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MEDEAS
MODELING THE RENEWABLE ENERGY TRANSITION IN EUROPE

Project Nr: 691287

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

pymedeas world user's manual

Version 0.3.0

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MEDEAS
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Abstract

This document provides the user's manual for the Python implementation of the Medeas-World and Europe models *(pymedeas_w and pymedeas_eu, respectively)*. The document also contains the description of the World model as an annex.

List of abbreviations and acronyms

BAU Business as Usual

IDE Integrated Development Environment

IO Input/output

PySD Python System Dynamics library

CLI Command line interface

GUI Graphical User Interface

CSV comma separated values

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Getting the code

The official releases of the code can be downloaded from the project website (https://medeas.eu/model/medeas-model).

A public git repository is also available on https://gitlab.com/MEDEAS/pymedeas_models so that anybody can follow the development of the code and make contributions if they so wish.

Structure of the code

The project folder contains the following files and folders:

- **config.ini**: configuration file that allows the user to select the model to run (pymedeas_w.py or pymedeas_eu.py).
- **LICENSE**: terms of the license through which the code is distributed (MIT).
- **Pipfile and Pipfile.lock**: requirements files to be installed with pipenv library.
- **plotting folder**: contains configuration files used by the plot_tool.py (will be removed from version 0.4.0).
- **plot_tool.py**: implements the plotting graphical user interface (GUI) using the tkinter module.
- **pymedeas_w and pymedeas_eu folders**: contain the World model file (pymedeas_w.py) and the European Union model file (pymedeas_eu.py) respectively. Each of the two folders also contains the inputs.xlsx spreadsheet, used to create user defined scenarios, as well as other configuration and json files. Results obtained with the World model are automatically stored in the pymedeas_w folder, while results obtained with the EU model are stored in the pymedeas_eu folder.
- **pysd folder**: fork from (https://github.com/JamesPHoughton/pysd). Contains the Vensim to Python model translator, the model builder and the model integrator. In further implementations pysd code will not be shipped with the project code, but a dependency to install.
- **README.md**: markdown file containing a description of the project as well as installation and execution instructions.
- **run.py**: file that needs to be executed to load the model, feed it with data, parametrize it based on user input (through a CLI), execute it and store and display the results.

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- **pytools folder**: contains the module tools.py which consists on functions that are called during run.py execution.
- **utils.ipynb**: jupyter notebook for illustration on how to change model parameters.
- **_version**: file containing the version number of the current release.

The CLI launched upon execution of the run.py module and the inputs.xlsx files (located in the pymedeas_eu and pymedeas_w folders) are the two sole ways users have to parametrize and launch simulations. PySD methods are hidden to the user.

The PySD library

pymedeas_w.py and pymedeas_eu.py model files were obtained by transpiling MEDEAS_w and MEDEAS_eu Vensim models to Python, using a fork of the PySD module (Houghton and Siegel, 2015). Accordingly, the two translated models inherit the main design principles of PySD.

PySD translator constructs a Python class (the model class) that represents the system dynamics model (Houghton and Siegel, 2015). Such class keeps track of both the current simulation time and the values of each of the system stocks. One of the main characteristics of the resulting model class is that all model equations are represented as functions.

In addition to the tranpiler, PySD also provides the simulation engine that allows running the transpiled models natively in Python. When running simulations, the pymedeas_w.py or the pymedeas_eu.py are loaded as PySD Model objects by the PySD.load() method.

By design, the model class maintains only a single state of the system in memory, and therefore the future state of the model is calculated strictly based upon their current state. The integration is carried out using the Euler method.

The interaction of the users with the translated models is through the PySD class. This class allows to run simulations, modify parameters and so on.

The outputs of the simulations run with PySD are stored in the form of a Pandas DataFrame.

For further information on PySD please refer to the original source (Houghton and Siegel, 2015).

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The model files: pymedeas_w.py and pymedeas_eu.py

The two model files have the following elements in common (please note that not all PySD functions are described hereafter, but just those that are used by the models described in this document):

- The model files are self-contained, in the sense that they contain all the required data to be run by the simulation engine included in PySD (no data needs to be imported).
- The models are loaded as a PySD Model object with the Model.load() method, before the simulation is executed using the Model.run() method.
- Parameter values can be modified at the time of executing the Model.run() method.
- All model equations are defined as Python functions.
- The _namespace is a Python dictionary containing the variable name as defined in the original Vensim code as keys, and the Python-safe name (replacing spaces by underscores) as values.
- The _subscript_dict is a Python dictionary containing the subscript name as key and the subscripts in a list as values.
- Matrices are represented as objects of the xarray DataArray class.
- Table functions are represented using the lookups function, which performs linear interpolation on the data, to be able to access intermediate values between actual data points.
- Initial, Integ and Delay objects are child objects of the Stateful class, which all have state (current state of the object) and ddt attributes that the integrator uses to obtain their value at the next time-step.
- PySD uses caching so that functions that are called several times at each time-step run much faster after the first call. The cache function wrappers serve to store the output of the function in memory. The ‘step’ cache stores the function return until the next time-step, while the ‘run’ cache stores it until the next model initialization.

The Plot GUI

The plot GUI (plot_tool.py) is a graphical user interface aimed at displaying simulation results obtained with the pymedeas models.

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Figure 1 shows a caption of the plot GUI .

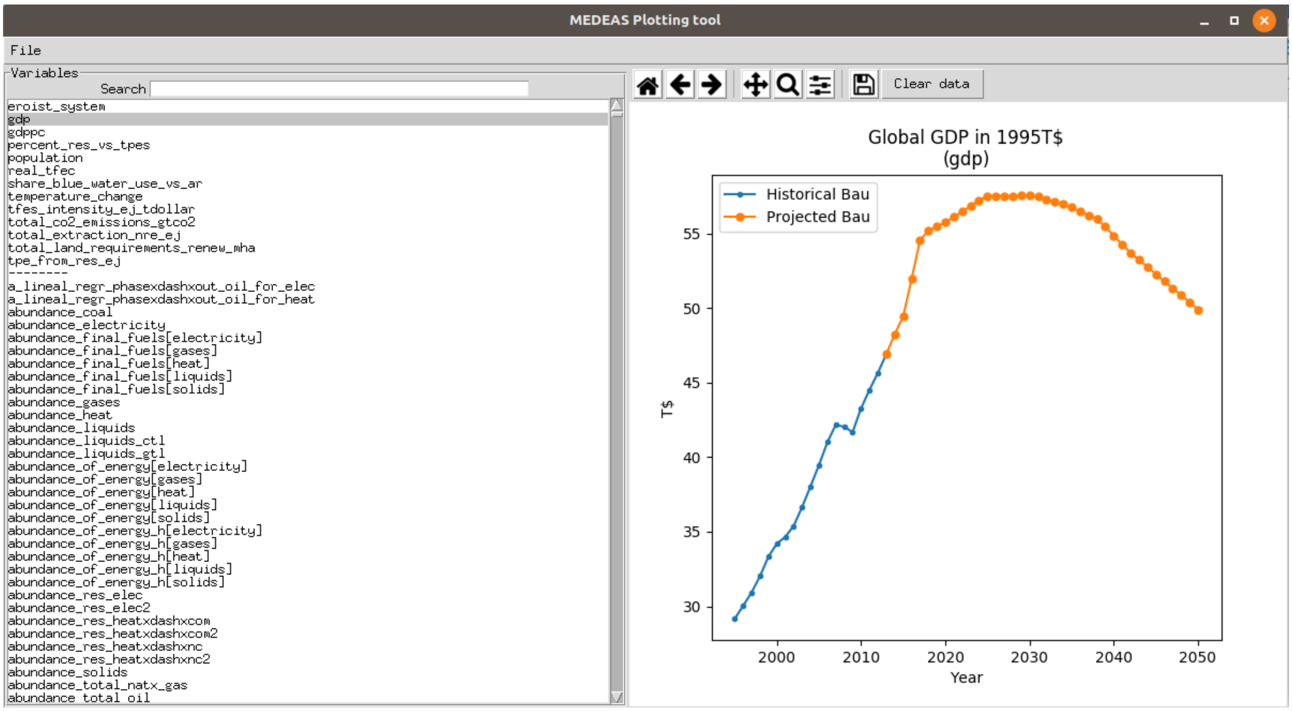

Figure 1 : Caption of the plot GUI (plot_tool.py)

The plot GUI can be used to plot simultaneously as many simulation results as needed. It can either be launched automatically at the end of a simulation or in standalone mode, to plot old simulation results (in csv format).

A different line style is used to distinguish between historical (until 2014) and projected data.

The search bar, limits the number of variable names displayed on the left panel to those that coincide with the keywords introduced by the user.

The *Clear data* button, resets the plot GUI to its default state : the list of variables and the displayed plots are cleared.

The Save button, allows the user to save the displayed plot in png format. The default file name is that of the variable selected by the user. The rest of the buttons serve to configure the display of the plot (zoom, pan).

For instructions on how to launch the plot GUI, refer to subsection *Using the plot GUI to plot simulation results* in section *Running simulations and plotting the results.*

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Setup of a Python development environment to use the pymedeas models

On MS Windows

1. Download the project code in your computer
2. Download and install Anaconda 3.5 (Python 3.7) using the default parameters (Miniconda could be used instead of Anaconda). Write down the installation directory, because you will need it later (we will call this **INSTALL_PATH** from now on). Read *NOTE 1* and *NOTE 2* at the end of this section for particular installation cases (e.g. Anaconda already installed)
3. Add the INSTALL_PATH to the Windows path. To do so, open the terminal (click on Windows Start Menu, write *cmd* and type Enter) and run the following command (replacing INSTALL_PATH by your actual installation path):

   SETX PATH "%PATH%;INSTALL_PATH\Scripts;INSTALL_PATH"

4. If you don't know where anaconda was installed, run the following command in cmd (the directory where the anaconda.exe resides will be your INSTALL_PATH):

   where anaconda

5. Log out from your user account and log back in to apply the changes. Verify that the INSTALL_PATH was added to your system PATH, by running:

   echo %PATH%

6. You should now be able to see the Anaconda installation directory among the other directories in your system PATH.
7. To install the *pipenv* package, open the terminal (cmd) again and run:

   pip install pipenv

8. Still in the terminal, go to the folder where you downloaded the MEDEAS model using *cd* command (replacing the below path with the actual path to the folder where you downloaded the model):

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cd C:\Users\UserName\MEDEAS-model

9. From there, run the following command to install all Python packages required to run the model in a virtual environment:

   pipenv install - -python=python.exe

10. In the output of the previous command you should be able to identify the path where the virtual environment was created. Write it down for later use.
11. Congratulations, you can move to the next step! Go to *Running a simulation from terminal* section to verify that everything went well during the previous steps, and to try to run the model.

NOTE 1: By default, Anaconda3 installs in your user directory as C:3 but if you have spaces in the UserName (e.g. C:\Users\Guido van Rossum\Anaconda3) Anaconda might have issues to install further packages. In that case chose to install for All Users (you will need adminstrative privileges), which will install Anaconda3 in C:3.

NOTE 2: If you have an older version of Anaconda installed (Current version 3.5 was released in Octorber 2018) you should install the new one while keeping/removing the old one.

On Linux

1. Download the project code in your computer
2. Download Anaconda 3.5 for linux (Miniconda could be used instead of Anaconda). Open the terminal, go to the folder where the package was saved and run (replacing Anaconda3-5.3.0-Linux-x86_64.sh by the name of downloaded file):

   bash Anaconda3-5.3.0-Linux-x86_64.sh

3. Follow the installation instructions, leaving all parameters by default. This will install anaconda in your home directory (e.g. /home/user/anaconda3). When asked: *Do you wish the installer to initialize Anaconda3 in your /home/roger/.bashrc ? [yes|no]*, Answer yes. You can say no to the installation of Microsoft VSCode.
4. The follwing command should point to your anaconda installation directory:

   which python

5. Install pipenv from terminal with the following command:

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pip install pipenv

6. Still from the console, go to the folder where the model files are, and execute:

   pipenv install - -python 3.7

7. In the output of the previous command you should be able to identify the path where the virtual environment was created.
8. You are done. Go to *Running a simulation from terminal* section of this document to verify that everything went well during the previous steps, and to try to run the model.

On MacOS

1. Download the project code in your computer
2. Download and install Anaconda 3.5 for MacOS (Python 3.7) (Miniconda could be used instead of Anaconda).
3. Open a terminal and install Xcode Command line developer tools with the following command:

   xcode-select - -install

4. Confirm that pip executable is inside the anaconda3 folder with the command below (you should see something like /Users/your_user/anaconda3/bin/pip):

   which pip**3.**

5. Install pipenv with the following command:

   pip install pipenv

6. Still from the console, go to the folder where the model files are, and execute:

   pipenv install - -python 3.7

7. If the previous step did not work, you need to add pipenv path to your system path. To do that, add the following line at the end of your .bash_profile (in your home directory, press Cmd + Shift + . (dot) to see the .bash_profile file) (replace the **ANACONDA_PATH** by the path where you installed anaconda e.g. */Users/medeas/anaconda3/*):

   export PATH="ANACONDA_PATH/bin:$PATH"

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8. After saving the file, run the following command in the terminal:

   source ~/.bash_profile

   Then try again the command of step 4.

9. Congratulations, you can move to the next step! Go to *Running a simulation from terminal* section of this document to verify that everything went well during the previous steps, and to try to run the model.

Installation and setup of a Python IDE (optional)

If you would like to use a graphical IDE instead of the command line, we recommend you to download **Pycharm Community Edition**, which is free and open source. You cand download it for Windows, Linux or macOS.

This instructions were written for Pycharm 2018.3.5 (Community Edition). If you use any other version of the software, the instructions shown below might difer slightly.

After installation, follow these steps to get the model working:

1. Open the folder where you downloaded the model: go to Fileand select the model folder
2. Make Pycharm use the virtual environment that you created for the current project (if it doesn't already):
   a. Go to *File (PyCharm in macOS) and start typing **project interpreter**.
   b. If the environment you created appears in the drop-down list, you can skip the next step.
   c. If the environment does not show up, you need to tell Pycharm where to find it. Click on the sprocket wheel icon, in the top right corner and click on **Add**. This will open a new window, where you should check the option **Existing environment**, and select the path where your environment was stored.
   d. You can get the path to your virtualenv by running the following command in a terminal:

      pipenv - -venv

   e. Click *Ok* and *Apply*
3. In the main menu, click on *Run/Edit* configurations

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4. Click on the plus sign on the top left corner and choose Python
5. Fill in the boxes as follows:
    a) *Name*: Run model
    b) *Script path*: select the run.py file from the project folder
    c) *Parameters*: -s -t 0.03125 -r 1.0 -x bau -p
    d) *Python Interpreter*: select the one you added in step 2 from the drop-down menu
6. Click Ok
7. On the top right corner of the screen you should now see a play icon beside the words **Run model**, click on it to run the simulation.
8. If you would like to be able to run the **plot GUI** to plot results of previous simulations in PyCharm, repeat step 3 changing the parameters to:
    a) *Name*: Plot
    b) *Script path*: select the plot_tool.py file from the project folder
    c) *Parameters*: (leave blank)
    d) *Python Interpreter*: select the one you added in step 2 from the drop-down menu

Running simulations and plotting the results

NOTE3: in order to run any simulation, users need to install all project dependencies and create a virtual environment, using the pipenv library. Section "Setup of a Python development environment to use the models" (above) gives step-by-step installation on how to do that. The steps described on that section need to be done just once.

Activating the virtual environment

NOTE4 : This step needs to be run every time the users opens a new terminal session to run the pymedeas code.

1. Open a terminal and go to the project folder (using the *cd* command)
2. If it's not active yet, activate the project virtual environment running the following command:

```
pipenv shell
```


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Printing CLI instructions

1. If it's not yet active, activate the project virtual environment, as shown in section Activating the virtual environment above.
2. To see the options the user can choose from, run the following command :

python run.py -h

Selecting the model to run (either pymedeas_w or pymedeas_eu)

NOTE5 : pymedeas_eu model needs to load simulation results of the pymedeas_w model. Therefore, the first simulation of pymedeas_eu will necessarily be preceeded by a pymedeas_w simulation.

1. To select the model to run (either pymedeas_w.py or pymedeas_eu.py) open the **config.ini** file with any text editor and set the MODEL field to either pymedeas_w or pymedeas_eu. Save and close the modified file.

Running a default simulation

NOTE6 : the default simulation will use the following default parameters :

1. Model: pymedeas_w
2. Scenario: BAU
3. Time-step: 0.03125 years
4. Initial time: 1995
5. Final time: 2050
6. Results frequency: 1 year
7. Results filename: results_BAU_1995_2050_0.03125.csv

1. If it's not yet active, activate the project virtual environment, as shown in section *Activating the virtual environment* above.
2. Execute the following command to run a simulation with default parameters.

python run.py

3. Follow the instructions displayed on the terminal. Simulation should start after that.
4. When finished, simulation results will be stored in csv format either in pymedeas_w or pymedeas_w folders (depending on your choice in step 1).

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Running a simulation with a user defined Scenario

Users can create new simulation Scenarios by modifying the model driver parameters available in the inputs.xlsx files.

The inputs.xlsx file for the world model is located in the pymedeas_w folder, while that of the EU can be found in the pymedeas_eu folder.

1. Go to either pymedeas_w or pymedeas_eu folder and open the inputs.xlsx file with any compatible spreadsheet software.
2. To create any new scenario, create a copy of either the BAU or OLT tabs, rename it, and change the parameters on the new tab as needed.

NOTE7 : spreadsheet tab names should only contain all capital or all lower characters and underscores. Any other characters might result in unexpected software behaviour, for now.

3. Save the modified spreadsheet, mantaining the original file name (inputs.xlsx).
4. If it's not yet active, activate the project virtual environment, as shown in section *Activating the virtual environment* above.
5. Run the simulation by specifying the name of the newly created scenario (e.g. MLT) after the –x option, as follows :

python run.py –x MLT

6. After the simulation finishes, the csv results file name will include the name of the newly created scenario (e.g. results_MLT_1995_2050_0.03125.py)

Using the plot GUI to plot simulation results

NOTE8 : The plot_tool.py provides a GUI to plot the model outputs. It can be run either in standalone mode (to plot existing simulation results) or it can be loaded automatically after the simulation ends.

Any number of simulation results can be loaded and plotted simultaneously in the plot GUI.

If the name of the simulation results file is the default one (results_{SCENARIO NAME}_{INITIAL DATE}_{FINAL DATE}_{TIME-STEP}.csv), the scenario name will be used in the plot legend.

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Otherwise, the user will be asked through standard input to provide a name for the simulation results.

To run the plot GUI in standalone mode :

1. If it's not yet active, activate the project virtual environment, as shown in section Activating the virtual environment above.
2. Run the following command to launch the plot GUI :

python plot_tool.py

3. Go to File/Load data on the top menu and select the simulation results (csv file) to load.
4. Repeat it again as many times as simulation results you want to compare.
5. Click on any of the variable from the list displayed on the left panel, to plot the values of the selected variable on the right panel.

To load the plot GUI at the end of a simulation :

1. If it's not yet active, activate the project virtual environment, as shown in section Activating the virtual environment above.
2. Run the simulation passing the –p parameter (in addition to any other parameters)

python run.py –p

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Houghton, James; Siegel, Michael. "Advanced data analytics for system dynamics models using PySD." Proceedings of the 33rd International Conference of the System Dynamics Society. 2015.

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Annex: MEDEAS_w model description

Annex Document info sheet

Lead Beneficiary: University of Valladolid

WP: 4, Model building and models implementation

Task: 4.1, MEDEAS Model and IOA implementation at global geographical level

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Annex Abstract

The global aim of MEDEAS project is to provide policy makers and stakeholders with a new tool, to better assess the impacts and limitations of the EU energy production/consumption system transition to a low-carbon sustainable socio-economy. This tool integrates energy, raw materials supply and socioeconomic behaviour in a set of energy-economy-environment dynamic simulation models. However, the European energy, social and environmental situation is strongly conditioned by the international context. Therefore, together with the European model, it is necessary to develop a global model, which establishes the framework of energy, socio-economic and environmental variables in which Europe is located.

This document constitutes the technical documentation of the MEDEAS-World model, and is organized in the following sections: section 2 includes an overview of the model followed by 6 sections which correspond with the 6 submodules in which the model is structured (Economy, Energy, Materials, Climate, Land-use and social and environmental impacts indicators), followed by a section about the alternative energy technologies modelled in MEDEAS; section 3 reports the policy options available in MEDEAS; section 5 reviews the identified limitations and further developments of the MEDEAS-World model (some of them could be also in the MEDEAS-EU and country level versions); and section 6 concludes.

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Annex List of abbreviations and acronyms

BAU: Business-as-usual

BECCS: Bioenergy and CCS

BEV: Battery electric vehicle

BG: Buest guess

CBM: Coal-bed methane

CCS: Carbon capture and storage

CED: Cumulative energy demand

CGE: Computable general equilibrium

CHP: Combined heat power

Cp: Capacity factor

CSP: Concentrating solar power

CTL: Coal to liquids

EJ: Exajoule

ELF: Energy loss function

EOL-RR: end-of-life-cycle recovery rate

EROI: Energy return on energy invested

EROIext: EROI extended

EROIpou: EROI point of use

EROIst: EROI standard

ESOI: Energy stored on energy invested

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EU: European Union

EV: Electric vehicle

EWG: Energy Watch Group

FED: Final energy demand

FEH: Final energy use for heat

GCAM: Global Change Assessment Model

GDP: Gross domestic product

GEA: Global environmental assessment

GFCF: Gross fixed capital formation

GHG: Greenhouse gases

GTL: Gas to liquids

HDI: Human development index

HVDC: High-voltage direct current

IAM: Integrated Assessment Model

IEA: International Energy Agency

ILUC: Indirect land-use change

IMAGE: Integrated Model to Assess the Global Environment

IOT: Input-output table

IPCC: Intergovernmental Panel on Climate Change

IR: Inferred resources

LCA: Life-cycle analysis

LDV: Light duty vehicles

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LNG: Liquefied natural gas

Mha: Megahectares

MLT: Mid-level transition

MSW: Municipal solid waste

NEA: Nuclear Energy Agency

NGLs: Natural gas liquids

NGV: Natural gas vehicle

NPP: Net Primary Productivity

NRE: Non-renewable energy

O&M: Operation and maintenance

OECD: Organisation for Economic Co-operation and Development

OLT: Optimum-level transition

PB: Planetary boundary

PHEV: Plug-in hybrid vehicle

PHS: Pumped hydro storage

PLEX: Plant life extension

PV: Photovoltaic

PV: Photovoltaic

R&D: Research and Development

RAR: Reasonably assured resources

RCP: Representative Concentration Pathway

RES: Renewable energy sources

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RoW: Rest of the world

RPM: Recommended Management Practices

RURR: Remaining ultimately recoverable resource

SD: System dynamics

SSP: Shared socioeconomic pathway

TFC: Total final consumption

TFEC: Total final energy consumption

TFES: Total final energy supply

TPES: Total primary energy supply

TTW: tank-to-wheel

URR: Ultimately recoverable resource

US: United States of America

USD: United States dollars

WEO: World Energy Outlook

WIOD: World input-output database

WNA: World nuclear association

WoLiM: World Limits Model

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Annex Executive summary

This report extensively documents the approach to build MEDEAS-World, a new global-aggregated energy-economy-environment model (or Integrated Assessment Model, IAM). It has been developed applying System Dynamics, which facilitates the integration of knowledge from different perspectives as well as the feedbacks from different subsystems. MEDEAS-World runs from 1995 to 2050 and is structured into 7 submodules: Economy, Energy, Infrastructures, Materials, Land Use, Social and Environmental Impacts Indicators and Climate Change. These submodules have been programmed in approximately 100 simulation windows and using more than 4,000 variables. The modules of economy and energy modules 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. Figure 1 shows the interrelations between the 7 modules represented by boxes, whose main characteristics are:

- 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 are modelled. A net energy approach has been followed.
- Energy infrastructures represent the infrastructures of power plants to generate electricity and heat.
- Climate: this module projects the climate change levels due to the GHG emissions generated by the human societies, which also feed-back through a damage function.
- Materials: materials are required by the economy and MEDEAS especially tracks the material requirements for the construction and O&M of the energy infrastructures. The extraction demands are subsequently compared with the levels of available metrics of reserves and resources.
- Land-use: this is the less developed module of MEDEAS, and it mainly accounts for the land requirements of the RES energies.
- 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

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module is to contextualize the implications for human societies in terms of well-being for each simulation.

The main variables connecting the different modules are represented in Figure 1 by arrows. Most modules have bi-directional linkages, excepting for the Land-use and Social and Environmental impacts indicators which mainly report outputs from the simulations without feed-backing to rest of the structure.

