change projections: A supply-side analysis. Futures 86, 58–72. doi:10.1016/j.futures.2016.04.007

Watkiss, P., Benzie, M., Klein, R.J.T., 2015. The complementarity and comparability of climate change adaptation and mitigation. Wiley Interdiscip. Rev. Clim. Chang. 6, 541–557.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 691287

doi:10.1002/wcc.368

WCED, 1987. Our common future (Report of the World Commission on Environment and Development). United Nations.

Wise, M., Calvin, K., Thomson, A., Clarke, L., Bond-Lamberty, B., Sands, R., Smith, S.J., Janetos, A., Edmonds, J., 2009. Implications of limiting CO2 concentrations for land use and energy. Science 324, 1183–6. doi:10.1126/science.1168475

World Bank database, 2018. World Bank database. http://data.worldbank.org/.

Zittel, W., 2012. Feasible Futures for the Common Good. Energy Transition. Paths in a Period of Increasing Resource Scarcities. Ludwig-Bölkow-Systemtechnik GmbH, Munich (Germany).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

MEDEAS
MODELING THE RENEWABLE ENERGY TRANSITION IN EUROPE

List of Tables

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

List of Figures

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287