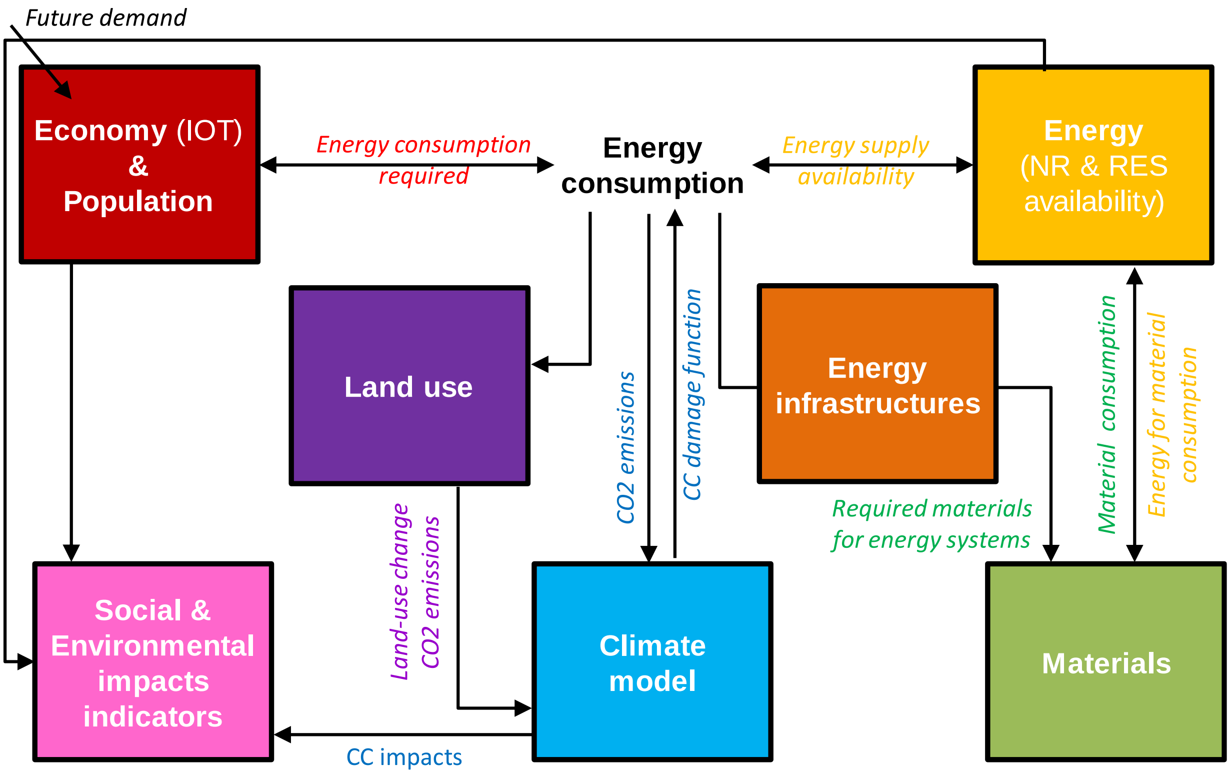

Figure 1: Overview of MEDEAS-World by modules and the modelled linkages between them

MEDEAS-world includes several novelties in relation to the current state-of-the art of the field:

- Integration of Input-Output Matrices in the Economy submodel within a System Dynamics structure,
- Comprehensive analysis of the techno-sustainable potential of RES for electricity and heat,
- Supply-demand closures model implementation. The energy shortage determines the feedback between the energy and the economic submodule.
- Comprehensive estimation of the EROI of those RES technologies for the generation of electricity with greater techno-sustainable potential.

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- Estimations of the potential mineral scarcity,
- Estimation of the EROI of the system and integration of its feedback within the system.
- The impacts of climate change are feedback into energy consumption.
- Implementation of environmental and socio-economic indicators.

Hence, MEDEAS incorporates three limits to growth that are rather rarely considered (even separately) in the literature: declining EROI levels, energy availability and consistent climate change impacts.

As any modelling framework, MEDEAS is subject to a number of limitations which will be addressed in further developments. On the one hand, the structure of the model should be improved in order to include more dynamics in the Economy module (e.g. endogenize the coefficients of the A matrix) and to improve the interlinkages between the Economy and the Energy modules (e.g. better modelling the allocation of scarcities); represent the potential constraints which mineral constraints may suppose in the future; fully develop and integrate a land-use module; improve the representation of climate damages on the system; or expand the social dimensions represented in the modelling framework. For these and other reasons detailed in the report, the interpretation of the results must be done with caution. Despite these limitations, the current version provides a solid enough basis to serve as a framework for the European scale model. A nested approach is required in order to assure consistency in the results obtained in the European model, given that the European energy, social and environmental situation is (and will continue to be) strongly conditioned by the international context.

We recall that global IAM models are not tools intended to predict the future, but rather to qualitatively guide the best options for the energy transition towards a low carbon economy and more sustainable society. Thus, MEDEAS-W is a tool to explore strategies, not specific policies, since the latter are applied at a different (reduced) political scale.

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1. Introduction

This report documents the simulation model MEDEAS-World v1.2 which dynamically integrates economic, energy and environmental variables at global level. The model has been originally programmed in System Dynamics Vensim software, and has been translated to open software Python within the MEDEAS project (the model in both codes is available in: http://www.medeas.eu/). MEDEAS-W v1.2 is a one region-aggregated economy-energy-environment model (or Integrated Assessment Model, IAM) which runs from 1995 to 2050. MEDEAS-World has not been developed from scratch, and is based on several previously developed models by the Group of Energy, Economy and System Dynamics of the University of Valladolid: (Capellán-Pérez et al., 2014; de Castro, 2009; Mediavilla et al., 2013).

MEDEAS-W 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. These submodules are: Economy, Energy, Energy Infrastructures, Materials, Land Use, Social and Environmental Impacts Indicators and Climate Change. These submodules have been programmed in approximately 100 simulation windows and using more than 4,000 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 submodel.
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 impacts of climate change are fed backed into energy consumption.

One of the major challenges during the development of the model has been the difficulty in obtaining reliable global public data on many of the variables that are used in the model. The availability of these data in the future may lead to significant improvements in the model results. Another challenge that the model has had to address is the uncertainty in some of the relationships between variables that are still under investigation. A clear example is the estimation of the economic, social and energy impacts that climate change may have in the future. Progress in research in these fields of knowledge may reduce the uncertainty in the results of the model. Despite these limitations, the qualitative interpretation of the results, supported by tools such as

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the sensitivity analysis, allows guiding the decision making to guide the best possible energy transition.

The report is organized as follows: section 2 represents the core of the report and documents the methods, assumptions and data to build the model. Section 3 presents the policy options available in MEDEAS, section 0 summarizes the main limitations of the current version of the model, identifying potential future developments, and section 5 concludes.

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2. Methodology

This section represents the core of the report and is organized as follows: section 2.1. provides a general overview of the model, while the following sections are each one dedicated to a module of the model: Economy (section 2.2); energy and infrastructures are collated together (section 2.3), Materials (section 2.4), GHG emissions and climate submodule (section 2.5), Land-use (section 2.6) and finally the Social and Environmental impacts indicators (section 2.7)

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2.1. Overview of MEDEAS-World

MEDEAS-World model is a global, one region-aggregated economy-energy-environment model (or IAM) which runs from 1995 to 2050. 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. Figure 2 shows the interrelations between the 7 modules represented by boxes, whose main characteristics are:

- 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 are modelled. A net energy approach has been followed.
- Energy infrastructures represent the infrastructures of power plants to generate electricity and heat.
- Climate: this module projects the climate change levels due to the GHG emissions generated by the human societies, which also feed-back through a damage function.
- Materials: materials are required by the economy and MEDEAS especially tracks the material requirements for the construction and O&M of the energy infrastructures. The extraction demands are subsequently compared with the levels of available metrics of reserves and resources.
- Land-use: this is the less developed module of MEDEAS, and it mainly accounts for the land requirements of the RES energies.
- 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.

The main variables that connect the different modules are represented by arrows. Most modules have bi-directional linkages, excepting for the Land-use and Social and Environmental impacts indicators which mainly report outputs from the simulations without feed-backing to rest of the structure.

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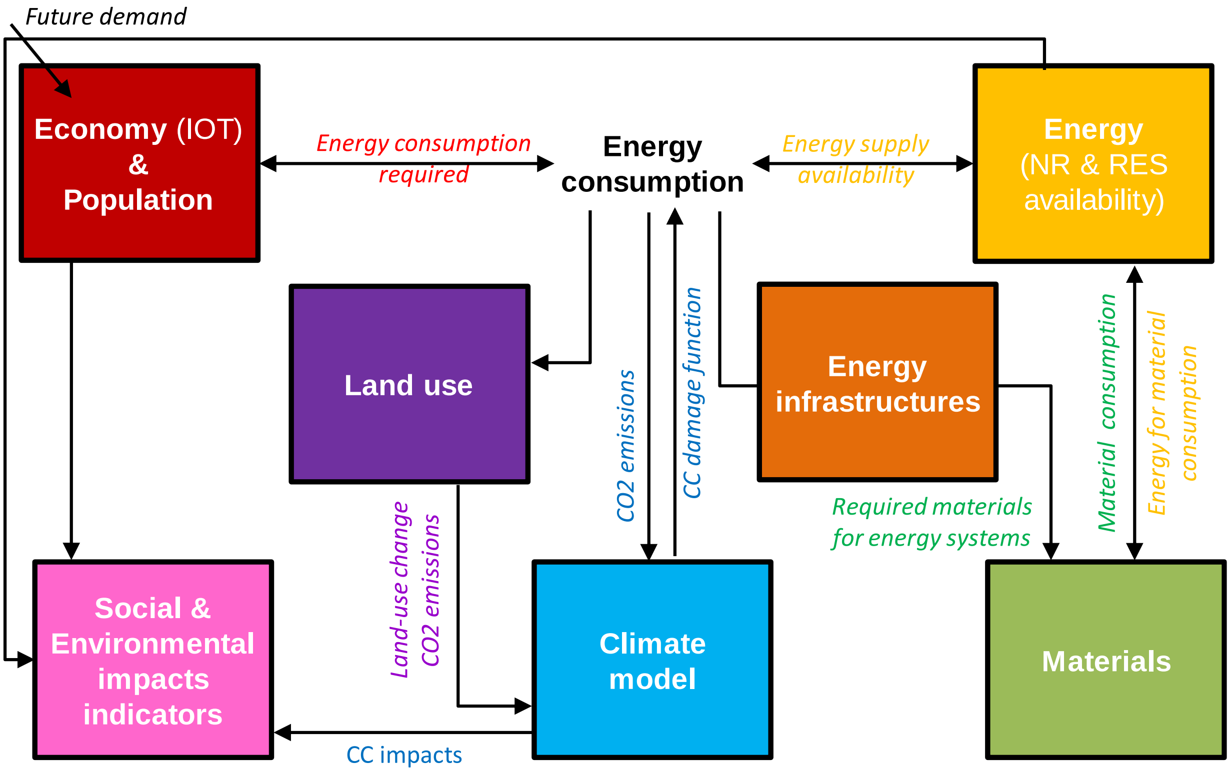

Figure 2: Overview of MEDEAS-World by modules and the modelled linkages between them

The model functions as follows: for each time-period, demand-led growth/reduction by households requires a certain amount of goods and services as given by the IOTs structure. This monetary demand is translated into final energy demand by fuel trough the final energy intensities by fuel. These final energy demands by final fuel are confronted with the available final energy from the energy module. This dynamic energy availability is given by stocks and flows limitations of non-renewable fuels –peak oil phenomena-, sustainable potential of renewables, realistic rhythms of technology deployment, etc. In the case that the final energy demands are lower than the final energy availability, the demand is fulfilled. If the opposite is true, the final demand adapts to the available final energy. In any case, the demand of the next time-period is estimated taking as reference the consumption in the previous time-period.

The consumption of final energy by final fuels is covered by a mix of technologies (Energy Infrastructures module), which derives in the consumption of primary energy. Special attention is devoted to the consideration in MEDEAS framework of those technologies which seem to be realistically available and with a positive net energy balance. In the current version of the model, material availability does not directly constrain the deployment of technologies given the

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uncertainty in the available metrics of reserves and resources. However, for those technologies depend on potential scarcity resources alternatives have been proposed.

The level of primary energy consumption by fuel translates into a certain level of GHG emissions. These emissions are absorbed by the atmosphere, leading to the worsening of climate change. A worse climate change feed-backs into the human societies through a certain level of unavoidable impacts.

This way, MEDEAS incorporates three limits to growth that are rather rarely considered in the literature: declining EROI levels, climate change impacts and energy availability.

The modules of land-use and social and environmental impacts indicators allow to account for the land requirements of the RES energies, as well as to contextualize the implications for human societies in terms of well-being for each simulation.

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2.2. Economy module

In order to provide homogeneity and enable comparability between monetary parameters in the model, a common reference year has been calculated. These monetary values are related to the investment costs of renewable energies and nuclear, balancing costs and grid reinforcement costs. All of them are expressed as the amount of US$[1] per energy unit (KWh, TWh). Since the different sources used to obtain this data provide it in distinct reference year, a common one had to be chosen. The reference year that homogenise the monetary values is 1995. This year was selected in order to facilitate, in turn, data homogenization in further developments of MEDEAS since WIOD – the core Input-Ouput database in the module requires taking 1995 as base year, as explained in section 2.2.3.2. Thus, prices are implicitly included in MEDEAS economy module throughout two points. On the one hand, monetary values are by definition prices times volumes. On the other hand, as carefully explained below, monetary values have been deflated in order to approximate to volumes rather than values. The key information for the model is not the value itself, but its rate of change. That is why it is not the most important to have the closer base year to the date of publication of this Technical Report, but a common base to precisely know the evolution in volume.

We took the US GDP deflator from 1995 to 2015, obtained in https://www.measuringworth.com and switched its reference year from 2009 to 1995. To change time series of renewable investments costs, data in current prices had to be determined as an intermediate step. As there is no deflator indicators beyond 2015 and no price assumptions was made, estimation for years 2020, 2030, 2040 and 2050 followed the same rate of change that the original series. Reference year (or current prices) value of the original data was selected following the indications in their respective sources and their publication years.

[1] Note: all dollars in MEDEAS refer to constant 1995$US.

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2.2.1. Literature review

The approach chosen for modelling Economy in MEDEAS has involved a revision of literature in the field to establish the most proper scope. The literature note different approaches which can be encompassed under the general definitions of optimisation/simulation models and top-down/hybrid/bottom-up models (Scrieciu et al., 2013a). 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., 2012a). 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 with demand, i.e. the direct and real expression of the productive factors capacity. In these models, however, supply can act as a constraining of 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; 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 equilibrium –throughout technologies market competition- in the energy sector. Hybrid models, nonetheless, combine a detailed macroeconomic and energy technologies view.

While at the early times, top-down optimisation models where dominant, critical remarks have been made to this approach. The assumption of perfect substitutability between factors has been widely

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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, 2016a; 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 economy module is defined as a simulation and hybrid model (see Figure 3). Furthermore, MEDEAS economy module is demand-led, sectorally disaggregated and based on a disequilibrium approach and Input-Output Analysis (IOA). MEDEAS consider 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, regardless 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 relation to this is the incorporation of supply constraints (energy availability and climate change impacts) which affect the economic process.

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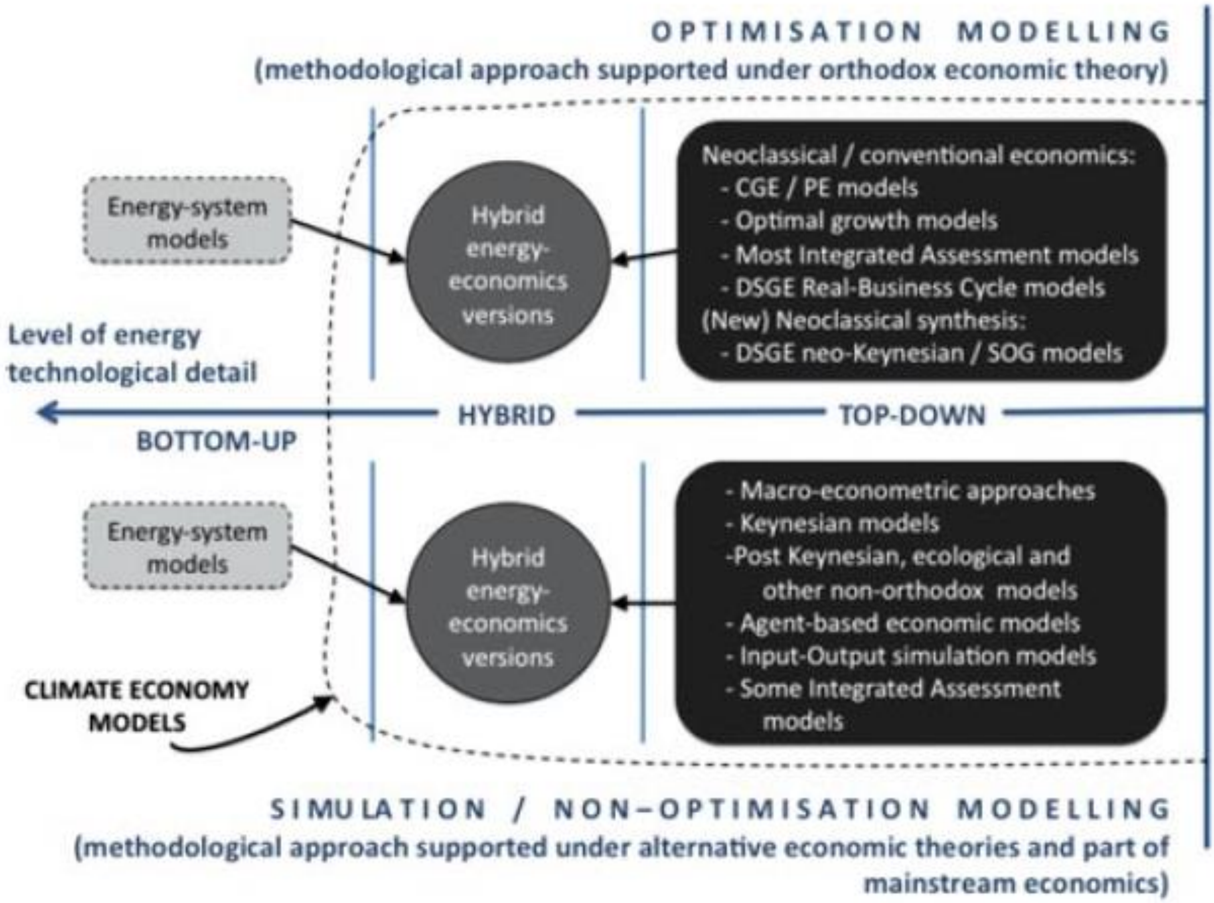

Figure 3. Macro-economic modelling in IAMs. Source: (Scrieciu et al., 2013b)

IOA reveals 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 assumes disequilibrium and is able to capture structural conditioners in transitions, something often missing in macro-economic modelling. IOT does not make assumptions on equilibrium nor in the goods market, neither 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 unemployment and under-utilisation of

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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 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).

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2.2.2. Overview of the economy module

The Economy module is demand led and sectorally disaggregated within 35 different industries (see Table 1). This structure is due to the election of a data source which meets these three requirements: to be a public database, at world level and with environmental satellite accounts. This way, World Input-Output Database (WIOD) (Dietzenbacher et al., 2013a), which is described below, fulfils all these requirements. WIOD provides interregional Input-Output tables (IOTs) in current and in previous year prices. The process to obtain a world IOT as if it was just one country has involved two tasks:

- Deflate interregional IOTs using value chains with a common base year (1995).
- Compile deflated interregional IOTs into a one region with no external trade.

Table 1. Industrial sectors from WIOD used in MEDEAS world. Source: own elaboration from WIOD (Dietzenbacher et al., 2013a)

Sectors			
1	Agriculture, Hunting, Forestry and Fishing	18	Construction
2	Mining and Quarrying	19	Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of Fuel
3	Food, Beverages and Tobacco	20	Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcycles
4	Textiles and Textile Products	21	Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods
5	Leather, Leather and Footwear	22	Hotels and Restaurants
6	Wood and Products of Wood and Cork	23	Inland Transport
7	Pulp, Paper, Paper , Printing and Publishing	24	Water Transport
8	Coke, Refined Petroleum and Nuclear Fuel	25	Air Transport
9	Chemicals and Chemical Products	26	Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies
10	Rubber and Plastics	27	Post and Telecommunications
11	Other Non-Metallic Mineral	28	Financial Intermediation
12	Basic Metals and Fabricated Metal	29	Real Estate Activities
13	Machinery, Nec	30	Renting of M&Eq and Other Business Activities
14	Electrical and Optical Equipment	31	Public Admin and Defence; Compulsory Social Security
15	Transport Equipment	32	Education
16	Manufacturing, Nec; Recycling	33	Health and Social Work
17	Electricity, Gas and Water Supply	34	Other Community, Social and Personal Services
		35	Private Households with Employed Persons

Since MEDEAS is an energy-economy-environment model with a number of biophysical variables, it is reasonable to evaluate monetary values, as much as possible, in volume. As a result of deflation of WIOD, monetary values in the economy module are given in million USD chained linked volumes (1995). From socioeconomic accounts (Timmer et al., 2015) MEDEAS takes the labour and capital incomes information and from environmental accounts (Genty, 2012) the energy and water consumption information.

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A schematic overview of the Economy module's rationale is shown in Figure 4. Income share, population and GDP per capita (GDPpc) growth take values according to the scenarios storylines. Using these values, the sectoral final demand growth is obtained. Depending on this and the structural relationship between sectors, Input-Output Analysis (IOA) provides the production required to meet demand. After that, taking final energy intensities by source, the energy-economy feedback results on a feasible sectoral production regarding resource scarcity. Finally, using IOA inversely, the sectoral final demand which is possible to meet with the current final energy availability is obtained. Economy module includes variables provided in monetary values, energy values and hybrid energy-economy values (mainly, energy intensities).

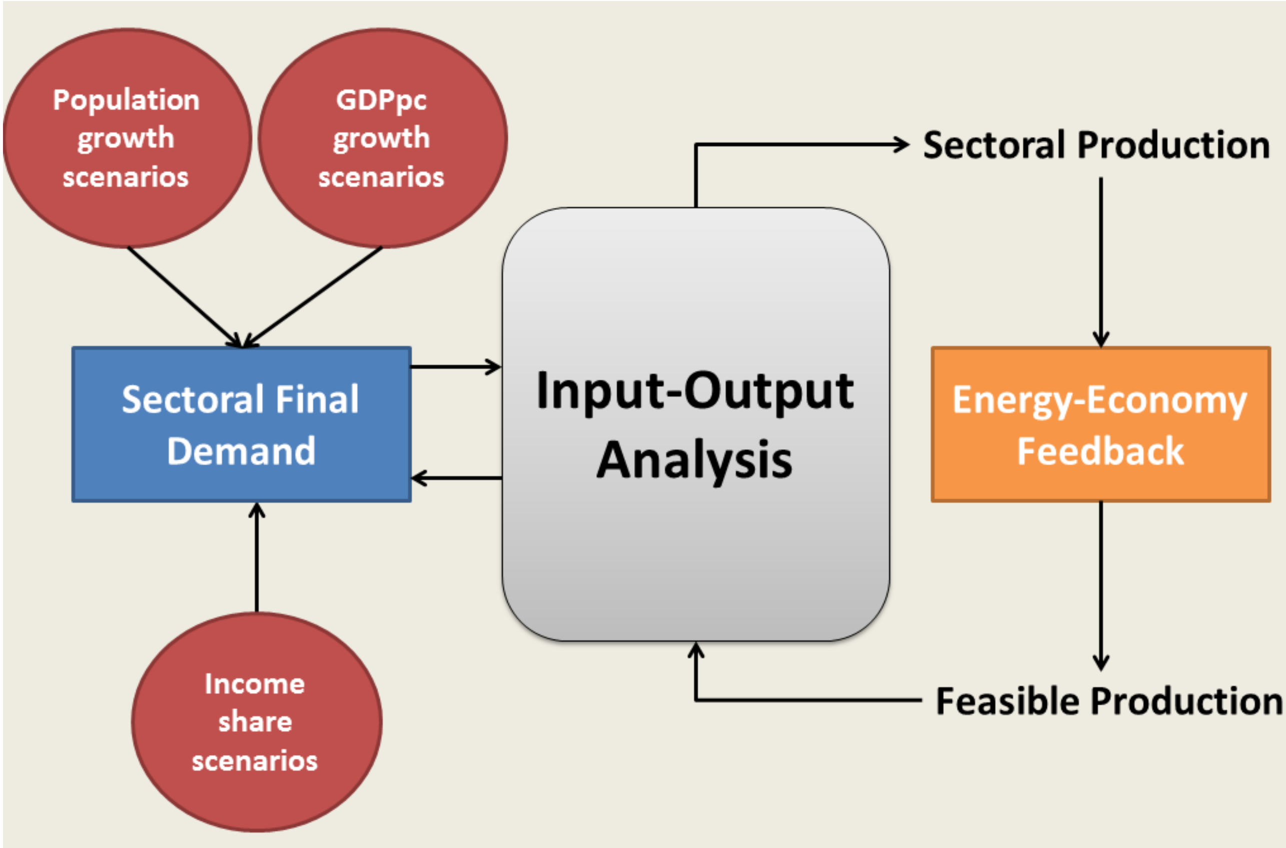

Figure 4. Schematic overview of MEDEAS Economy module. Own elaboration

A deeper insight on the Economy module is given by its Causal loop diagram (Figure 5). Here can be seen, as explained below, that income (labour and capital compensations) depends on demand growth, exogenously determined as mentioned before. After that, income determines the distribution of this growth amongst the industries using a sectoral demand function. Then, IOA and energy intensities –which endogenously evolve over time- enable the energy-economy feedback, whose final result is the feasible final demand regarding energy scarcity.

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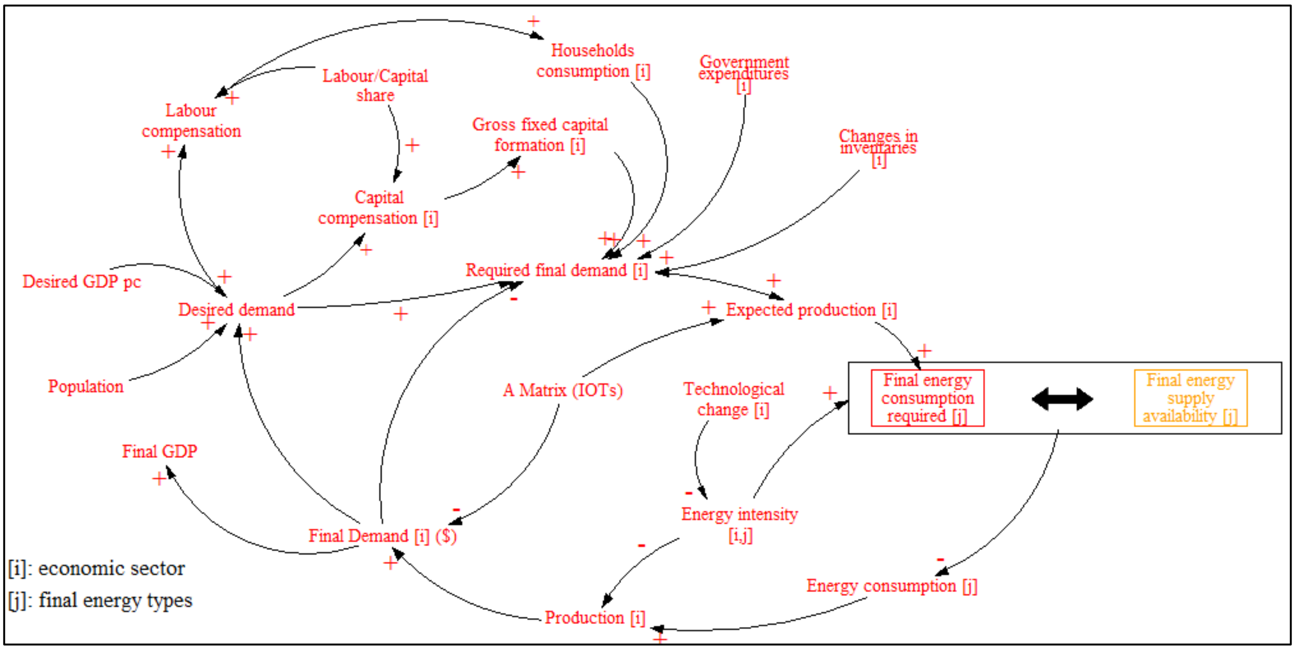

Figure 5. Causal loop map of MEDEAS Economy module. Source: own elaboration.

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2.2.3. Description of the economy module

In this section, the economy module is described regarding the main features represented in Figure 4. Firstly, the sectoral demand function, paying special attention to income, as its main determinant. Secondly, the description of how IOA is integrated into the model. Thirdly, the energy-economy feedback is deeply explained.

2.2.3.1. Sectoral demand function

The demand function is constructed from industries to the whole economy, which would be the aggregation of all sectors. Moreover, based on the assumption that economy has 'memory' and what happens in the past conditions the present and the future, it is not a theoretical function, but based on previous observation. Hence, regressions on each sector are grounded in measurable data –so, no 'preferences' function was used- in order to estimate the evolution of sectoral final demand. The following equation shows the basic structure of how final demand is obtained:

$$FD_i = HH_i + GFCF_i + GE_i + INVENT_i. \quad i \in 1 \ldots 35$$

where HH stands for households' consumption, GFCF for gross fixed capital formation, GE for government expenditures and INVENT for changes in inventories. Therefore, HH is the direct demand of products from each sector made by households; GFCF is the final demand of investment assets made by enterprises; GE represents the expenses in final goods made by governments (not salaries); and INVENT is the gap between goods produced and demanded. As final demand is calculated by sector, subscript i stand for the 35 industries. Whilst HH and GFCF can be determined –considering the limitations of data and the methodology itself- throughout an econometric function, different assumptions have to be made for GE and INVENT. Firstly, GE is relatively autonomous or, at best, inversely linked to economic cycle. Even in this case, nothing can assure that GE would perform this way, because it depends basically on policy choices. Because of this, GE by industries follows the last observation's share over FD that could be eventually increased or decreased through policies. The same approach is followed to obtain changes in inventories. Further developments of the model could explore obtaining INVENT subtracting intermediate consumption and rest of final demand (HH+GFCF+GE) from production. That would yield a more accurate indicator, being calculated as what it really is: the production not met by demand, both intermediate and final. Therefore, the essence of final demand is HH and GFCF (over 80% of total final demand from 1995 to 2009). Thus, Final Demand evolution in MEDEAS follows this equation:

$$\Delta FD_i = \Delta HH_i + \Delta GFCF_i \quad i \in 1 \ldots 35$$

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Because of the limits of WIOD, time series only accounted with 15 observations for each sector, which made regressions difficult to fulfil all statistical requirements. As projections must run until 2050, it is mandatory to test the robustness of the models estimated. Non stationarity of the data required one or two differences depending on the sector and thus, losing one or two observations respectively. The result was models with non-significant independent variables. Since each variable is organized by industries and years, they can be treated as panel data. This way, regressions increase their number of observations from 15 to 525 (15 years x 35 sectors). Moreover, it is a reasonable assumption that the final demand evolution of each sector has intertwines with the others. It is worth to mention that the aim was not to construct a consistent theoretical function, but a robust regression to estimate demand evolution. Therefore, supported in distributional theory, it was assumed that households' consumption is mainly driven by the workers' income. Likewise, gross fixed capital formation by industry would be driven by the gross operating surplus (CAP) in each industry. As expressed below, the main statistical figures for the panel data regression were high enough to validate the equations. Thus, regressions for HH and GFCF are represented in the following equations:

$$lnHH_i = \beta_0 + \beta_{1,i} Sec_i + \beta_2 lnLAB. \qquad i \in 1 \ldots 35$$

$$lnGFCF_i = \beta_0 + \beta_{1,i} Sec_i + \beta_2 lnCAP_i. \qquad i \in 1 \ldots 35$$

Sec_i is a dichotomous variable whose value is 1 for the sector that is being calculated and 0 for the other sectors. Hence, $\beta_{1,i}$ is a coefficient which captures the different influence of income (labour and capital) depending on the sector. Since this coefficient is obtained in panel data regressions in reference to sector 1, $\beta_{1,1}$ is always equal to 0. So, there are 34 different β_1 according to sectors 2 to 35. As mentioned above, LAB stands for labour compensation and CAP_i for capital compensation by sector. There is no economic justification to assume that wages paid in one sector will be spended in the same sector. Hence, total labor compensation is the independent variable, whilst we assume capital compensation for each sector determines investments made by the same sector. We use labour compensation instead of disposable income because of the availability of data at world level. In addition, using primary income allows us to model final demand in the subsequent periods throughout the income stage, described above.

In Table 2 and Table 3 are shown the parameters of the robust data panel regressions with R^2 0.9989 and 0.9948 respectively. β_0 value is that in the first column (Coef.) and the last row (_cons). β_1 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.

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Table 2. Panel data regression for Households consumption. Source: own elaboration.

log_hh	Coef.	Panel-corrected Std. Err.	z	P>|z|	[95% Conf.	Interval]
log_labworld	1.135449	.0722175	15.72	0.000	.9939052	1.276993
sector						
2	-3.041303	.1029176	-29.55	0.000	-3.243017	-2.839588
3	.8496438	.0178643	47.56	0.000	.8146305	.8846572
4	-.4561882	.0247997	-18.39	0.000	-.5047947	-.4075818
5	-2.064467	.0266671	-77.42	0.000	-2.116734	-2.012201
6	-3.356857	.0418603	-80.19	0.000	-3.438902	-3.274812
7	-1.226881	.0243813	-50.32	0.000	-1.274668	-1.179095
8	-1.186757	.0218333	-54.36	0.000	-1.22955	-1.143965
9	-.712791	.0273736	-26.04	0.000	-.7664422	-.6591397
10	-2.035976	.0252128	-80.75	0.000	-2.085392	-1.98656
11	-2.704609	.0494949	-54.64	0.000	-2.801617	-2.607601
12	-2.061479	.0283227	-72.79	0.000	-2.11699	-2.005967
13	-1.488448	.0472131	-31.53	0.000	-1.580984	-1.395912
14	-.675253	.0796737	-8.48	0.000	-.8314106	-.5190954
15	-.1846172	.0480791	-3.84	0.000	-.2788506	-.0903839
16	-1.18592	.0308985	-38.38	0.000	-1.24648	-1.12536
17	-.5334909	.0274566	-19.43	0.000	-.5873048	-.479677
18	-2.756193	.0511498	-53.88	0.000	-2.856445	-2.655941
19	-.7490777	.0333044	-22.49	0.000	-.8143531	-.6838023
20	.3986385	.0408055	9.77	0.000	.3186613	.4786157
21	.7057005	.0229108	30.80	0.000	.6607961	.7506049
22	.4404486	.023511	18.73	0.000	.3943678	.4865294
23	-.3547073	.0160907	-22.04	0.000	-.3862446	-.3231701
24	-2.553138	.0656082	-38.91	0.000	-2.681728	-2.424548
25	-1.624648	.0419716	-38.71	0.000	-1.706911	-1.542386
26	-1.630129	.0292079	-55.81	0.000	-1.687375	-1.572882
27	-.3472749	.1009354	-3.44	0.001	-.5451047	-.1494451
28	.4875999	.0539839	9.03	0.000	.3817935	.5934064
29	1.229081	.0174615	70.39	0.000	1.194857	1.263305
30	-.7056298	.0386818	-18.24	0.000	-.7814447	-.6298149
31	-.7456611	.0435173	-17.13	0.000	-.8309535	-.6603688
32	-.7185996	.0217232	-33.08	0.000	-.7611762	-.676023
33	.5389905	.028544	18.88	0.000	.4830452	.5949358
34	.3212347	.021888	14.68	0.000	.2783349	.3641345
35	-2.770384	.0193929	-142.86	0.000	-2.808393	-2.732374
_cons	-5.520417	1.21937	-4.53	0.000	-7.910337	-3.130496
rho	.7451225					

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Table 3. Panel data regression of Gross fixed capital formation. Source: own elaboration.

log_fbc	Coef.	Panel-corrected Std. Err.	z	P>|z|	[95% Conf.	Interval]
log_capworld	.4346747	.0601151	7.23	0.000	.3168513	.552498
sector						
2	.6549913	.1077517	6.08	0.000	.4438019	.8661808
3	-2.409549	.057718	-41.75	0.000	-2.522674	-2.296424
4	-.7288079	.0965689	-7.55	0.000	-.9180794	-.5395364
5	-2.802861	.1944668	-14.41	0.000	-3.184009	-2.421713
6	.2653398	.141998	1.87	0.062	-.0129712	.5436508
7	.3796384	.067163	5.65	0.000	.2480013	.5112754
8	-3.044304	.0874614	-34.81	0.000	-3.215725	-2.872883
9	-1.282831	.0646754	-19.83	0.000	-1.409592	-1.156069
10	-.5025426	.0772178	-6.51	0.000	-.6538868	-.3511984
11	-1.428307	.0813883	-17.55	0.000	-1.587826	-1.268789
12	1.431519	.0557784	25.66	0.000	1.322195	1.540843
13	3.098772	.0559442	55.39	0.000	2.989123	3.20842
14	2.975706	.0659929	45.09	0.000	2.846362	3.105049
15	2.985555	.0583299	51.18	0.000	2.871231	3.09988
16	1.702436	.1017802	16.73	0.000	1.502951	1.901922
17	-1.410645	.0862236	-16.36	0.000	-1.57964	-1.24165
18	4.458449	.0439451	101.45	0.000	4.372318	4.54458
19	.0193238	.0856398	0.23	0.821	-.1485271	.1871748
20	1.628343	.0917465	17.75	0.000	1.448524	1.808163
21	1.206609	.0646651	18.66	0.000	1.079867	1.33335
22	-2.001936	.0963525	-20.78	0.000	-2.190783	-1.813088
23	.4501797	.048613	9.26	0.000	.3549	.5454594
24	-1.538287	.1394538	-11.03	0.000	-1.811611	-1.264962
25	-1.335444	.1461897	-9.14	0.000	-1.621971	-1.048917
26	-1.169046	.0854367	-13.68	0.000	-1.336499	-1.001593
27	-.8956122	.1217277	-7.36	0.000	-1.134194	-.6570304
28	-2.335751	.1292775	-18.07	0.000	-2.58913	-2.082372
29	.3825687	.1605201	2.38	0.017	.0679551	.6971824
30	2.065982	.1008094	20.49	0.000	1.8684	2.263565
31	-1.44898	.1421418	-10.19	0.000	-1.727573	-1.170387
32	-2.976849	.1216132	-24.48	0.000	-3.215207	-2.738492
33	-2.671927	.0814757	-32.79	0.000	-2.831616	-2.512237
34	-.4900947	.0719673	-6.81	0.000	-.631148	-.3490414
35	-3.099085	.4257751	-7.28	0.000	-3.933589	-2.264582
_cons	5.09048	.7595629	6.70	0.000	3.601764	6.579196
rho	.6807459					

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The approach followed to translate these equations into system dynamics programming relies on considering it as variations. These variations are the fluxes that feed households final demand (HH) and gross fixed capital formation (GFCF) as stocks. Taking equation 2, HH can be expressed as:

$$HH_i = e^{\beta_0} e^{\beta_1 Sec_i} Lab^{\beta_2}$$

Equivalently, GFCF would be expressed equally but using Cap instead of Lab. In order to calculate in the model the new final demand flow to their respective stocks, the variation is taken.

$$\Delta HH_i = e^{\beta_0} e^{\beta_1 Sec_i} (Lab_{t+1}^{\beta_2} - Lab_t^{\beta_2})$$

Income scenarios

Besides the influence of the other sectors' performances, income is the main driver of sectoral final demand in MEDEAS. As it is a world model and, thus, without external sector, this identity can be established:

GDP=FD=∑GVA

Where GDP is the gross domestic product and GVA stands for gross value added which, in turn, can be divided into labour and capital compensation. Labour compensation comprises wages, salaries and social earnings paid by employer. Meanwhile, capital compensation includes the gross operating surplus which consists of yields obtained by enterprises, dividends, rents, fixed capital consumption, etc. Hence, the GVA distribution (at factor costs) amongst labour and capital composes the primary income (before taxes on production and transfers). It is considered a basic index of inequality which is used in MEDEAS in exogenous scenarios. These scenarios assume different income shares according to their respective storylines.

Income shares stands for the following equations:

$$\alpha_{lab} = \frac{LAB}{GDP} ; \alpha_{cap} = \frac{CAP}{GDP}$$

where $\alpha_{lab/cap}$ are the labour and income shares respectively and LAB and CAP labour and capital compensations. In MEDEAS, we assume exogenously different $\alpha_{lab/cap}$ according to the storylines of each scenario (see

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Table 4). In the standard version of MEDEAS we consider 3 possible income shares for 2050. Business as usual (BAU) scenario takes into consideration the historical declining of labour shares but reduced by the growing importance of emergent countries in GDP. As these countries, in their respective modernisation processes are improving their labour shares, it is to be expected that the decline in labour share can be hampered by these countries. Although China is following the opposite evolution, it is due to its relatively higher labour share. For storylines do not taking into consideration distributional issues, it is assumed a labour share of 45% (55% capital share) in 2050, deepening the current trends. It is worth to say that scenarios with a capital share higher than labour share are found in countries with a low developed welfare state and high rates inequality indexes (Dafermos and Papatheodorou, 2015; Daudey and García-Peñalosa, 2007).[2] However, there is also literature that links the growth in capital share with technological change, the computer age and the current structural changes in labour market (Ellis and Smith, 2010; Elsby et al., 2014; Karabarbounis and Neiman, 2014). Therefore, it is consistent that these storylines have associated a slightly higher decline of labour share than BAU scenario. On the other hand, for thoses storylines including the improvement of the current inequality levels we assume an income share by 2050 similar to current Europe and well developed welfare state countries.

Primary income scenarios can be activated or, conversely, deactivated (considering primary income shares as static with its 2014 value) by the user. Since the addition of both labour and capital share equals 1, scenarios just change labour share and then, capital share is considered as 1-α_{lab}. From 1995 to 2009, MEDEAS uses historical data from WIOD-socioeconomic accounts (Timmer et al., 2015) assuming the hypothesis that the rest of the world has the same primary income distribution than the dataset countries mainly OECD and BRICS (approx. 85% world GDP). Then, from 2009 to 2014, OECD data has been used to smoothly reach the 2015 distribution. Applying different labour shares in 2050, its value in the first year of simulations smoothly evolves according to the cumulative mean growth rate required to reach it.

This way, those sectors which increase their output when the labour share increases is due to the fact that the final demand of their products is more dependent on the final consumption of the households than from the GFCF.

[2] In those countries represented in the WIOD database, this low ratio of labour share was only found for India, Turkey and Indonesia.

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Table 4. Income share scenarios

Scenario	Labour share (2050)	Capital share (2050)
BAU	52%	48%
Increased inequality	45%	55%
Decreased inequality	60%	40%

Then, by multiplying it by the evolution of Final Demand (equivalent to GDP at world level), we obtain the labour and capital compensations which enter back as inputs in the demand function, described below. Therefore, income is calculated regarding final demand evolution, which would be the main driver of this module.

$$LAB_{t+1} = FD_{t+1} * \alpha_{lab,t+1};$$

$$CAP_{t+1} = FD_{t+1} * \alpha_{cap,t+1};$$

$$FD_{t+1} = FD_t + \Delta FD$$

However, in the model labour compensation is calculated as a flow, similarly to final demand, according to the following equations.$\Delta LAB = LAB_{t+1} - LAB_t$

$$\Delta LAB = \alpha_{lab,t+1} FD_{t+1} - \alpha_{lab,t} FD_t$$

After that, throughout simple operations, equation computed in MEDEAS for labour compensation evolution is the following:

$$\Delta LAB = \alpha_{lab,t} FD_t \,(\Delta \mathrm{FD} + \Delta\alpha_{lab} + \Delta\alpha_{lab}\Delta \mathrm{FD})$$

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2.2.3.2. Input-Output Analysis (IOA)

The core of the economy module falls in world IOTs. By using IOA, demand-led evolution is granted and in addition, no equilibrium assumption is made as historical data does not have to necessarily reflect equilibrium. There is no production function to optimize, nor perfect substitutability between factors. Conversely, disequilibrium is assumed as production not always meets demand, remaining it as changes in inventories. Besides, IOA implies complementarity between inputs needed to produce each industry's goods, according to a technological state given by technical coefficients.

IOA is a methodology which allows evaluating direct and indirect changes in sectoral production in response to exogenous final demand variations, according to the fixed input requirements to produce 1 unit of product (A Matrix). To make it, the main flows of an economy and its industries are organized in Input Output Tables (IOTs) as shown in Figure 6.

National IOT

Industry demand	Final demand		Total
IC^N	FD^N	FD^{FN}	X^N
IC^F	FD^{NF}		
VA^N			
X^N			

Interregional IOT

Industry demand			Final demand			Total
$IC^{1,1}$	$IC^{1,\dots}$	$IC^{1,n}$	$FD^{1,\dots}$	$FD^{1,1}$	$FD^{1,n}$	X^1
$IC^{\dots,1}$	$IC^{\dots,\dots}$	$IC^{\dots,n}$	$FD^{\dots,1}$	$FD^{\dots,\dots}$	$FD^{\dots,n}$	$X^{\dots}$
$IC^{n,1}$	$IC^{n,\dots}$	$IC^{n,n}$	$FD^{n,1}$	$FD^{n,\dots}$	$FD^{n,n}$	X^n
VA^1	$VA^{\dots}$	VA^n				
X^1	$X^{\dots}$	X^n				

Figure 6. Schematic national and interregional Input-Output Tables.

IC: Intermediate consumption; FD: Final demand; VA: Value added; X: Production.

National IOT superscripts. N: National; FN: foreign in national; NF: National in foreign.

Interregional IOT superscripts. Regions: 1…n.

Source: own elaboration.

In a national IOT, intermediate consumption (IC) is represented in two sub matrixes which gather sales (by rows) and purchases (by columns) amongst industries. IC^N stands for the intermediate consumption within the national industries and IC^F represents the sales of foreign industries to national industries (industry imports). Final demand stands for the direct purchases made by the different institutional sectors (see previous section) and is also divided regarding the territory where

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it is made. IC^{N}stands for national final demand, $IC^{FN}$for foreign demand of national products (exports) and $IC^{NF}$for national demand of foreign products (final imports). Production (X) is the summation of IC and value added (VA): salaries, gross surplus and net taxes on products. Production can be expressed as the summation of IC and final demand. Interregional IOT nest different regions (from 1 to n) with its respective ICs and FDs between them. Finally, it offers production and value added for each region.

As MEDEAS is a World model, the IOTs used must cover the whole world and, in addition, include energy and socioeconomic satellite accounts. World Input Output Database (WIOD) (Dietzenbacher et al., 2013a) fulfils these requirements, so it is the source used in MEDEAS. WIOD provides interregional IOTs at the world level -as they include a Rest of the World (RoW) region- at current and at precious year prices. The latter were deflated in order to avoid price effects and approximating as much as possible to quantities in volumes. The easiest way to deflate the huge amount of data included here, implies having 1995 as the reference year (in billion dollars). Then, interregional IOT is compiled into a World IOT as if the world was just one country. So, structure of the IOT table used in MEDEAS is similar to a national IOT but, obviously, without external trade as shown in Figure 7.

Industry demand	Final demand	Total
IC^{W}	FD^{W}	X^{W}
VA^{W}		
X^{W}		

Figure 7. World Input-Output Table without external trade used in MEDEAS. IC: Intermediate consumption; FD: Final demand; VA: Value added; X: Production. Source: own elaboration.

IC in WIOD is the square matrix of sales from sector i to j (IC=$\sum z_{ij}$) amongst 35 different industries according to NACE. Moreover, final demand (FD) is split by institutional and industrial sectors, as mentioned before. In IOA it is crucial to know the structural relationships between industries, i.e. the amount of inputs from each industry needed by another to produce 1 unit of product. This way, production in each sector requires a certain share of inputs from the others, assuming complementarity between them. Hence, technical coefficients weight the proportion of input from sector i to produce 1 unit of production of sector j as in the next equation.

$$a_{ij} = \frac{z_{ij}}{x_j} \qquad i,j \in 1 \ldots 35$$

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and, in matrix notation:

$$A = IC\, X^{-1}$$

Being a_{ij} technical coefficient of sector i over sector j, z_{ij} the value of sales from sector i to sector j and x_j total production in sector j. From a demand-side view, production is the summation of intermediate consumption and final demand. In matrix notation X=IC+FD and then:

$$X = AX + FD$$

$$X(I - A) = FD$$

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

Being L=$(I - A)^{-1}$ the so-called the Leontief inverse, it reflects the production (X) elasticity to changes in final demand (FD). Therefore, to analyse how production reacts in order to satisfy a variation in final demand (FD), the following equation is used:

$$\Delta X = L\, \Delta \mathrm{FD}$$

Therefore, production required to satisfy demand reflects the direct changes induced by final demand but also indirect effects due to intermediate demand. This relationship is grounded in the fixed proportion of inputs required to produce in each sector, namely the technical coefficients (collected in the A Matrix). Analysis of the world IOT resulting from WIOD, shows that in the data sample this A Matrix experiences sectoral changes but is relatively stable as a whole in the available period 1995-2009. For the sake of simplicity, A Matrix is static for the simulation period, taking the last dataset values. Further developments of the model could involve the evolution of A Matrix according to scenarios and endogenous dynamic adaptation to the rest of the model.

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2.2.3.3. Energy-Economy feedback

Most energy-economy-environment models consider economic growth independent from biophysical limits. In MEDEAS, economy cannot trespass the boundaries settled by nature. 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 climate change that, in MEDEAS, are disseminated throughout energy, as described in section 0. As the direct feedback to economy comes from the energy module, it is worth to focus here in this relationship, a key point of the model.

Once production required to satisfy demand by sectors is calculated as described in the previous sections, the final energy required to satisfy demand is obtained:

$$\hat{I}_e = \hat{E}\hat{x}^{-1} = \begin{pmatrix} \frac{E_{ij}}{x_i} & 0 \\ 0 & \frac{E_{nn}}{x_n} \end{pmatrix} = \begin{pmatrix} I_{e,ij} & 0 \\ 0 & I_{e,nn} \end{pmatrix}, \qquad \mathrm{i} \in 1 \ldots 35; \mathrm{j} \in 1 \ldots 5$$

$$E = \hat{I}_e x = \hat{I}_e * L * D$$

Let's 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, 2012) and balanced with International Energy Agency accounts. Pre-multiplying production by the energy coefficients (intensities), the model estimates the final energy required to satisfy demand. In this point, the energy demand of the economic system has to be confronted 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 8).

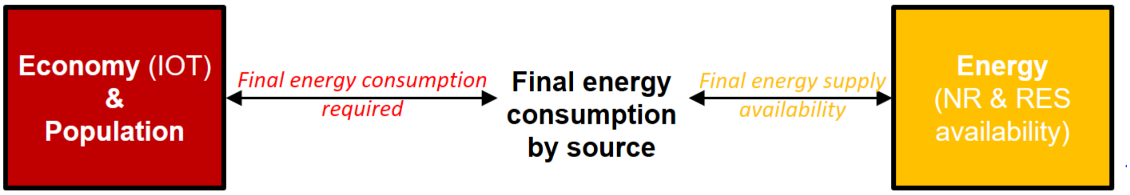

Figure 8. Energy-Economy feedback in MEDEAS. Source: own elaboration.

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Then, scarcity in one source, forces 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 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:

$$shortage\ coefficient_j = \frac{FES_j}{FED_j}$$

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

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

$$FEC_{i,j} = ShC \cdot FED_{i,j}$$

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. 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.

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

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

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Finally, the inverse process followed in eqs. 4-6 (from FD to X) takes places (from X' to FD') as described in the following equations:

$$X' = AX + FD'$$

$$FD' = X(I - A)$$

In the model, this feedback is present not only in this spot, but in all relevant variables, which include 'not covered' as an addendum. In each variable which it is attached, the not-covered variables quantify the gap between the value of that variable without the feedback and including it. Hence, when energy demand is lower than energy supply, not-covered variables equals 0. Contrarily, when energy scarcity appears, 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 for the year 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, see sections 2.4.6 and 0), obtaining a more realistic approach in energy-economy-environment modelling. Without a feedback between energy and economy, energy demand shall grow exogenously not taking into consideration availability of resources (Capellán-Pérez et al., 2016a; 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 is not independent from 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

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Table 5 and are calculated as $\hat{I}_e$L: diagonal matrix of energy intensities times Leontief Matrix. Interpretation is the amount of final energy required to satisfy changes in final demand (monetary). For instance, we can see how sensitive are the liquids consumption of sector 1 (Agriculture, Forestry, Hunting and Fisheries) to changes in demand. If demand of sector 1 rises in 1 million US$, there will be needed 1.26 EJ of electricity in order to satisfy it. Or how much liquids must be demanded by transport sectors (24 and 25, inland and water transport) in order to satisfy an additional US$ of demand. Sector 24 (inland transport) would require 30.07 EJ of liquids and sector 25 (water transport) 28.05TJ.

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Table 5. Sectoral final energy sensitiveness by sources (EJ/million 1995 US$). Source: own elaboration.

Sectors	Electricity	Gas	Heat	Liquids	Solids
1	1.2604	0.8024	0.1731	3.9956	0.7569
2	1.9068	5.5801	0.3084	2.1787	1.7372
3	1.4298	1.1466	0.2930	2.9174	1.9248
4	2.1354	1.3166	0.5246	2.6010	1.6472
5	1.4820	1.0488	0.3352	2.6031	1.3554
6	1.9092	1.2077	0.4235	2.9851	2.7856
7	2.2181	1.3649	0.5148	2.0450	2.9113
8	2.0711	5.1699	1.0166	10.0047	1.7876
9	2.8579	2.9973	1.0546	3.3531	2.1684
10	3.4463	2.5391	0.6704	3.9130	3.9723
11	3.4141	3.3618	0.3624	4.0617	10.7241
12	4.2591	2.9724	0.5043	2.3414	5.0805
13	1.8583	1.2758	0.2671	1.8224	1.7978
14	1.4670	0.9970	0.2092	1.6179	1.2955
15	1.7310	1.1953	0.2760	1.8296	1.5845
16	2.0473	1.6743	0.4177	3.2579	2.4026
17	3.9585	4.3197	0.3942	1.8406	3.4511
18	1.4375	1.2885	0.2041	2.5032	2.1383
19	0.9036	0.5968	0.1275	1.4772	0.5528
20	0.5067	0.3456	0.0935	1.3525	0.2726
21	0.7972	0.4629	0.0886	1.6453	0.2804
22	1.4688	0.9628	0.1627	2.2406	1.0519
23	1.0697	2.3843	0.1392	7.8553	0.6085
24	0.6356	0.8003	0.1631	30.0728	0.5120
25	0.7150	0.9139	0.1817	28.0519	0.5661
26	1.0688	0.8377	0.2162	4.7723	0.5845
27	0.6377	0.5142	0.0822	1.1927	0.3045
28	0.4368	0.2703	0.0596	0.8617	0.2089
29	0.4995	0.2640	0.0820	0.5033	0.2201
30	0.6042	0.4348	0.0881	1.3682	0.3577
31	1.0051	1.2297	0.1257	1.7730	0.5026
32	1.1066	0.5375	0.1279	1.5187	0.4437
33	0.9420	0.6454	0.1619	1.6249	0.5247
34	0.9939	0.6601	0.1699	1.9672	0.5344
35	0.1711	0.3744	0.0271	0.2787	0.1463

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Finally, it is worth a brief comment on the evolution of energy intensities, described in detail in sections 0 and 2.3.1.1. The historical data observed shows that sectoral energy intensities (by final energy sources) are slightly declining, but are more or less stable. However, different changes can occur in their evolutions, 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.

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2.2.4. Dynamic modeling of final energy intensities in MEDEAS

2.2.4.1. Overview

Energy intensity expresses a ratio between the energy used in a process and its economic output. This general expression can be applied to the energy intensity of a country, taking the total energy required and GDP as an economic output. In this way, the energy intensity is a highly aggregated indicator. However, the same concept can be applied at sectoral level (Heun et al., 2015, chap. 7). With the objective of disaggregating this indicator, the MEDEAS model considers 5 types of final energy consumption (electricity, solids, liquids, gases and heat) and 35 economic sectors (according to the WIOD classification). In addition, the energy intensity of households is calculated as the ratio between each of the final energy types and their total consumption in economic terms. Consequently, a total of 180 (36x5) energy intensities are obtained. Each of them is still an aggregate indicator that expresses, as statistical mean value, the consumption of each type of energy by each of the economic agents modeled.

If the energy intensity (I_e) and the economic output (E_o) of each economic agent is known, the required energy (E) can be easily obtained as E = I_e x E_o. In this expression, the energy intensity, I_e, is a 5x36 matrix and the economic output, E_o, is a vector of 36x1. Consequently, the energy required, E, will be a 5x1 vector. The economic output, E_o, in the form of demand or consumption is calculated in the economic module, while the availability of each of the final energy types is calculated in the energy module.

This section explains the modeling of the dynamic behavior of final energy intensities which has been developed and applied in MEDEAS.

Each of the energy intensities of the I_e matrix remains an aggregate indicator that generically expresses the energy requirements in terms of final fuels of each economic agent to produce a certain level of economic output. In that sense, in general, one could say that the lower energy intensity indicates greater economic efficiency. Frequently, historical data show the gradual reduction of energy intensity, which would show this improvement of efficiency over time. However, this is not always the case, and in each case (combinations of economic sector and final fuel) the evolution of final energy intensities over time has been different. For example, the mining sector may require more and more energy to obtain the mineral, as the ore grades decrease over

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time. Another case would be the electric power production industry. This sector may have greater self-consumption of energy per energy unit produced when the energy sources decrease their EROEI. Both examples can lead to an increase in energy intensity in these economic sectors. On the other hand, the change of the technology used in each sector can lead to a change in the type of final energy used. This change of type of energy that is consumed in a sector also implies a change in their energy intensities with respect to each one of the types of energy.

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2.2.4.2. Final energy intensity historic data

The starting point for modelling the dynamic behaviour of final energy intensities is the available historical data. These data have been taken from WIOD database, but it has been necessary to transform them to use the appropriate units in the model, grouping them by the aforementioned types of final energy and avoid double counting in some cases.

Once the historical data of the energy intensity matrix is obtained, the modelling of final energy intensity by fuel and sector/households has been developed, trying to explain its historical behaviour and justifying its foreseeable future evolution.

Available historical data generally show stable trends over time with some exceptions. In order to model the dynamic behaviour of the energy intensities the historic trends that can be justified by structural reasons are considered (thus neglecting specific variations due to temporary reasons).

Figure 9 shows an example of the evolution of energy intensities (1995-2009) in some sectors for the electricity.

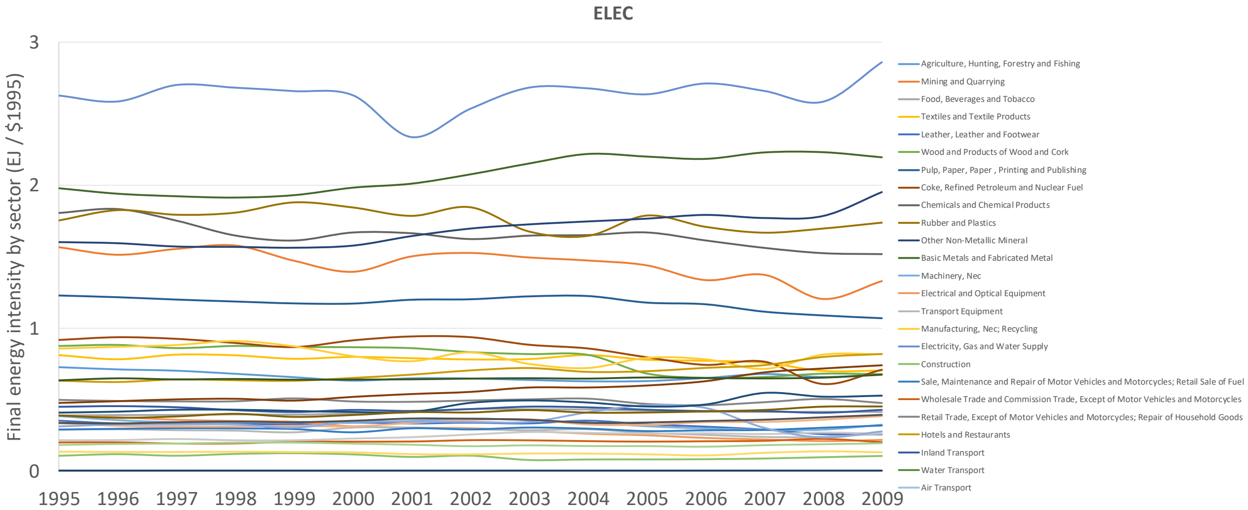

Figure 9: Historical evolution of electricity intensity by sector for the period 1995-2009. Source: WIOD and own work.

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2.2.4.3. Final energy intensity trend evolution

A conventional way for characterizing the evolution of energy intensity is shown in equation below (Schenk and Moll, 2007):

$$I_t = I_{t=0} \cdot (1 - AEI)^t$$

which can also be written as equation below, where annual Intensity (It) decreases each year at a constant rate (a=1-AIE) in relation to the previous year (It-1):

$$I_t = I_{t=0} \cdot (1 - AEI)^t = (1 - AEI) \cdot I_{t-1} = a \cdot I_{t-1}$$

AEI represents the Annual Efficiency Improvements.

Ordinary Least Square (OLS) method has been used in order to estimate “a” variable. When “a” variable is greater than 1, the regression is not valid. In these cases, MEDEAS model applies a linear evolution from historic trends. The results of the energy intensity by sector and type of final energy regressions for “a” <1 are shown in

Figure 10.

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OLS for the estimation of the model: I(t)=a*I(t-1)	ELEC	HEAT	LIQUIDS	GASES	SOLIDS
Agriculture, Hunting, Forestry and Fishing	0,9941	0,8799	0,9830		0,9580
Mining and Quarrying	0,9871	0,9548	0,9897	0,9953	
Food, Beverages and Tobacco		0,9686	0,9882		0,9932
Textiles and Textile Products	0,9901	0,9805	0,9546	0,9869	0,9381
Leather, Leather and Footwear	0,9798	0,9502	0,9684	0,9763	0,9542
Wood and Products of Wood and Cork	0,9822	0,8751	0,9718		0,9927
Pulp, Paper, Paper , Printing and Publishing	0,9905		0,9595	0,9879	
Coke, Refined Petroleum and Nuclear Fuel	0,9811	0,9815	0,9681	0,9716	0,9970
Chemicals and Chemical Products	0,9872	0,9775	0,9774	0,9846	0,9514
Rubber and Plastics	0,9984	0,9512	0,9801	0,9885	0,9832
Other Non-Metallic Mineral		0,9837	0,9860		0,9997
Basic Metals and Fabricated Metal		0,9448	0,9616	0,9870	0,9973
Machinery, Nec	0,9852	0,8639	0,9499	0,9910	0,9119
Electrical and Optical Equipment	0,9585	0,8518	0,9246	0,9578	0,8785
Transport Equipment	0,9910		0,9610		0,9694
Manufacturing, Nec; Recycling	0,9943	0,9596	0,9783	0,9981	0,9454
Electricity, Gas and Water Supply			0,9632	0,9767	
Construction	0,9916	0,6888	0,9955		
Sale, Maintenance and Repair of Motor Vehicles and Motorcycles; Retail Sale of		0,9858	0,9781	0,9891	0,8299
Wholesale Trade and Commission Trade, Except of Motor Vehicles and Motorcyc	0,9996	0,9809	0,9587	0,9727	0,9210
Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Go	0,9961	0,9867	0,9703	0,9954	0,9034
Hotels and Restaurants		0,9874	0,9687		0,9777
Inland Transport	0,9960			0,9913	0,9335
Water Transport			0,9626	0,9523	0,9293
Air Transport			0,9953	0,9877	0,2659
Other Supporting and Auxiliary Transport Activities; Activities of Travel Agencies		0,8133		0,9593	0,9029
Post and Telecommunications		0,9592	0,9591	0,8929	0,9624
Financial Intermediation	0,9955	0,8602	0,9525	0,9899	0,6535
Real Estate Activities	0,9836	0,9508	0,9749	0,9827	0,8195
Renting of M&Eq and Other Business Activities		0,9763	0,9680	0,9995	0,9834
Public Admin and Defence; Compulsory Social Security		0,9754	0,9778	0,9409	
Education		0,9952	0,9992		0,9273
Health and Social Work		0,9791	0,9749	0,9928	
Other Community, Social and Personal Services		0,9424	0,9850	0,9798	0,9862
Private Households with Employed Persons					
Final consumption expenditure by households		0,9553		0,9891	0,9780

Figure 10: "a" parameter by sector and type of energy.

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2.2.4.4. Changes on inertial trend of final energy intensity

On this inertial trend, it is considered that different changes can be produced due to the energy policies.

The changes that can occur in the future are:

a) Accelerating the change in energy efficiency due to policies pressures. (Eg increased R & D investment, rising energy prices, etc.).
b) Change of energy technology in a sector. For example, the change of combustion engines by electric motors in the transportation sector. This change implies that the energy intensity of one of the final energies increases (in this example, electricity) and another one decreases (in this example, liquid fuels). Both changes will be balanced but may differ depending on the energy efficiency of each technology. The case of transport has been considered of special relevance and a specific model has been developed. This submodel estimates possible changes in energy intensities depending on the technological options of the transport sectors that occur in the future according to the policies or the market conditions.

Figure 11 shows a simplified structure of the energy intensities model in MEDEAS; where "Efficiency energy acceleration" corresponds with the cause a), "Increase and Decrease of intensity due to energy a technology change" responds to the cause b) and it is related with the "efficiency rate of substitution". The "historical mean rate energy intensity" considers the inertial trends, and it corresponds to a'; where:

$$a' = a - 1$$

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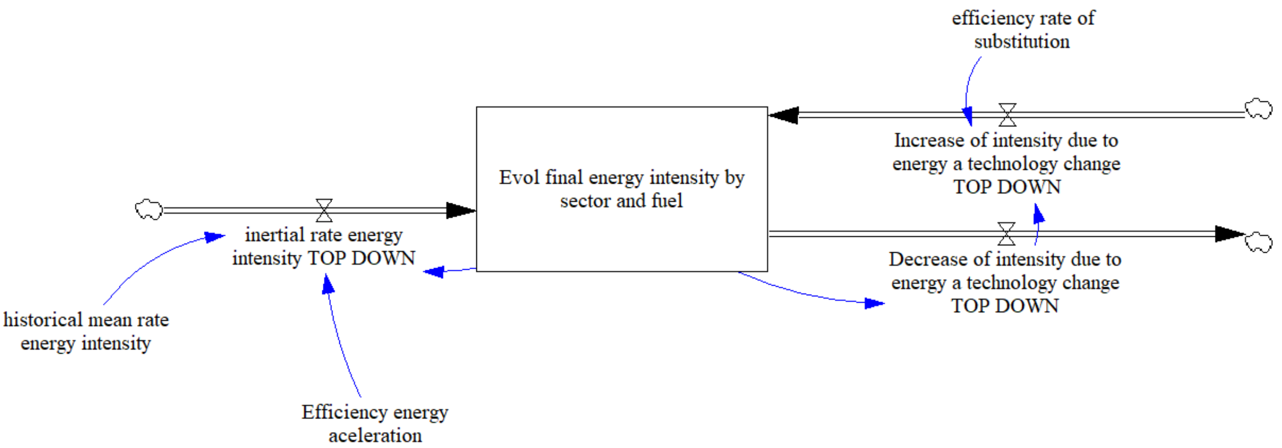

Figure 11: Simplified structure of the energy intensities model.

In the cases where “a”<1 a limit is necessary because a zero energy intensity cannot be reached (thermodynamical limits, see (Capellán-Pérez et al., 2014)).

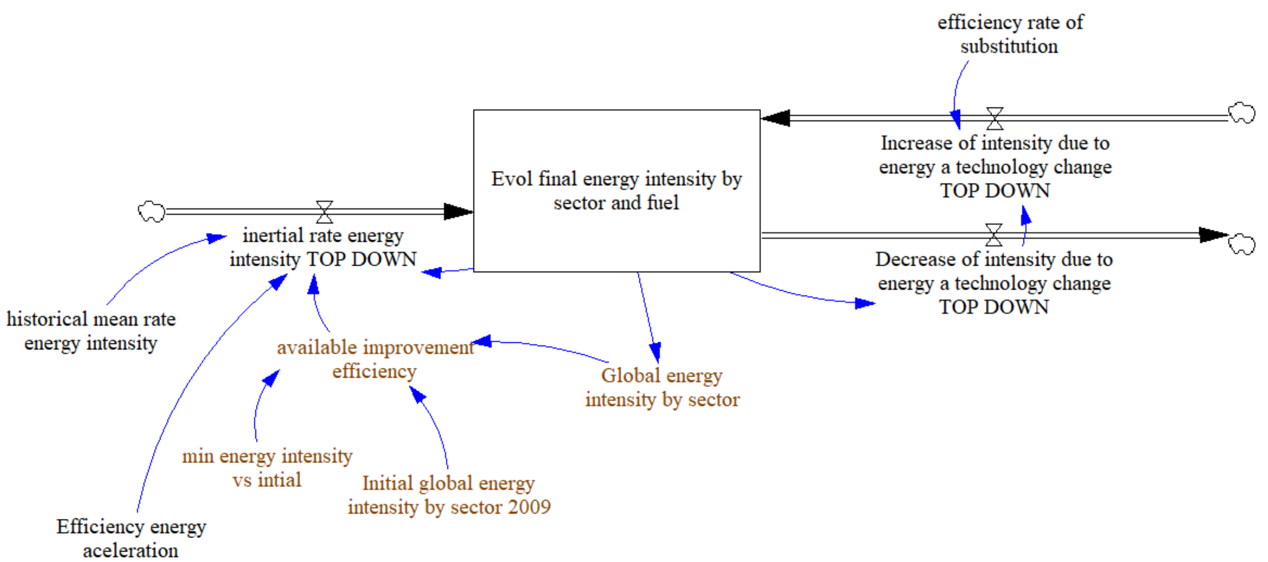

Figure 12: Simplified structure of the energy intensities model with a limit in energy intensity.

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The limit is function on the global energy intensity by sector in 2009 and it is defined in the variable "min energy intensity vs initial", by default 0.3 as in (Capellán-Pérez et al., 2014).

Available improvemente efficiency=
IF THEN ELSE(Time<2009, 1, (Global energy intensity by sector-
*(min energy intensity vs intial*Initial global energy intensity by sector 2009]))*
*/(1-min energy intensity vs intial)*Initial global energy intensity by sector 2009)*

As stated above, this historic trend value is affected by different factors. At first, (cause a) accelerating the change in energy efficiency due to policies pressures. (Ex. increased R&D investment, rising energy prices, etc.). The pressure of the policies will depend on the years in which the policy is applied and the speed of application. Also the variation in energy efficiency is limited by an annual maximum of improvement for each sector. These variables can be defined by sector and final source in the excel file.

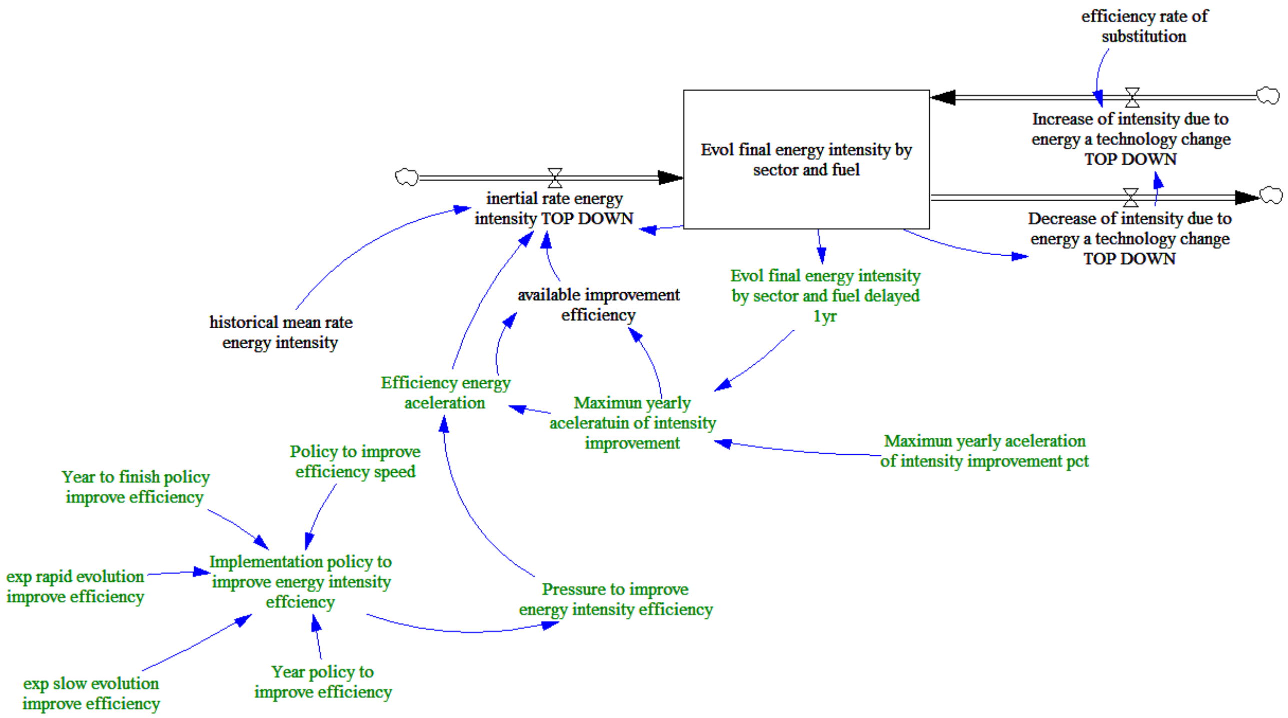

Figure 13: Simplified structure of the energy intensities model with efficiency energy acceleration.

"Efficiency energy acceleration" is added to "historical mean rate energy intensity" to estimate "inertial rate energy intensity TOP DOWN"

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$$Inertial\ rate\ energy\ intensity\ TOP\ DOWN = Evol\ final\ energy\ intensity\ by\ sector\ and\ fuel * (historical\ mean\ rate\ energy\ intensity + Efficiency\ energy\ aceleration) * available\ improvement\ efficiency$$

The change in energy intensity as a result of the technological substitution of the energy source (cause b) has also been taken into account. In other words, the change between final energy types in a sector is modelled using the following variables:

- "Efficiency rate of substitution": when a technology based on one type of energy is changed for another based on another type of energy, it is possible that energy efficiency will change.
- "Minimum fraction": minimum energy of each type of energy that should be used in each sector because it is irreplaceable.
- "Max yearly change": maximum annual change for one type of energy in a sector.

As in the cause a), the pressure of the policies will depend on the years in which the policy is applied and the speed of application.

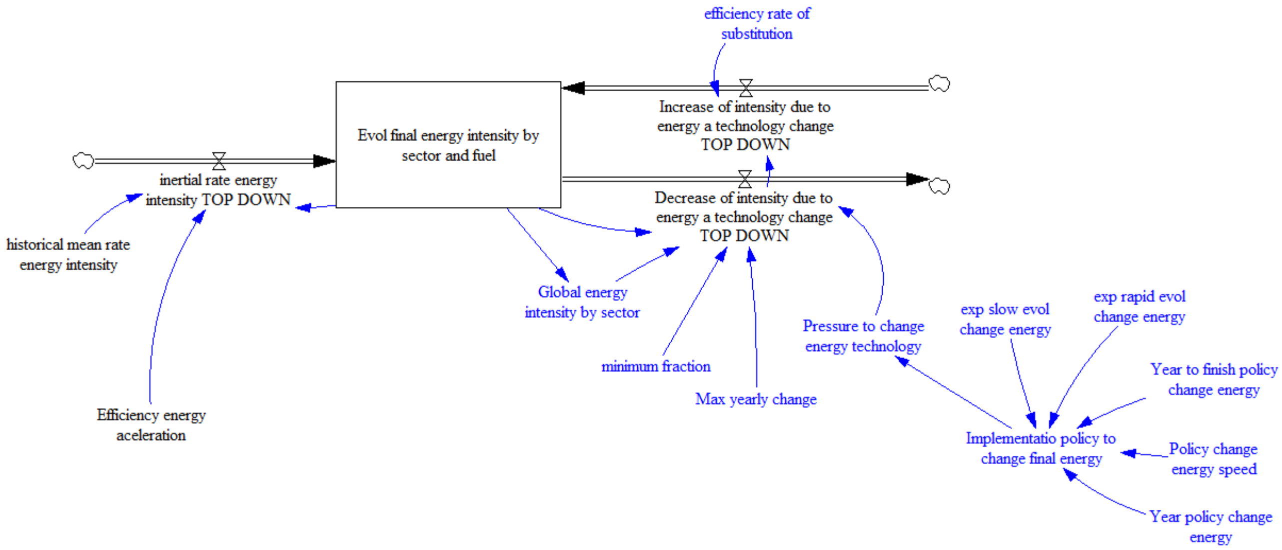

Figure 14: Simplified structure of the energy intensities model with the change in energy source.

All the parameters of this part of the model can be chosen by the user for each sector and type of final energy.

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2.3. Energy and Infrastructures module

This section documents the modelling of the estimation of energy demand (section 0), the energy supply (section 0), the energy resources availability in MEDEAS (non-renewable resources in section 0 and renewable-resources in section 0), the modelling of electricity generation (section 2.3.5) and heat generation (section 0), the modelling of transportation (section 0) and the modelling of non-energy use (section 0). Primary energy in the model refers to the direct equivalent method.[3]

[3] 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).

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2.3.1. Estimation of energy demands

2.3.1.1. Historic final energy demands from WIOD and IEA balances

The WIOD database 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 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., 2013b; Timmer et al., 2012) (which ultimately was built from the IEA database (IEA, 2018)). Table 6 shows the equivalence between sources of different databases and MEDEAS.

Table 6: Equivalence between MEDEAS final energy categories and the WIOD and IEA categories. Losses and non-energy use of materials are not considered.

MEDEAS	WIOD	IEA
SOLIDS	HCOAL	Anthracite
		Other bituminous coal
		Coking coal
		Patent fuel
		Sub-bitumious coal
	BCOAL	BKB
		Coal tar
		Lignite
		Peat
		Peat products
	COKE	Gas coke
		Coke oven coke
	WASTE	Industrial waste
		Municipal waste (renewable)
		Municipal waste (non-renewable)
	OTHRENEW	Charcoal
		Non-specified primary biomass and waste
		Primary solid biomass
LIQUIDS	CRUDE	Crude oil
		Natural gas liquids
		Refinery feedstocks

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MEDEAS	WIOD	IEA
		Additives/blending components
		Other hydrocarbures
	DIESEL	Gas/Diesel oil exc. Biofuels
	GASOLINE	Motor gasoline excl. Biofuels
	JETFUEL	Aviation gasoline
		Gasoline type jet fuel
		Kerosene type jet fuel excl. Biofuels
	LFO	Gas/Diesel oil
	HFO	Fuel oil
	NAPHTA	Napthta
	OTHPETRO	Bitumen
		Ethane
		Liquefied petroleum gases (LPG)
		Lubricants
		Other oil products
		Other kerosene
		Paraffin waxes
		Petroleum coke
		Refinery gas
		White spirit & SBP
	BIOGASOL	Biogasoline
		Other liquid biofuels
	BIODIESEL	Biodiesels
GASES	NATGAS	Natural gas
	OTHGAS	Blast furnace gas
		Coke oven gas
		Gas works gas
		Coal gases non-specofied
		Other recovered gases
	BIOGAS	Biogases
ELECTRICITY	ELECTRICITY	Electricity
HEAT	HEAT	Heat

The estimation of the 5 MEDEAS categories of final fuels requires some calculations from the available energy data from WIOD. The environmental accounts report two types of energy variables

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(time scope: 1995-2009 and country coverage: 40 countries and rest of the world) (Genty et al., 2012):

- Energy use, Gross: Gross energy use by sector and energy commodity,
- Energy use, Emission Relevant: Emission relevant energy use by sector and energy commodity.

However, neither "Energy use, Gross" variable nor "Energy use, emission relevant" variable correspond with what is needed for estimating the final energy following MEDEAS categories.

The metric "Energy use, Gross" includes double accounting since it considers the primary energy and the final energy (see (Iñaki Arto et al., 2016) for more details). In the "Energy use, Emission relevant" variable, although the double accounting of refineries is avoided, it still exists in the electricity/heat production sector. Therefore, in order to estimate the final energy, using this variable, we need to subtract the energy that is account both in electricity and heat production. For this process, data from the IEA Balances (IEA, 2018) are used since data from WIOD were estimated from this database: *"Energy accounts are compiled using extended energy balances from IEA (2011a) as a starting point"* (Genty et al., 2012).

For electricity and heat production, the IEA distinguishes between main activity production y autoproduction. In order to remove the double accountability, we have to take away both. The main hypotheses assumed in this process are the following:

- For each final source, the main activity production of electricity and heat is taken away from Electricity, Gas and Water Supply sector.
- The self-production is subtracted in a proportional way in the industrial sectors.
- Only "general use fuels" which are natural gas, fuel oil and diesel, are considered as final sources for self-production. The rest are very small and can be considered negligible (less than 0.01% of total energy).

Data obtained after subtracting the double accounting do not consider the transformation losses neither the non-energetic use of materials.

Figure 15 shows the contribution of each category in the TFC according to MEDEAS classification for year 2009. Liquids represents the main energy source (38%), while heat only covers 3% of total demand. Note that following the IEA accounting, the heat reported by the IEA balances corresponds solely to commercial heat. See section 0 in relation to the corrections performed to account for the non-commercial heat in MEDEAS.

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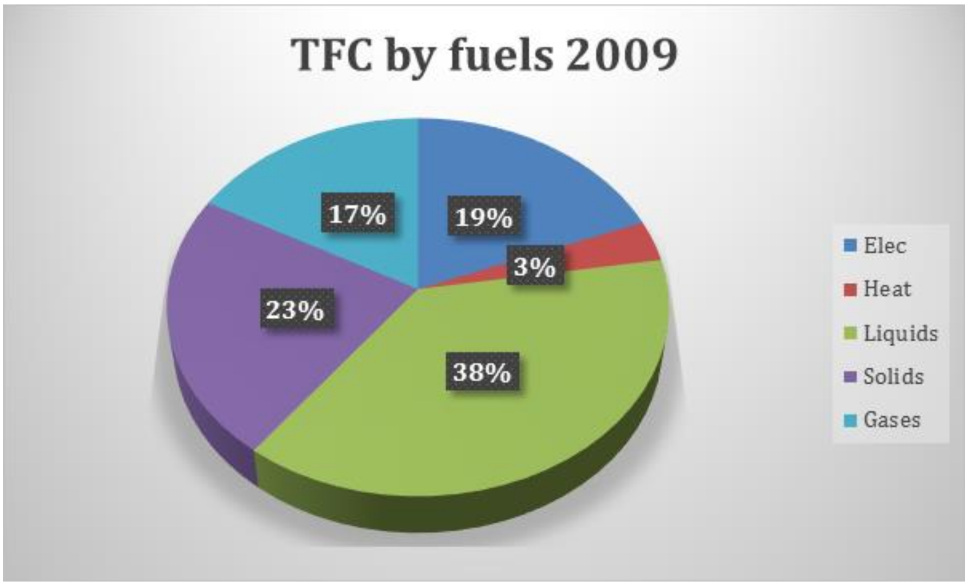

Figure 15: TCF by fuels 2009. Source: WIOD database.

Figure 16 shows the historical evolution 1995-2014 for each MEDEAS final energy category:

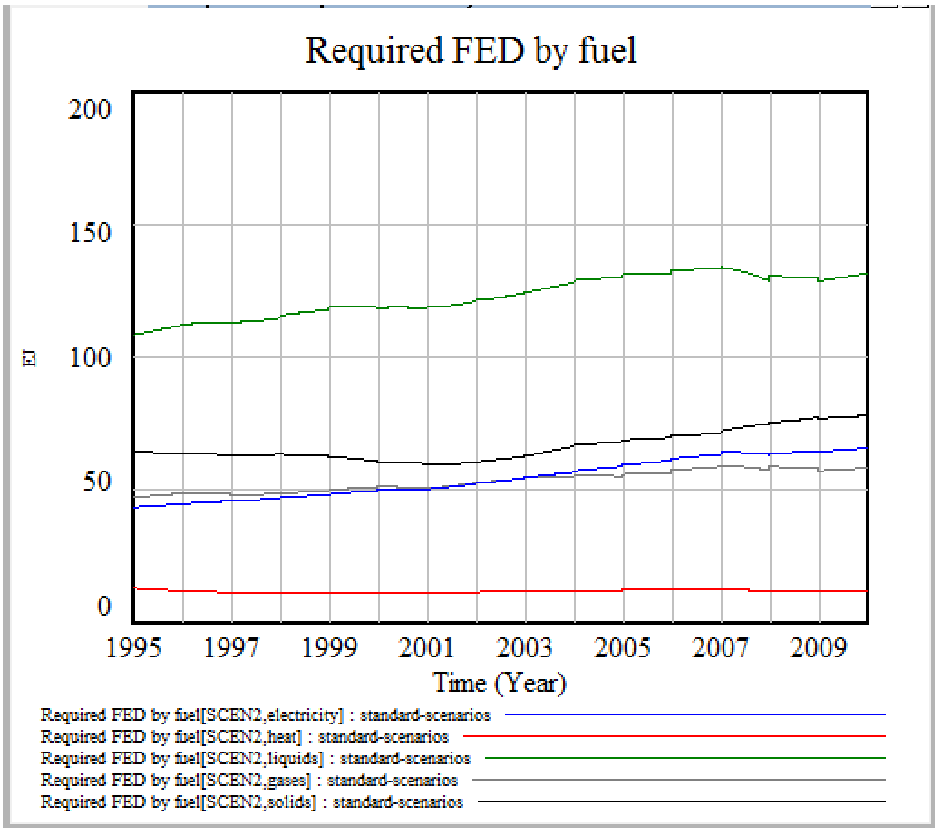

Figure 16: Historic FED by fuel after adjusting WIOD data from IEA balances. Heat refers solely to commercial heat.

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In terms of primary energy, in 2009, around 70% of the total primary energy supply was used as final energy. A 6% of the energy materials were used for non-energetic use. The rest is lost in transformation processes or other causes (see Figure 17).

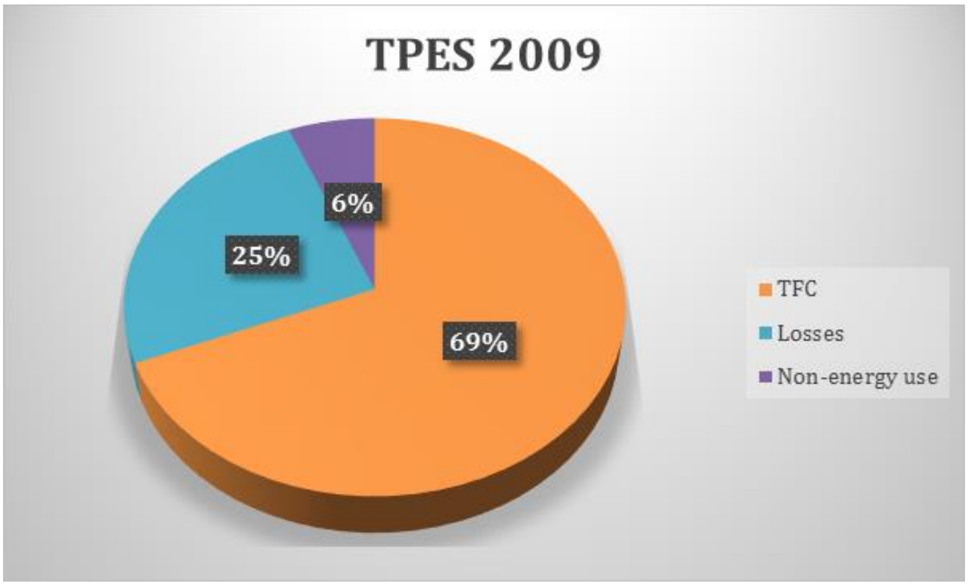

Figure 17: TPES 2009. Source: (IEA, 2018).

The modelling of losses in MEDEAS is described in detail in next section 0.

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2.3.1.2. Energy losses

Losses are really important in the quantification of the total energy. As it is shown in previous section 2.3.1.1, around 25 % of total primary energy in 2009 were losses. As shown in Figure 18, most losses currently refer to losses in the process of electricity and heat generation (81%). The relationship between final energy (FE), primary energy (PE), losses and efficiency of transformation is given by the following equation:

$$\frac{FE \cdot (1 + Losses)}{\chi} = PE$$

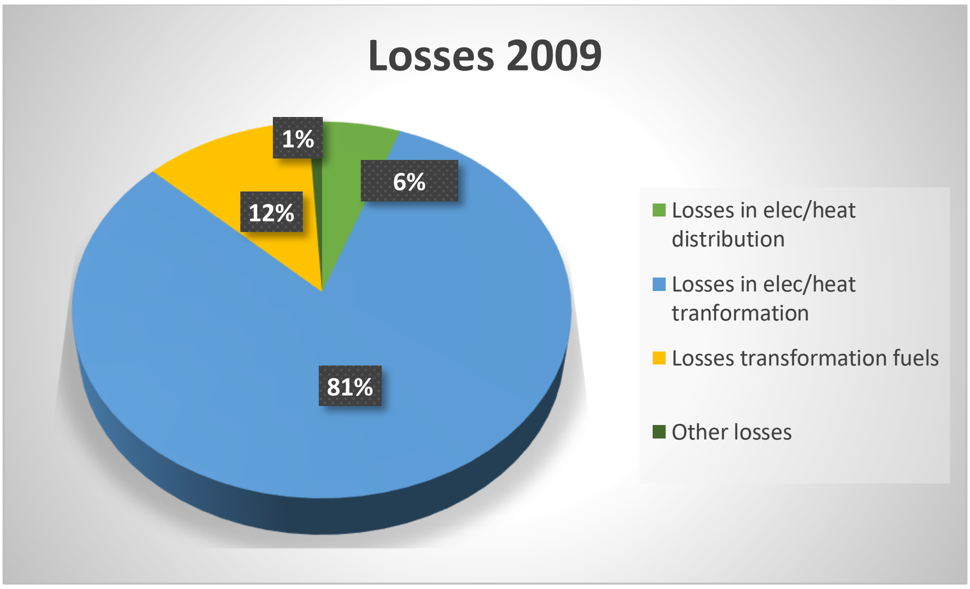

Figure 18: Losses in 2009. Source: (IEA, 2018).

The majority of these losses are due to the transformation of primary energy to obtain (81%) and (6%) distribute electricity and heat. See sections 2.3.5 and 0 for the modelling of transformation losses.

Losses in fossil fuels energy distribution, transmission and transport have been modelled assuming that the losses for each fossil fuel are proportional to their extraction. This hypothesis is appropriate as we have verified it with historical data from the IEA for years 1995 to 2014.

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Table 7. Parameters for the modelling of energy distribution losses

	MEAN	SDEVIATION
COAL share dist. losses vs total extraction	0.00159169	0.00112364
OIL share dist. losses vs total extraction	0.00162263	0.0001716
NAT GAS share dist. losses vs total extraction	0.00842251	0.00106954

.

So we considered these average values to calculate fossil fuels losses in energy distribution, transmission and transport as a function of the extraction.

Last but not least, transformation losses between fuels covered around the 12% of the total losses. Some of these losses are: Coal-to-liquids plants, Gas-to-liquids plans, Heat pumps, Electric boilers, Blast furnaces, Coke ovens, BKB plants, Oil refineries, Patent fuel plants...

At this moment, only CTL y GTL are modelled separately in MEDEAS. The remaining are modelled through the extrapolation of the historical trend. Further work might improve this representation.

We estimate the losses as a function of fossil fuel extraction (for oil and coal). We do the same for distribution losses.

Table 8. Parameters for the modelling of energy transformation losses.

	MEAN	SDEVIATION
OIL share transf. losses vs total extraction	0.01172461	0.00302965
COAL share transf. losses vs total extraction	0.12415545	0.00393162

Oil and coal transformation losses depend on the extraction.

This is different for gases. In the vast majority of the transformation processes in which gases are obtained (especially in Blanst furnaces y coke ovens), there are not gas losses but gas profit. In these processes between solids, almost all the gases generated are produced in transofrmation processes. So, in the same way, using data from the IEA, we make the hypothesis that the gas profit in transformation processes is inversely proportional to the solid losses in these processes.

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Table 9. Parameters for the modelling of gain gas in transformation processes losses.

	MEAN	SDEVIATION
Ratio gain gas vs lose solids in tranf processes	-0.44642151	0.01449316

What we mean is that for 1 EJ of solids that is lost in transformation processes, they are obtained 0.4464EJ of gases.

We need to underline that in further work we will develop separately the main transformation procceses. In this way we will obtain a more realistic approximation and even better to the actual approximation in which we have assumed several hypothesis.

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

The IEA balances report as heat only the heat traded commercially, i.e. heat that is produced and sold to a different end user. The heat is produced through co-generation or heat plants and is often distributed through district heating networks. On the other hand, the non-commercial heat is implicitly included in the FEC of those fuels which are used for generating heat (gas, coal, oil and bioenergy). Thus, in order to promote policies of substitution of non-renewable fuels by renewables sources in the heat sector in MEDEAS framework, it is necessary to adjust the demands of fuels which are used for generating non-commercial heat as heat. As reported by a report of the IEA, the difference is large: around 170 EJ of FEH (final energy use for heat) were dedicated to the production of heat in 2011 in comparison to the almost 12 EJ that were used as heat (final energy), i.e. around an order magnitude difference (IEA, 2014). Note that the FEH is in fact primary energy from the point of view of heat since it includes the distribution and generation losses of heat.

The report estimates the FEH as the FEC of a specific fuel (i) in each sector (j), plus the share of commercial heat produced by the same fuel (i) that is consumed in the same sector (j), see following equation:

$$FEH_{i,j} = FEC_{i,j} + (\%Commercial\ heat_i) \cdot FEC_{Commercial\ heat,j}$$

However, the data on renewable energy use for heat suffer from a number of deficiencies, such as data quality and availability, as well as methodological issues. The applied approach in MEDEAS 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.
- In addition, around 20% each of world primary supply of coal and oil are used for the same purpose.
- 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).

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Figure 19 shows the obtained modifed energy demands accouting for non-commercial heat for the historical period 1995-2009. It can be observed that after the adjustement, the final energy for heat becomes the largest final energy demand in the analyzed period together with the liquids (~100 EJ in 2009). On the other hand, the demand of gas as final fuel decreases more than 80% to around 10 EJ per year in 2009. The demand of solids as final fuel also decrease significantly to reach 38 EJ by 2009, most of it representing solids bioenergy for traditional biomass.

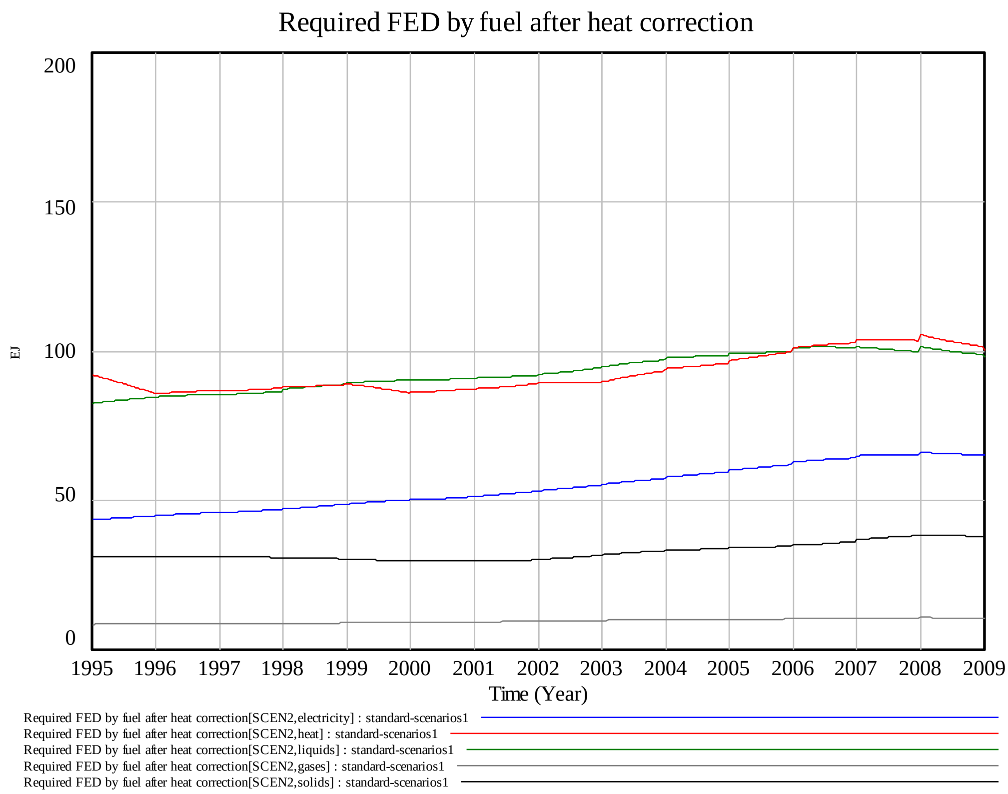

Figure 19: FED by fuel after heat correction

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2.3.2. Energy supply in MEDEAS

In MEDEAS primary total energy demand is covered with different primary energy sources (see Table 10)

Table 10 : Sources of energy supply in MEDEAS. 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
		Waste
	RES	Charcoal
		Primary solid biofuels (modern)
		Primary solid biofuels (traditional biomass)
Liquids	NRE	Conventional oil
		Unconventional oil
		CTL
		GTL
	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

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		Waste
	RES	Geothermal
		Solar
		Solid biomass
		Biogas

Although in practice heat can be demanded at different temperature levels (IEA, 2014),[4] for the sake of simplicity in this model version all heat demand and supply is aggregated.

[4] 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 enduse sectors (IEA, 2014).

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2.3.3. Non-renewable energy resources availability

MEDEAS 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. Biofuels, CTL, GTL and refinery gains are modeled separately (see sections 2.3.3.5 and 0).
- Conventional gas.
- Unconventional as: includes shale gas, tight gas, coal-bed methane (CBM) and hydrates.
- Coal: includes anthracite, bituminous, sub-bituminous, black, brown and lignite coal.
- Uranium.

We assume that the technologies that claim 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 (see section **¡Error! No se encuentra el origen de la referencia.**). Nuclear fusion is not considered since the ITER and DEMO projects estimate that the first commercial fusion power would not be available before 2040 (http://www.iter.org), which would prevent this technology to substantially contribute to the mix in the timeline of MEDEAS.

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2.3.3.1. Modeling of primary non-renewable energy resources in MEDEAS

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

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

Figure 20 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. 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.

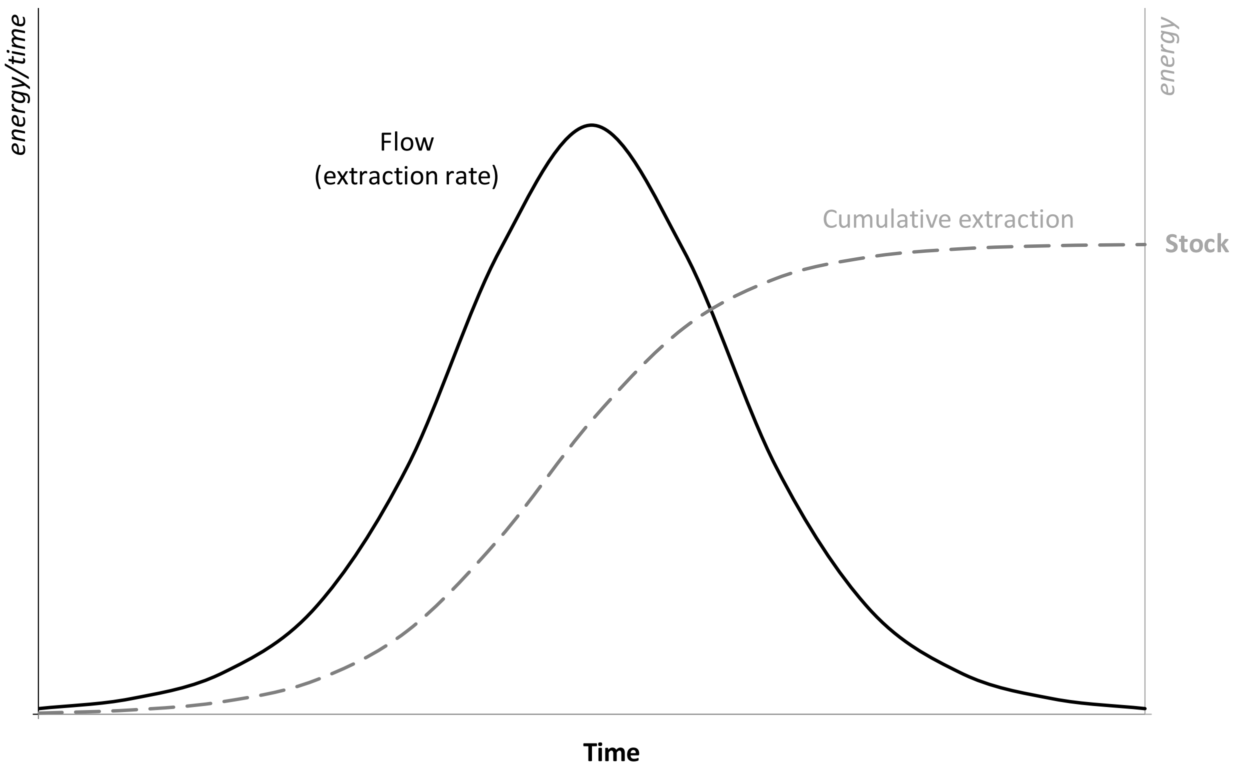

Figure 20 : (Kerschner and Capellán-Pérez, 2017): Simplified representation of the depletion of a non-renewable resource in the absence of non-geologic constraints. Stocks and flows of energy relative to time.

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:

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$$RURR_t = URR - cumulative\_extraction_t$$

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 on dynamically estimating the likely extraction rate of wells and mines globally (Aleklett et al., 2010; ASPO, 2009; EWG, 2013, 2008, 2007, 2006; Höök et al., 2010; Laherrère, 2010, 2006; Maggio and Cacciola, 2012, 2012; Mohr, 2012; Mohr et al., 2015; Mohr and Evans, 2011, 2009, 2009; Patzek and Croft, 2010; Zittel, 2012). These curves (see Figure 23 to Figure 29) should not be interpreted as projections of the extraction of a given fuel, but instead 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 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 (see Figure 21a). To do this, the depletion curves have been converted into maximum production curves as a function of remaining resources. 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 when physical limits start to appear and maximum extraction rates are gradually reduced. In this way, the model uses a stock of resources (the RURR) and it studies how this stock is exhausted depending on production, which is in turn determined by demand and maximum extraction (see Figure 21b).

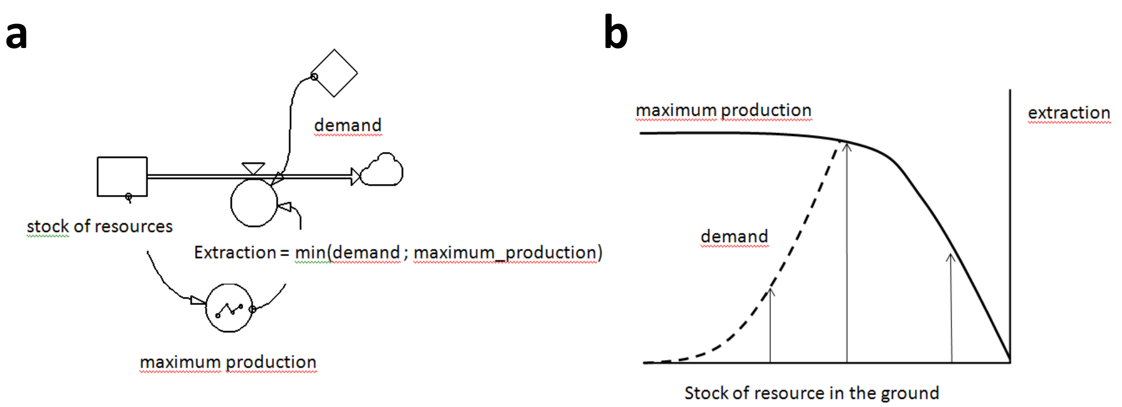

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Figure 21 : (Mediavilla et al., 2013): Integration of depletion curves in the model. (a) SD model. (b) A curve of maximum extraction (solid) compared with the demand (dashed).

As illustration, Figure 22a shows the depletion curves as a function of time and Figure 22b the associated curves of maximum extraction as a function of the RURR as applied in (Capellán-Pérez et al., 2014).

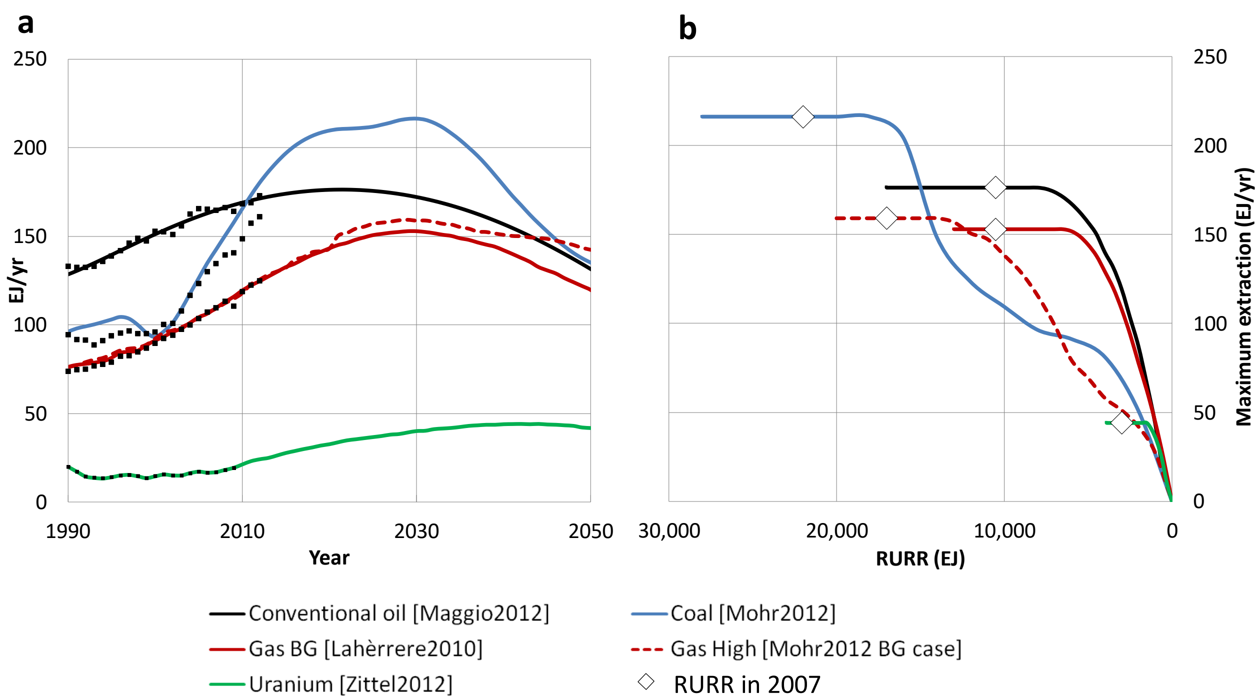

Figure 22 : (Capellán-Pérez et al., 2014): Non-renewable primary energy resources availability: (a) depletion curves as a function of time from the original reference; (b) curves of maximum extraction in function of the RURR as implemented in the model. The y-axis represents the maximum achievable extraction rate (EJ/year) in function of the RURR (EJ). For each resource, the extreme left point represents its URR. 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 RURR in 2007 for each resource is represented by a rhombus.

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 found in the literature by fuel together with a brief discussion: oil (section 0), natural gas (section 0), coal (section 0) and uranium (section 0). 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).

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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 additional constraint that limits the maximum annual growth extraction rate to avoid unrealistic growth extraction rates (see section **¡Error! No se encuentra el origen de la referencia.**).

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2.3.3.2. Literature review of depletion curves by fuel

The following subsections review the depletion curves of non-renewable energy resources found in the literature by fuel together with a brief discussion: oil (section 0), natural gas (section 0), coal (section 0) and uranium (section 0). See also (Wang et al., 2017) for a recent and comprehensive review. Additionally, the projections from the World Energy Outlook "Current Policies scenario" (WEO, 2012), essentially following the energy demand-driven paradigm, are represented for comparison.

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2.3.3.2.1. Oil

Figure 23 shows the depletion curves for oil found in the literature compared with the projection of the Current Policies Scenarios of the IEA (WEO, 2012). Due to the lack of standardization, we have collected projections from solely conventional oil to total oil (ie., including unconventional oil). Among the depletion curves, the main foreseen trend is that global oil extraction will reach a peak followed by an irreversible decline in the next years (e.g. (ASPO, 2009; EWG, 2013, 2008; Laherrère, 2006; Maggio and Cacciola, 2012)), whereas few estimates find profiles that follow an undulating plateau (Aleklett et al., 2010; Skrebowski, 2010). Analyses do not expect to substantially exceed the maximum of 90 Mb/year. In turn, only the IEA estimates that future oil extraction will be growing by the year 2035. The estimate of Laherrère (Laherrère, 2006) applying logistic models is the highest and exceeds the historic data since about 2005, although it is the most accurate in relation to the most recent data of total oil extraction.[5] Aleklett et al., (2010) critically assessed the global oil production forecast of the IEA's WEO (2008), producing an alternative estimate by introducing correction factors to account for geological factors not included in the report. Maggio & Cacciola (2012) provide three estimates associated to three different URR levels; its lower projection is similar to that of ASPO (2009). EWG projections are the most pessimistic among the set analysed, projecting a step decline from the date of the assessment.

[5] It is noteworthy that the last published projection from J. Laherrère from May 2015 (http://aspofrance.viabloga.com/files/JL%5fHubbertlineraization24May) is very much alike to that of the year 2006.

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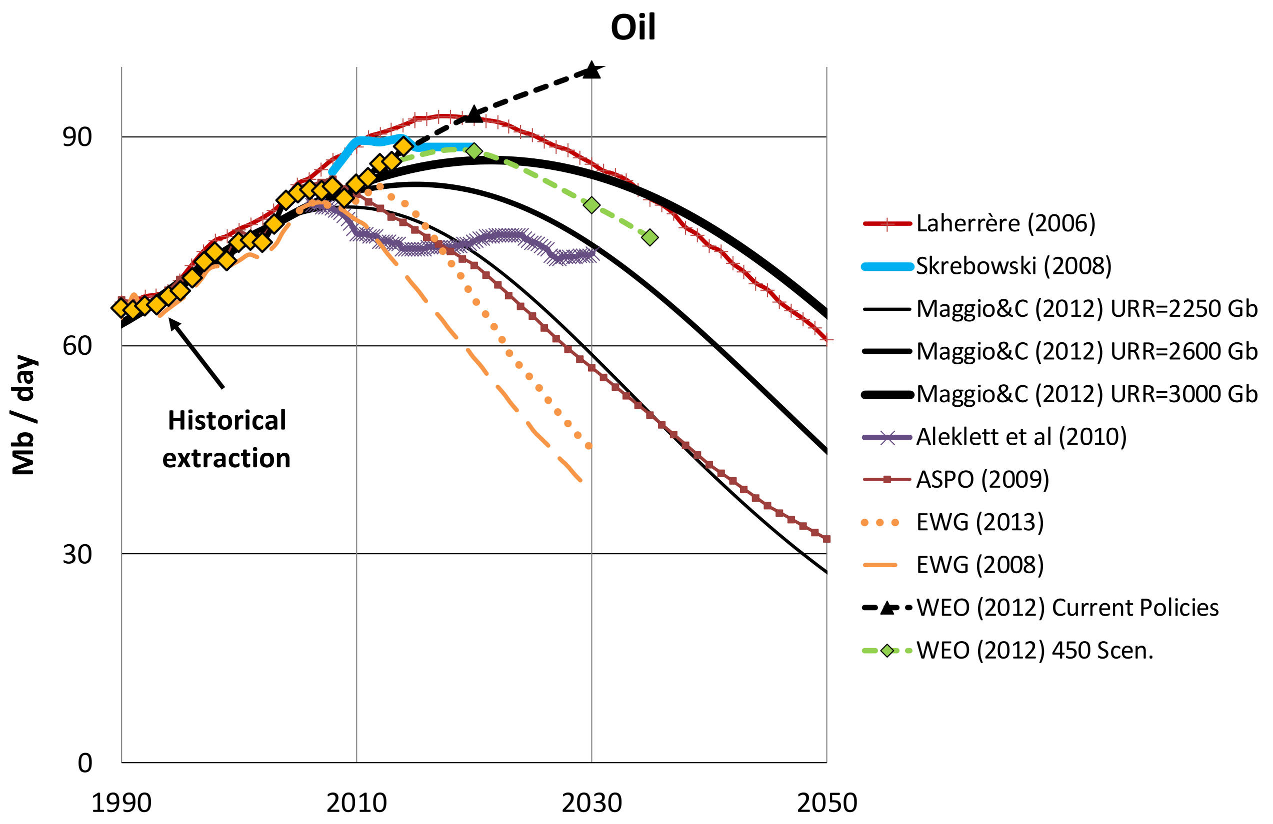

Figure 23: Depletion curves for oil by different authors and comparison with (WEO, 2012) scenarios "Current Policies" and "450 Scenario". Historical data (1990-2014) from BP (2015). There is a lack of standardization in the literature. For each study, "oil" refers to only crude oil (including NGLs) (Maggio and Cacciola, 2012); crude and unconventional (ASPO, 2009; EWG, 2013, 2008); crude, unconventional and refinery gains (Aleklett et al., 2010; Skrebowski, 2010; WEO, 2012); crude oil, unconventional, refinery gains and biofuels (Laherrère, 2006); finally (BP, 2015) historical data (1990-2014) include crude oil, shale oil, oil sands. (Aleklett et al., 2010) adjust the total volume to the energy content since 1 barrel of NGL contains in reality 70% of the energy of an oil barrel.

While the estimations for conventional oil tend to converge for similar patterns, the highest uncertainty is on the future development of unconventional oil (Mohr and Evans, 2010). Its main issue is that what extent technological improvements will be able to compensate the fact that, due to the viscosity and physical properties of unconventional oils, pumping becomes more energy consuming and slower. As an example, Mohr et al (2015) analyze 3 scenarios with (very) different RURR levels (see Figure 24). Although the numbers vary at the end of the century, the difference in extraction levels in 2050 between the highest and the lowest case is just around 20% (54 vs 66 EJ/yr). However, given the current obstacles to the global-scale deployment of unconventional oil even Mohr et al (2015)'s lower scenario may prove too optimistic (Murray, 2016).

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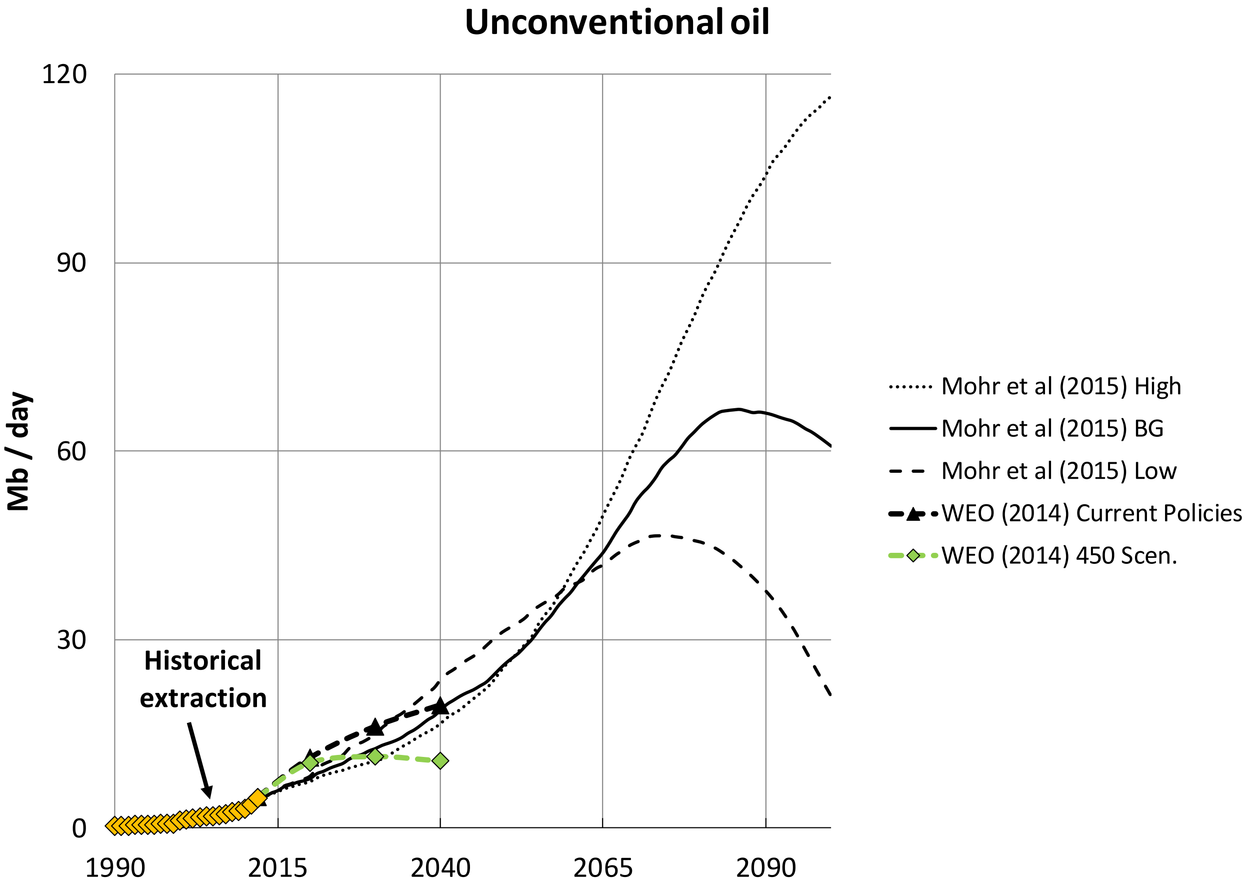

Figure 24: Depletion curves for unconventional oil from Mohr et al. (2015), WEO (2014) projections and historical extraction (1990-2012) from Mohr et al (2015).

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2.3.3.2.2. Natural gas

Figure 25 shows the results of collecting estimates for total natural gas (ASPO, 2009; Laherrère, 2010; Maggio and Cacciola, 2012; Mohr, 2012; Mohr et al., 2015; Mohr and Evans, 2011) compared with the projection of the Current Policies Scenarios of the IEA (WEO, 2012). We observe that ASPO (2009)'s projection for the last years is below recent historical data of extraction, and coincides with the lower case from Maggio & Cacciola (2012). Maggio & Cacciola (2012) found that, for different RURR levels, the maximum extraction rate would not trespass 140 TCF/year, reaching its peak before the mid-century. Mohr (2012)'s projections for natural gas (which are very similar to Mohr and Evans (2011)'s), offer a wide range between their "low case" and "best guess", although both depict a peak at around 2025-2030 between 130 and 150 TCF/year. Lahèrrere's (Laherrère, 2006) estimate broadly falls between Mohr (2012) two lower cases, although with a greater steepness after reaching the peak. The "high case" from Mohr (2012) assumes that very large amounts of unconventional gas (coal bed methane, shale gas and tight gas) will be available in the future (RURR of 11 ZJ) in comparison with the other estimates (e.g. RURR of 2.1 ZJ considered by Lahèrrere (Laherrère, 2006)). Mohr et al (2015) updated Mohr (2012)'s analysis, including methane hydrates and updating the RURR for different types of unconventional gas. As a result, the RURR for total natural gas was substantially increased in the best guess (+55%) and high scenarios (+70%). Both cases (as well as the high case from Mohr (2012)) reach maximum extraction levels that are well above the range of the rest of forecasts. These are the only cases which the projections of the IEA are consistent with. Mohr et al BG (2015) reaches a plateau at around 180 TCF/year that lasts several decades, while the high scenario assumes that natural gas extraction might increase during the next decades until a maximum extraction close to 300 TCF/yr around 2075.

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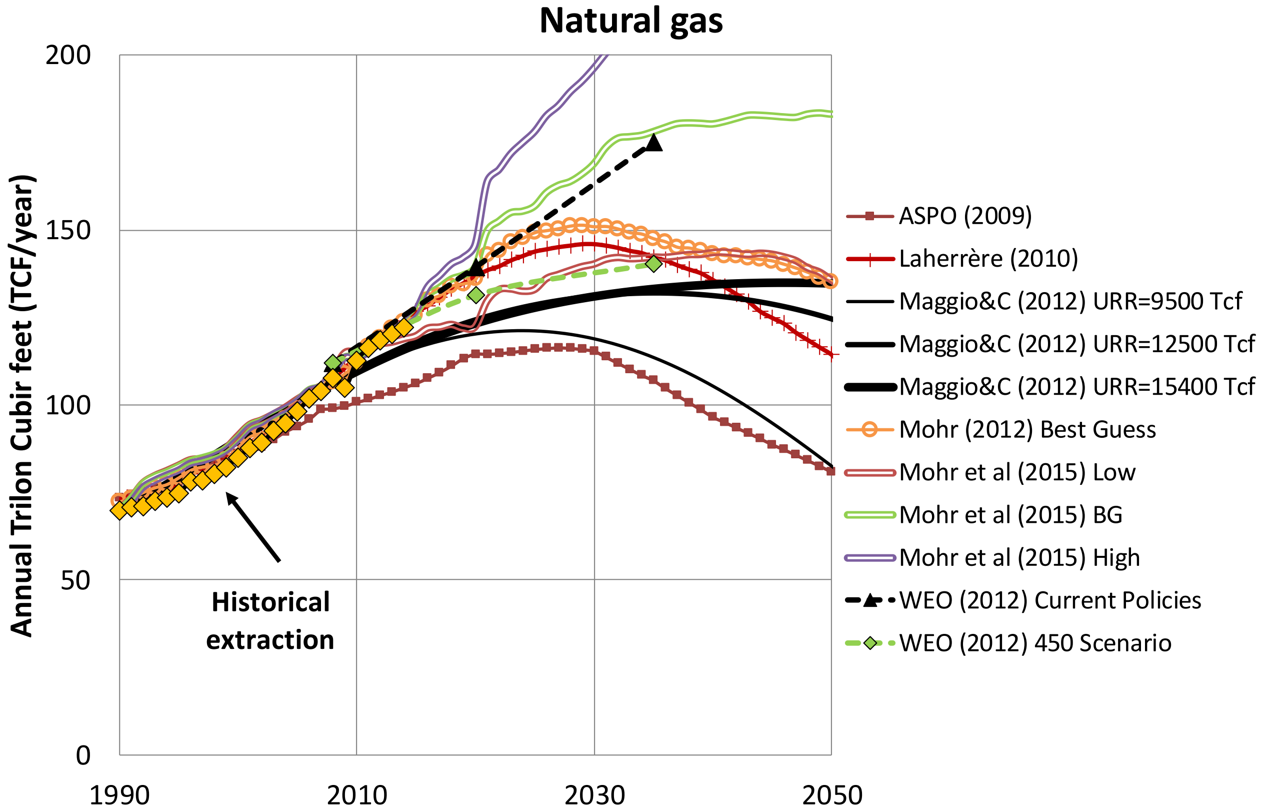

Figure 25: Estimations of total natural gas extraction by different authors and comparison with (WEO, 2012) scenarios “Current Policies” and “450 Scenario”. Historical data (1990-2014) from BP (2015).

As for unconventional oil, few studies have focused on unconventional gas. Figure 26 shows the low, best guess and high depletion curves from Mohr et al (2015).

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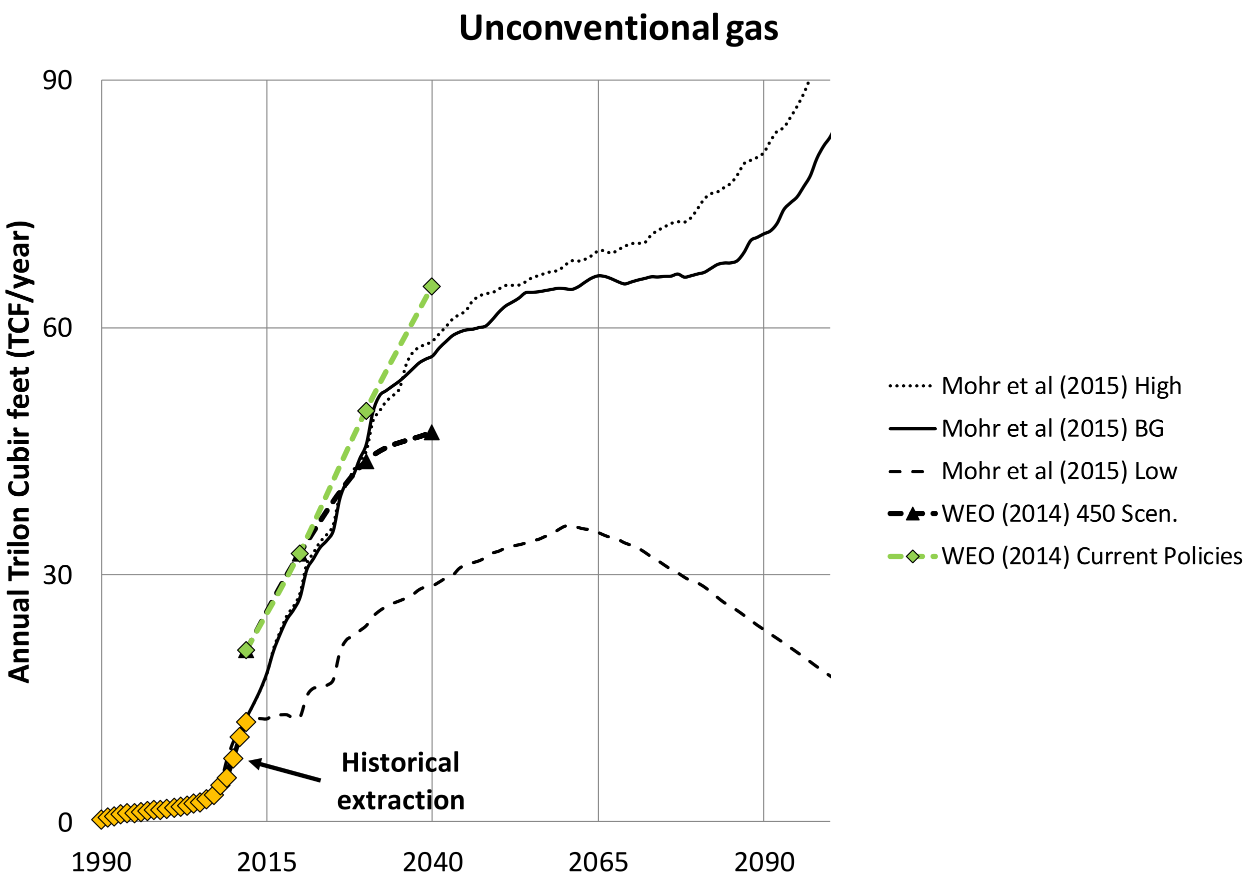

Figure 26: Estimations of unconventional natural gas extraction from Mohr et al (2015), WEO (2014) projections and historical extraction (1990-2012) from Mohr et al (2015).

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Natural gas energy content per volume

Gas reserves are usually reported in volume units (e.g. tcf[6]). However, and similarly to oil, different agencies apply different energy equivalence attending to different composition of the gas, etc.

Table 11: Equivalence between volume and energy applied by different agencies and authors. *Equivalence used by de Castro (2009).

	Original conversion given	1 bcf in Mtoe
(ASPO, 2009)	1 bcf = 166 Mboe	22.1
(EIA US, 2014, chap. Appendix G)	1 cf = 1,022 Btu	25.8
(BP, 2013)*	324.6 bcf = 3,034 Mtoe	25.6
(IEA, 2013)	3,435 tcm = 2,787 Mtoe	23.0
(Mohr and Evans, 2011)	133 tcf = 140 EJ	25.1

In this model we have adopted the equivalence from the *US Energy Information Administration*.

6 tcf: trillon cubic feet, that equals 10^3 bcf (1e9 cf).

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2.3.3.2.3. Coal

Coal is usually seen as a vast abundant resource however there are large uncertainties related to the available resource base due to the lack of robust global estimates. Recent studies are pointing to potentially large overestimates in coal resource assessments as geologists uncover restrictions on the coal that is extractable. In fact, scenarios in IPCC assessments use a coal backstop as the conceptual basis for business-as-usual projections with a strong carbon signal (Capellán-Pérez et al., 2016b; Ritchie and Dowlatabadi, 2017).

Figure 27 shows the different estimates for coal production that have been collected from the literature (EWG, 2013, 2007; Höök et al., 2010; Maggio and Cacciola, 2012; Mohr, 2012; Mohr et al., 2015; Mohr and Evans, 2009; Patzek and Croft, 2010). The first remark is that most of the proposed depletion curves are not consistent with the recent surge in coal extraction globally. In fact, most of the studies are based on logistic curves similar to the ones used for oil. The liquid nature of oil makes fast extraction in mature fields impossible, no matter how much infrastructure is used. Coal is a mineral and, therefore, more infrastructure and extraction effort can replace the low quality of the resource. If the maximum extraction is higher, this means that, with the same amount of resource, the curve goes up more and then goes to zero faster (EWG, 2013, 2007; Höök et al., 2010; Maggio and Cacciola, 2012; Patzek and Croft, 2010). On the other hand, the analyses by Mohr and Evans (2009), Mohr (2012) and Mohr et al (2015) are based on a modelling methodology taking into account the particularities of solid mined resources.

Since different types of coal exist with different thermal equivalent (e.g. lignite, hard coal, etc.), we take the average value of the last 30 years as reported by (BP, 2013): 1Mt = 0,4844 Mtoe, as done by other studies (e.g.(Höök et al., 2010)).

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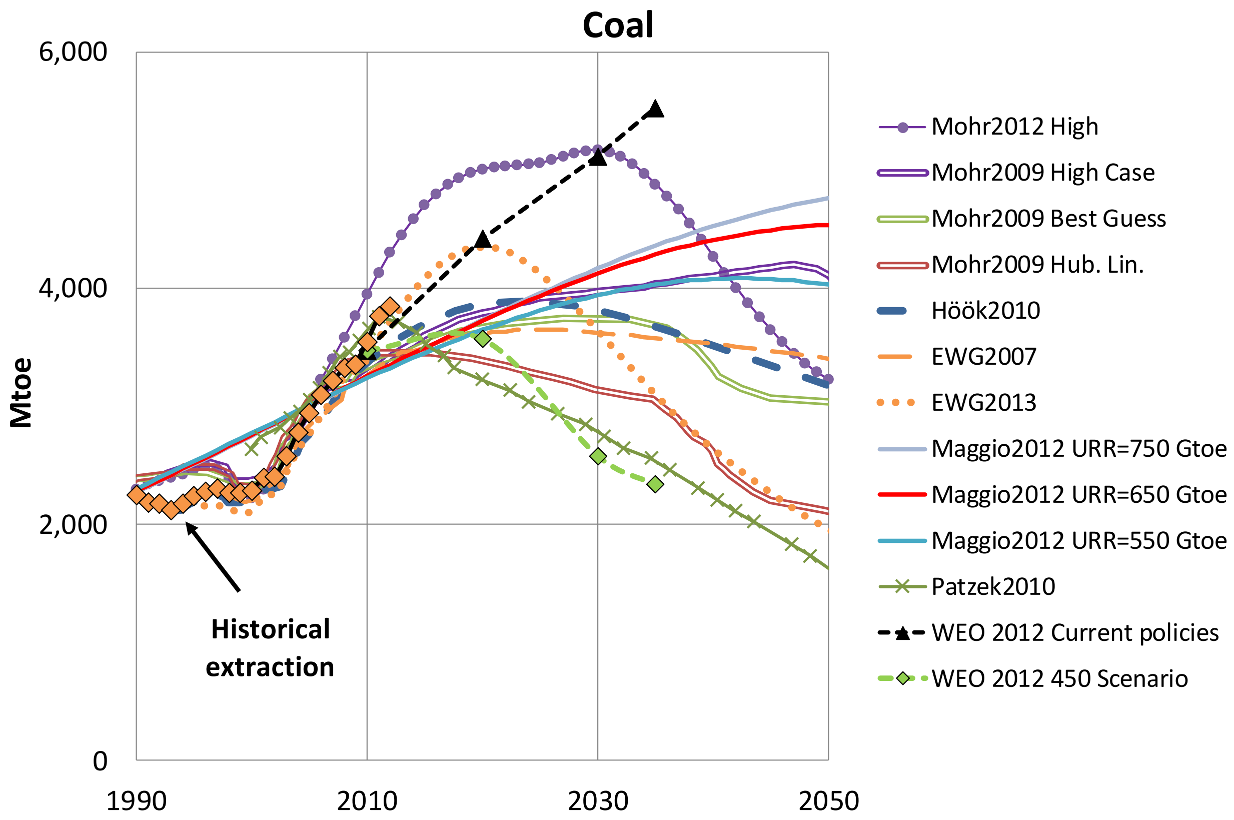

Figure 27: Estimations of coal extraction by different authors and comparison with (WEO, 2012) scenarios "Current Policies" and "450 Scenario". Historical data (1990-2014) from BP (2015). (1 Mt = 0.4844 Mtoe (Höök et al., 2010)).

Figure 28 represents the stock and flow diagram of coal extraction to illustrate the modelling of non-renewable energy resources extraction. "RURR coal" is the main stock, and "extraction coal EJ" is the main flow, which is compared with the "Total demand coal EJ".

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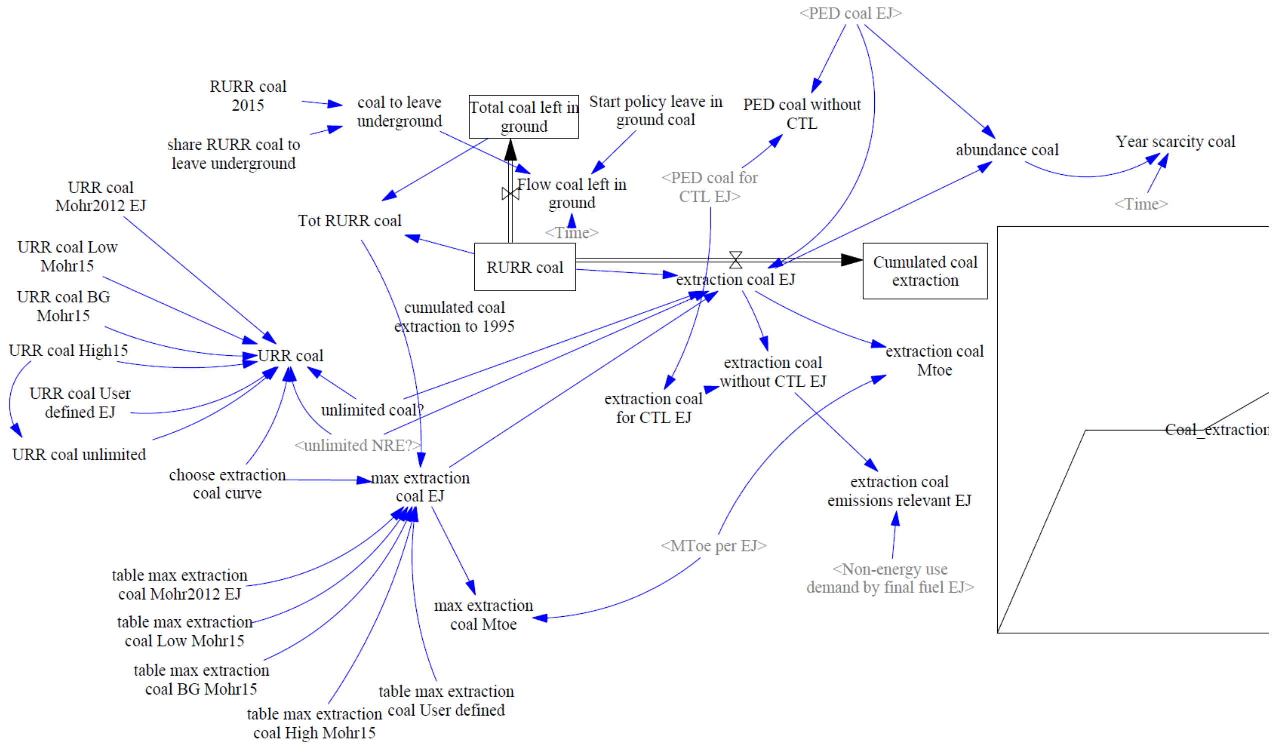

Figure 28: Stock and flow map diagram of coal extraction.

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2.3.3.2.4. Uranium – nuclear fuels

Figure 29 shows the uranium depletion curves found in the literature, which are in fact produced by the same research team (EWG, 2013, 2006; Zittel, 2012). In the most recent study (EWG, 2013) applies the most recent data from the Nuclear Energy Agency (NEA): individual country-specific extraction profiles are obtained, derived by mine-by-mine analysis of reserves and production. Especially for Kazakhstan the proposed time schedules for new mine openings is implemented. The reserves however have been adjusted by including uranium mining and preparation losses, depending on the extraction methods. In extreme cases these amounted up to 30% (personal communication).

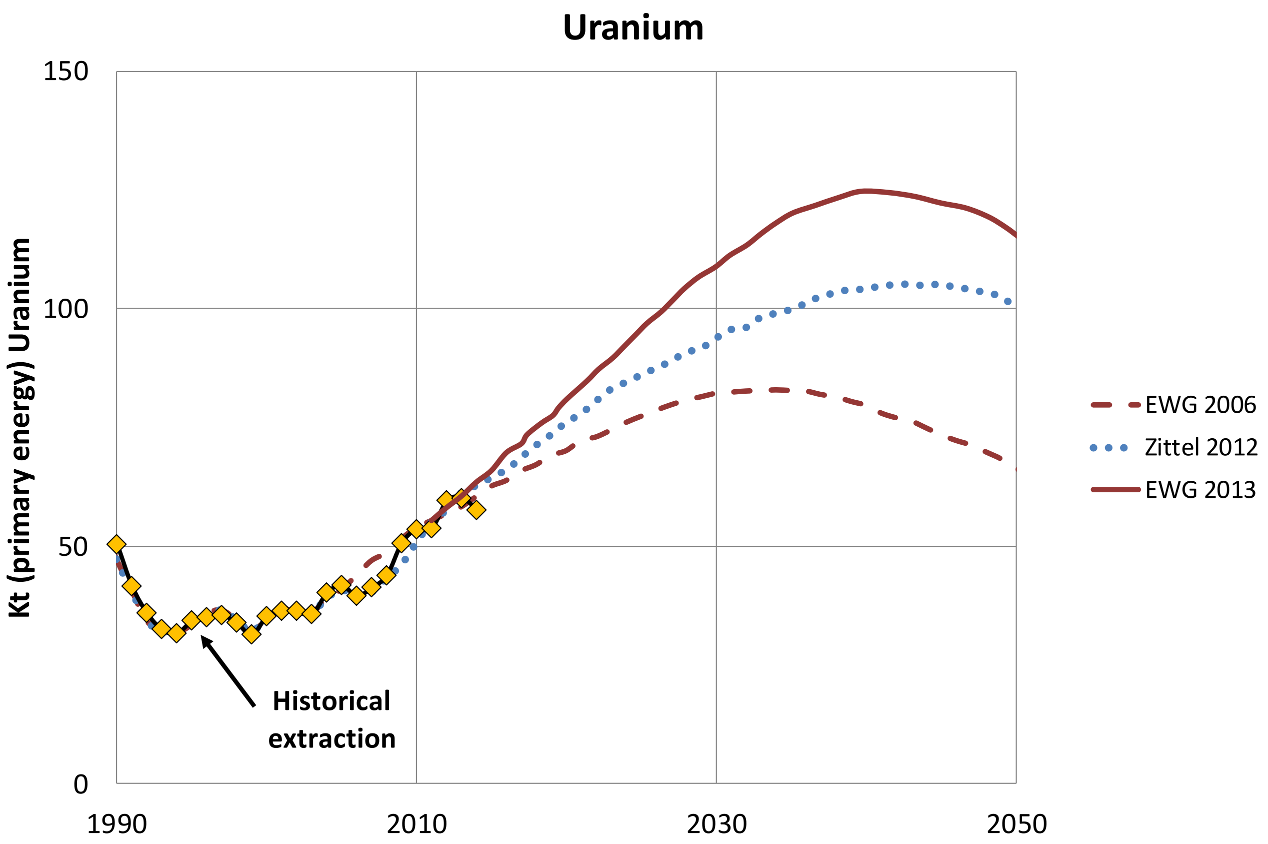

Figure 29: Estimations of uranium extraction by different authors. Historical data (1990-2014) from WMD (2016); conversion from kt U3O8 to ktU following EWG (2006).

The reduction of net energy production of nuclear power plants as a function of the decreasing ore grade of uranium are thus implicitely taken into account in the analysis by the URR level (Van Leeuwen and Smith, 2008; van Leeuwen, 1985).

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2.3.3.3. Depletion curves available in MEDEAS

Table 12 collates the depletion curves and their respective URR level available in MEDEAS. Note that all curves are in energy terms (neither volumes nor mass).

Table 12: Depletion curves of non-renewable energy resources implemented in MEDEAS. The depletion curves applied in Capellán-Pérez et al. (Capellán-Pérez et al., 2014) are marked with an asterisk (*). Note that an exogenous constant growth was assumed for unconventional oil in Capellán-Pérez et al. (Capellán-Pérez et al., 2014). Tb: terabarrels (1012 barrels); RAR: reasonably assured resources; IR: Inferred resources; NEA: Nuclear Energy Association.

Resource		Reference	Description	URR	
				(Mass)	(ZJ)
Oil	Total	(Laherrère, 2006)	Hubbert method (2,000 Gb of conv. + 1,000 Gb of unconv.)	3 Tb	16.7
	Conv.	(Maggio and Cacciola, 2012) [low; middle; high*]	Hubbert method	[2.3; 2.6; 3] Tb	[12.6; 14.5; 16.7]
	Unconv.	(Mohr et al., 2015) [low; BG; high] cases	Mining model extraction	[2.5; 2.7; 3.8] Tb	[5.8; 10.5; 22.1]
Natural gas	Total	(Laherrère, 2010)*	Hubbert method ("creaming curve")	13,000 tcf	13.6
		(Mohr, 2012) best guess*	Mining model extraction (12,900 tcf of conv. + 7,200 tcf of unconv.)	19,100 tcf	19.9
	Conv.	(Mohr et al., 2015) [low; BG; high] cases	Mining model extraction	[11.6; 13.8; 23.6] tcf	[11.1; 13.1; 22.5]
	Unconv.	(Mohr et al., 2015) [low; BG; high] cases	Mining model extraction	[2.9; 15.4; 25.3] tcf	[2.8; 14.7; 24.2]
Coal		(Mohr, 2012) high case*	Mining model extraction.	670 Gtoe	27.8
		(Mohr et al., 2015) [low; BG; high] cases	Mining model extraction.	[660; 1160; 1720] Gtoe	[14.5; 22.4; 31.6]
Uranium		(Zittel, 2012)*	Hubbert method, considering RAR (<260 $/KgU) and IR of NEA (2011)	8,900 ktU	3.7
		(EWG, 2013)	Hubbert method, considering RAR (<260 $/KgU) and IR of NEA (2012)	9,700 ktU	4.0

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For comparison, the meta-analysis of non-renewable energy resource estimates performed by (Dale, 2012) that review over 300 studies obtained the following URR values as medians: 13.2 ZJ (conventional oil), 10.5 ZJ (conventional gas) and 24.8 ZJ (coal). Thus, we are assuming values in the upper range of the literature. The studies that focus on non-conventional resources are much less abundant and (Dale, 2012) did not report significant statistical results.

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2.3.3.4. Constraints to the (growth) extraction of unconventional fuels

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 additional constraint that limits the maximum annual growth extraction rate to avoid unrealistic growth extraction rates.

Unconventional oil

As in the previous version of the model, we consider a "Best Guess" case, extrapolating the +4.5% annual growth past trends and an optimistic "High Case" of +6.6% annual growth as estimated by (Grushevenko and Grushevenko, 2012; Söderbergh et al., 2007). This assumption is consistent with the annual growth from the depletion curves projected by Mohr et al. (2015) for unconventional oil. Figure 30 shows that, after an initial very high growth extraction rate, the growth stabilizes at lower levels for the three scenarios (low, BG, high) at between +2.5 and +5% to 2050.

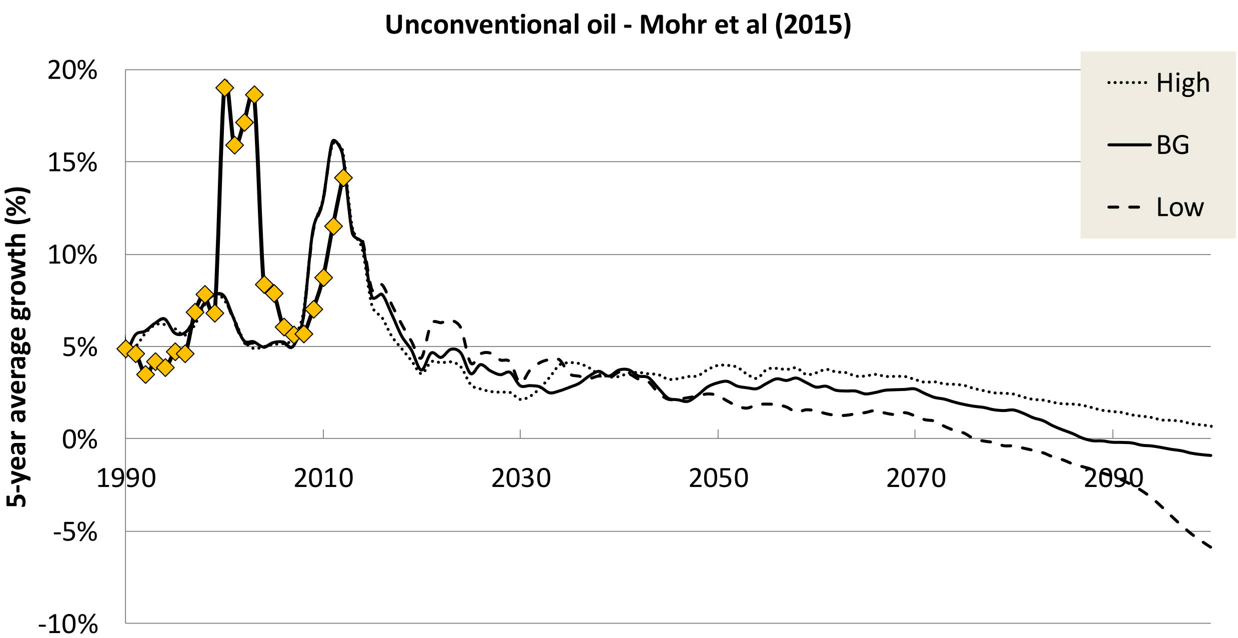

Figure 30: 5-year average growth (%) of unconventional oil for the high, BG and low scenarios from Mohr et al (2015). Historical extraction (1990-2012).

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Unconventional gas

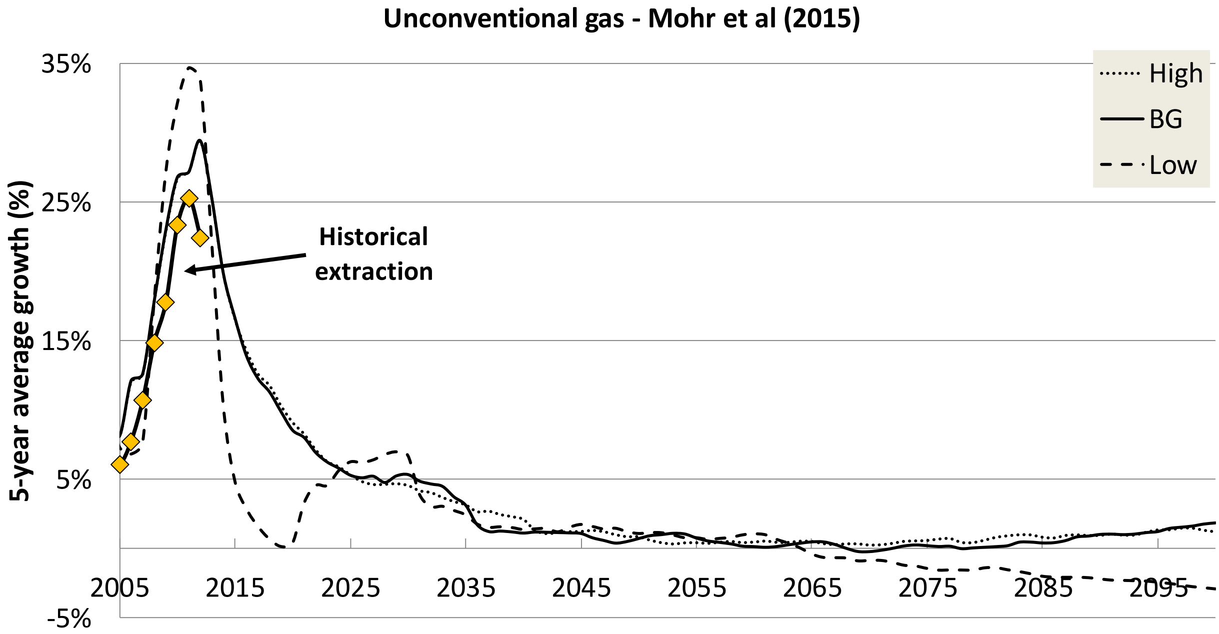

Figure 31: 5-year average growth (%) of unconventional gas for the high, BG and low scenarios from Mohr et al (2015). Historical extraction (1990-2012).

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2.3.3.5. CTL and GTL

CTL (*Coal-to-Liquids*) and GTL (*Gas-to-liquids*) refer to the transformation of coal and gas into liquid hydrocarbons. Different technologies currently exist,[7] mostly based on the Fisher-Tropsch process. However, all are characterized by low efficiencies: GTL conversion technologies are around 55% efficient and coal conversion between 27-50% (Greene, 1999; Höök and Aleklett, 2010; IPCC, 2007a). Their current production is exiguous: less than 0,3 Mb/d in 2014 (IEA, 2018). Usually growth projections from international agencies are relatively modest (e.g. +11%/yr for GTL in the *New Policies Scenario* of (WEO, 2012)), due to their high cost and the common assumption that no significant liquids/oil restrictions will exist in the scope of their projections. MEDEAS reacts to an eventual liquid scarcity by boosting these sources of energy.

CTL faces compelling challenges that limit its potential to significantly deploy at global level: very high capital costs (financing CTL projects can be difficult unless public incentives and subsidies are provided), a very low efficiency, significant related environmental impacts (Höök et al., 2013). In fact, the recent published works a considerable reduction in planned CTL plant capacity (Höök et al., 2013; WEO, 2012). Moreoever, any new CTL plant that would be planned to be built outside of South Africa (only country where the technology can be considered as mature) may behave more like an early mover (i.e. the cost penalty was estimated in more than a 50% (Williams et al., 2009)).

There are many ways to liquefy natural gas, and several pilot plants, trial projects and research initiatives exist. However, only two companies – Sasol and Shell – have built large scale commercial plants (>5,000 b/d capacity). The GTL industry is currently essentially immature and many important patents are held by relatively few companies (Wood et al., 2012). Unlike CTL plants, the construction and operation of large scale GTL plants is now a reality, with increasing momentum. After the experiences of Sasol's Mossgas GTL plant in South Africa and Shell’s Bintulu plant in Malaysia the first decade of the 21st century has witnessed the construction and start of the Oryx 34,000 b/d GTL plant and the Pearl 140,000 b/d plant, both in Qatar. Moreover, a 34,000 b/d GTL plant was built in the Escravos region in Nigeria and started its operation in summer 2014. From 2000, the average global growth trend has been slightly over +16% per year (IEA, 2018).

[7] It can be achieved through either coal gasification into syngas (a mixture of hydrogen and carbon monoxide), combined using the Fischer-Tropsch or methanol-to-gasoline synthesis process to produce liquid fuels, or through the less developed direct-coal liquefaction technologies in which coal is directly reacted with hydrogen (WEO, 2012).

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CTL and GTL are modelled as exogenous growth technologies, the annual growth in installed capacity can be selected from the user. Given the high GHG emissions of these processes, in MEDEAS there are not considered as a suitable substitutes for oil liquids.[8]

2.3.3.6. Waste-to-energy

Industry and municipal waste (renewable and non-renewable) are aggregated in the same category. In the period 1995-2014 its TPES has doubled surpassing 2 EJ by 2014 (+4.5% annual growth) (IEA, 2018). However, from a sustainable and social point of view, waste-to-energy is the the worse option in terms of residues management. This 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 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, 2018).

[8] In WoLiM, for example, a crash program is activated when there is scarcity of liquids (Capellán-Pérez et al., 2017b, p. 5).

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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 concern is 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 relation to their integration in the electricity mix due to their intermittency, seasonality and uneven spatial distribution requiring storage (Lenzen, 2010; Smil, 2008, p. 362; Trainer, 2007), their lower energy density (de Castro et al., 2014, 2013b, 2011; Smil, 2008, pp. 383–384), most have lower EROI than fossil resources (Prieto and Hall, 2013), their dependence on minerals and materials for the construction of power plants and related infrastructures that pose similar problems than non-renewable energy resources depletion (de Castro et al., 2013b; García-Olivares et al., 2012), and their associated environmental impacts (Abbasi and Abbasi, 2012; Danielsen et al., 2009; Keith et al., 2004; Miller et al., 2011), which all together significantly reduce their sustainable potential (Capellán-Pérez et al., 2014; de Castro et al., 2014, 2013b, 2011; Smil, 2008; Trainer, 2007).

In this section we discuss the techno-ecological potential of renewable energies considered in the model. Special attention is devoted to the land requirements of RES technologies given that the transition to RES will intensify the competition for land globally (e.g. (Capellán-Pérez et al., 2017a; Scheidel and Sorman, 2012)), in a context where the main drivers of land-use are expected to continue to operate in the next decades: population growth, urbanization trends and shift to more land-intensive diets (FAO, 2009; Kastner et al., 2012; Smith et al., 2010). RES from bioenergy can be used to obtain heat, biofuels and electricity. Section 0 focus on bioenergy, which can be used for generating heat and electricity, as well as producing biofuels. Section 2.3.4.2 refers to other RES for heat other than biomass (solar thermal and geothermal for heat). Section 0 focuses on the assumptions related to the RES for electricity generation. Finally, section 0 documents how MEDEAS takes into account the intermittency of variable RES.

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2.3.4.1. Bioenergy

Biomass is globally limited by a total terrestrial net primary productivity of roughly 60 TW (humans already appropriate indirectly 20-50% in an unsustainable way (Cramer et al., 1999; Haberl et al., 2013, 2007; Imhoff et al., 2004; Imhoff and Bounoua, 2006; Smil, 2008; Vitousek et al., 1986)). Bioenergy provides approximately 10% of global primary energy supply and is produced from a set of sources (dedicated crops, residues and Municipal Solid Waste (MSW), etc.) that can serve different uses (biofuels, heat, electricity, etc.), although traditional biomass use dominates. We model bioenergy in 4 main categories: traditional biomass, conventional solid biomass, dedicated crops and residues.[9] Peatlands[10] are the most efficient terrestrial ecosystems in storing carbon. Degradation of peatlands is a major and growing source of anthropogenic greenhouse gas emissions. Peatlands are important natural ecosystems with high value for biodiversity conservation, climate regulation and human welfare (Parish et al., 2008). For these reasons, MEDEAS does not considered this energy source will contribute to a sustainable energy mix in the future.

Since bioenergy can be used for different final uses (heat, electricity, solids, biofuels), a number of assumptions in relation to the use of the potential need to be made to run MEDEAS.

[9] 4th generation (algae) is not considered due to the high uncertainties of the technology and the long-term of its eventual commercial appearance (Janda et al., 2012). Moreover, preliminar tests show that capturing CO2 by microalgae to produce biodiesel has 2.5 times higher GWP than fossil diesel with other environmental impacts also significantly higher (Cuéllar-Franca and Azapagic, 2015).

[10] Peatlands are wetland ecosystems that accumulate plant material to form layers of peat soil up to 18 meters thick. They can store, on average, 10 times more carbon dioxide (CO2), the leading greenhouse gas, than other ecosystems. As such, the world's peat bogs represent an important "carbon sink"—a place where CO2 is stored below ground and can't escape into the atmosphere and exacerbate global warming. When drained or burned, however, peat decomposes and the stored carbon gets released into the atmosphere.

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2.3.4.1.1. Uses of bioenergy

1- Traditional biomass: It is the biomass used by large populations in poor-countries. There is much uncertainty around the amount of traditional biomass currently used (IEA, 2014): WEO (2010) estimates that 2.5 billion people used 724 Mtoe in 2008, while WBGU (2009) cites 47 EJ (i.e. 1,120 Mtoe). We asume the consumption ratio constant over time (0.29 toe per capita). The demand of traditional biomass in MEDEAS is driven by the demand of solids by the households (IOTs).

2- Conventional solid biomass refers to modern uses of solid biomass for heat and electricity, excluding plantations in marginal lands and residues, i.e. mainly from tree plantations. Since current conventional modern bioenergy use for heat and electricity (18+4 EJ/yr harvestable NPP respectively (IEA, 2018; REN21, 2016)) already surpasses sustainable levels (de Castro et al., 2013a; Foley et al., 2005; GFN, 2015; Pimentel, 2006), we (optimistically) assume that in the future better practices could be adopted allowing to increase the sustainable potential to 25-30 EJ/yr (NPP harvestable). An eventual reduced dependence on traditional biomass in the next decades might also allow to use bioenergy resources in a more sustainable way, although this would be limited by the fact that most of the traditional biomass is infact extracted in an unsustainable way.

3- Dedicated crops in marginal lands and land subject to competition with other uses. Marginal land use refers to lands whose use does not reduce food security, remove forests or endanger conservation lands (Field et al., 2008). We assume that these dedicated crops for bioenergy will be mainly used for biofuel production as it currently the case (2nd -current bioethanol and biodiesel) and given that previous work found that liquids would likely be the first final energy source to face scarcity (e.g. (Capellán-Pérez et al., 2014)). It is assumed that the 3rd generation biofuels (cellulosic) do not require additional land, but instead substitute the 2nd generation when the technology is available at a rate depending on the scenario. We assume an improvement of +15% in the power density in relation to the 2nd generation (WBGU, 2009).

4- Residues (agricultural, forestry, municipal, industry, etc.). Currently, only biogas and MSW[11] exist at commercial level. Biogas potential is assumed to focus on the promotion of small plants for agricultural and industrial residues, as well as animal dung which provide major ecological co-benefits (WBGU, 2009). Current final use share and efficiencies are assumed constant given its past evolution. The 3rd generation biofuels (cellulosic) are still in R&D and doesn't appear in the standard

[11] Waste includes industrial and municipal (both renewable and non-renewable) waste is modelled separately in MEDEAS given that the production of energy is the less sustainable use of waste (see section **¡Error! No se encuentra el origen de la referencia.**).

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version of the model before 2025 as suggested by the literature (Janda et al., 2012). By-default, residues potential are assigned mostly (75%) for generating heat and electricity, as it currently happens (IPCC, 2007a, 2007b), the rest being used for biofuels production (although this parameter can be modified by the user). There is currently a controversial debate about the potential of the valuation of agricultural and forestry residues, because of its threat to soil fertility preservation in the long run, biodiversity conservation and ecosystem services (Gomiero et al., 2010; Wilhelm et al., 2007). We take the estimation of WBGU (2009) of 25 EJ NPP taking into account economic restrictions. However, it should be kept in mind that that this potential will tend to be progressively degraded by time.

Next section 0 focuses on the followed assumptions to model dedicated crops for biofuels in MEDEAS given the complexities and detailed modelled in MEDEAS.

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2.3.4.1.2. Dedicated crops

The approach followed in MEDEAS to estimate the techno-ecological potential of marginal lands and dedicated crops is to exogenously set a potential land availability (hectares) for each category, and subsequently derive the energy potential taking into account the corresponding power density. For those technologies that currently do not exist at commercial level, we assume that their output in the first years will follow the historic deployment rates of the take-off of 2nd generation biofuels during the period 2000-2014.

The estimation of land availability for each category is a sensitive and difficult task. The foreseeable additional demand of land for food for the next few decades (due to population and affluence growth) is projected to be 200–750 MHa (Balmford et al., 2005; FAO, 2003; Rockström et al., 2007; Schade and Pimentel, 2010), while the projected growth of new infrastructures because of population and affluence growth is more than 100 MHa. Humans also use biomass for other uses such as livestock feed (including grazing), fibre, material, etc. Currently there is a worldwide rush for land, (around 1.7% of agricultural area has been reported to have been bought or rented for long periods of time since the year 2000 (Anseeuw et al., 2012)). Moreover, it is estimated that current and future crop yields will be affected negatively by climate change (IPCC, 2014a), offsetting potential productivity gains from technological innovation. According to FAOSTAT, there were 1,526 MHa of arable land and permanent crops in 2011 (FAOSTAT, 2015).

However, the new land that we could convert to agriculture is 200-500MHa (FAO, 2009; Schade and Pimentel, 2010), or 386MHa in a sustainable way, converting abandoned agricultural land (Campbell et al., 2008; Rockström et al., 2009). This means that it may be not possible to meet the current trends of demand for food if the degraded land continues to grow, as more than 350MHa will be lost if present trends continue (Foley et al., 2005; Pimentel, 2006). Simultaneously, a recent review found that <2ºC stabilization scenarios in IAMs require a range of 380-700 MHa by 2100 for BECCS (considering high-productivity dedicated energy crops), which represents 7–25% of current global agricultural land, and 25–46% of arable plus permanent crop area, a range of land demand which is the magnitude order than land identified as abandoned or marginal (Smith et al., 2016). However, the deployment of such vast amounts of bioenergy crops faces biophysical constraints due to the requirement of large areas, high fertilizer and water use, and that likely compete with other vital land uses such as agriculture of biodiversity conservation (Fuss et al., 2014; Scott et al., 2013; Smith, 2016). In the light of these facts and considering that currently almost 15% of the world population is undernourished (FAO, 2012), a very large surface for bioenergy (or other land-intensive RES such as solar, see section 0) at global level is not compatible with sustainable future scenarios.

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Two types of land availability for bioenergy are taken into consideration depending on the competition with other uses:

- **Marginal lands**: they do not imply a competition with current crops or biodiversity conservation. The model considers the analysis from Field et al., (2008) who find that 27 EJ of NPP can be extracted from 386 Mha of marginal lands avoiding the risk of threatening food security, damaging conservation areas, or increasing deforestation. They expect that the average NPP in biomass energy plantations over the next 50 years is unlikely to exceed the NPP of the ecosystems they replace.
- **Land subject to competition with other uses**, which is to be defined exogenously by each scenario. We consider that only the dedicated crops would require additional land. Related to the gross power density of 2nd generation biofuels under land competition, we will consider as reference the world average value given by (UNEP, 2009) based on real data (36 Mha occupied for 1,75 EJ in 2008) that estimates at 0,155 W/m2. Assuming a similar energy density for current production, almost 60 MHa are nowadays used (BP, 2016). However, the real occupied surface might substantially higher given that the methodology applied by the UNEP is conservative (see (de Castro et al., 2013a)), this number might in fact be closer to 100 MHa.

In relation to the potential land for dedicated crops for bioenergy, taking into account the future land requirements for food, urbanization and biodiversity conservation, the scenarios implemented in MEDEAS standard version take two values: (1) roughly two-fold present occupation (taking as reference the conservative estimate) for the standard scenario (100 MHa) and (2) a high scenario considering up to 200 MHa (see Table 13). However, these values can be changed when implementing a customized scenario: for example (Doornbosch, 2007) estimates in 440 MHa the additional land potentially available for biofuels (mainly in Latin America and Africa). As a reference, since 2000 the area from Southern countries that has been bought or long-term rented by trasnationals and investment funds has been estimated to surpass 80 MHa (Anseeuw et al., 2012). In any case, it should be highlighted that from a net energy perspective, biofuels are far from contributing positively to the society, with typical EROI levels in most of the globe below 2:1 (de Castro et al., 2013a) (see section **¡Error! No se encuentra el origen de la referencia.**).

Figure 32 represents the Forrester diagram of the 2^{nd} and 3^{rd} generation biofuel production in land competing with other uses, as well as the biofuel production in marginal lands:

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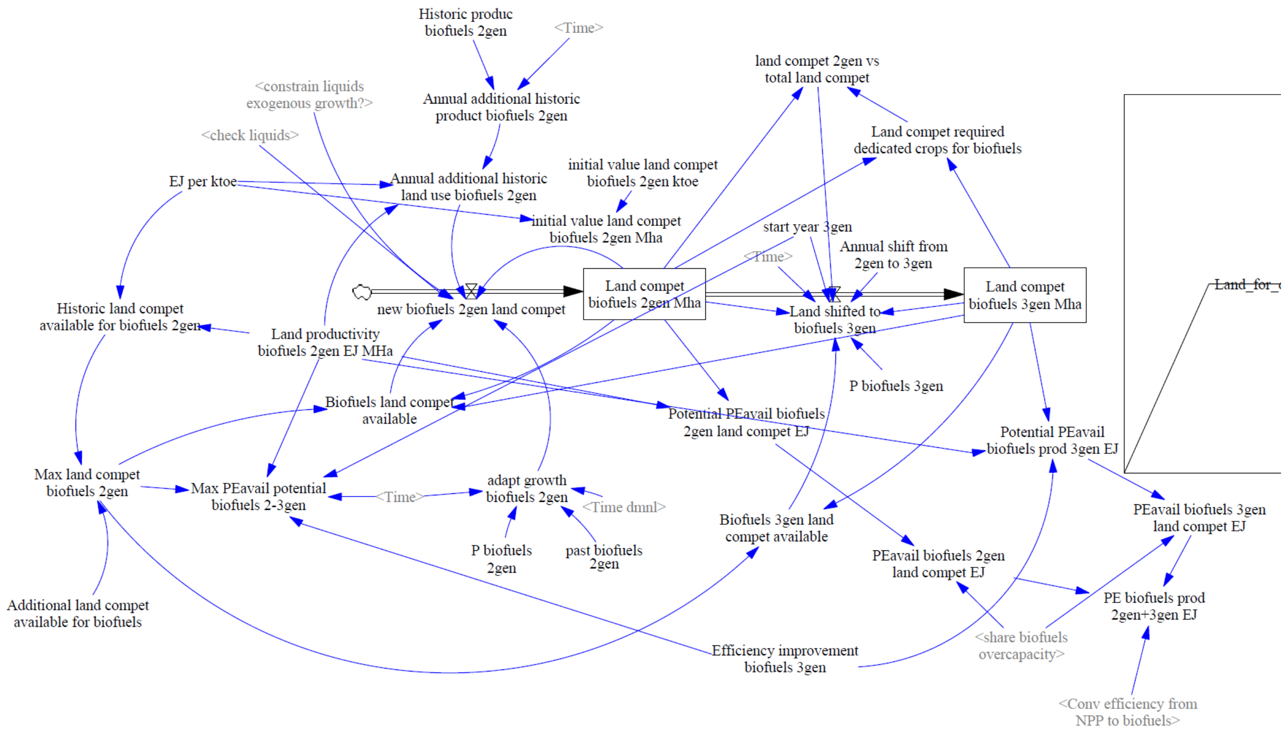

Figure 32: Stock and flow map of the model of the bioenergy in land subject to competition in MEDEAS.

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2.3.4.1.3. Summary of bioenergy uses

Table 13 summarizes the potential for bioenergy for heat and liquids considered in the model (for the biomass for electricity see next section):

Table 13: Techno-sustainable potential of bioenergy by technology and final energy use considered in MEDEAS.. NPP: Net Primary Production. The following conversion factors from NPP (harvestable) to final (gross) power are assumed: 80% for heat, 20% for electricity and 15% for liquids (de Castro et al., 2013a). However, it should be noted that the efficiencies in real power and heat plants are lower considering factors such as non-optimal operation (e.g. low Cp), use in CHP plants, etc.

		Reference	**Surface availability**	**Gross power density**	**Potential**		**Use in MEDEAS**
					NPP harvestable	Final (gross) power	
			MHa	W/m2	EJ/yr	EJ/yr	
Conventional bioenergy		Own estimation (see text)	-	-	30	4-24 (0% heat-100% heat)	Heat&Elec
Marginal lands (no competition other uses)	-	(Field et al., 2008)	386	0.033[a]	27	4.1	Biofuels
Dedicated crops (competition with other uses)	2nd gen.	(de Castro et al., 2013a)	100 (standard scenario)	0.155[b]	33	4.9	Biofuels
	3rd gen. (from 2025)	(WBGU, 2009)	0[c]	0.18	+5.0[c]	+0.7[c]	Biofuels
Residues	Agriculture & Forestry residues 3rd gen. (from 2025)	(WBGU, 2009)	-	-	18.75	3.75-15 (0% heat-100% heat)	75%[e] Heat&Elec
			-	-	6.25	0.95	25% biofuels
	Biogas	Own estimation	-		5	3	Heat, Elec and TFC[d]
Total					125	21.4-52.65	All uses

a (Field et al., 2008) find that 27 EJ of NPP can be extracted from 386 Mha of marginal lands.

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b In reality, the global average power density is less than 0.155 since it has been shown that the methodology applied by the UNEP is conservative. As a reference, the gross power density for the best quality lands was estimated at 0.3-0.36 W/m2 in Brazil (de Castro et al., 2013a).

c The 3rd generation of biomass is modelled without additional land requirements due to the assumption that it will replace previous land occupied by 2nd generation crops.

d Assuming current final energy use shares and efficiencies (IEA, 2018).

e This share can be set by the user of the model.

Previous studies of the global potential of bioenergy have yielded a wide range of conclusions, spanning almost three orders of magnitude (Haberl et al., 2013). However, Haberl et al., (2013) estimated that the maximum physical potential of the world's total land area outside croplands, infrastructure, wilderness and denser forests to deliver bioenergy at approximately 190 EJ/yr.[12] The sustainable technical primary potential of bioenergy considered in MEDEAS amounts to around 125 EJ/yr (harvestable NPP) and ~21-53 EJ/yr of final gross power depending on the share of final uses (heat/electricity/liquids). These values are located in the lower-medium range of the literature. Our comparatively low figure arises from the consideration given to the competing claims of other forms of land use and from the fact that some other estimates have assumed unrealistically high yields and do not take into account rigorous biophysical and sustainable limits. The considered potential matches well with a recent analysis which found that the global sustainable technical primary potential of bioenergy amounts up to 100 EJ (Creutzig et al., 2014).

However, we judge that the considered potentials in MEDEAS for bioenergy are optimistic due to a number of aforementioned reasons such as the fact that from a net energy approach some uses might not be worthwhile at a system level (e.g. liquids biofuels with an EROI < 2:1); the controversial potential of the valuation of agricultural and forestry residues or the uncertain capacity of modify current unsustainable trends in the exploitation of bioenergy.

[12] "At present, humans harvest ~230 EJ/yr worth of biomass for food, livestock feed (including grazing), fibre and bioenergy (a substantial fraction of which is derived from residues and waste flows). In order to produce that biomass, humans affect or even destroy roughly another 70 EJ/yr of biomass in the form of plant parts not harvested and left on the field and biomass burned in anthropogenic vegetation fires. Hence, some 800 EJ/yr worth of biomass currently remain in the aboveground compartment of global terrestrial ecosystems. Of this 800 EJ/yr, 48% grows in forest ecosystems, and much of the remainder in ecosystems which either cannot easily be exploited, such as tundra and drylands (28%), in national parks, conservation areas and wilderness or in cultivated ecosystems which are already heavily harvested (grazing lands, cropland). In order to meet their biomass demand, humans affect approximately three quarters of the earth's ice-free land surface [10] with huge implications for ecosystems and biodiversity" (Haberl et al., 2013).

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2.3.4.2. RES for heat other than biomass

MEDEAS considers 3 RES technologies for the supply of heat: solid bioenergy, geothermal and solar thermal. The modelling is similar than for the RES electricity technologies, but distinguishes between commercial and non-commercial uses of heat due to the reporting of the IEA balances (see section 0).

Figure 33 shows the Forrester diagram of the extraction of (primary energy) from thermal RES.

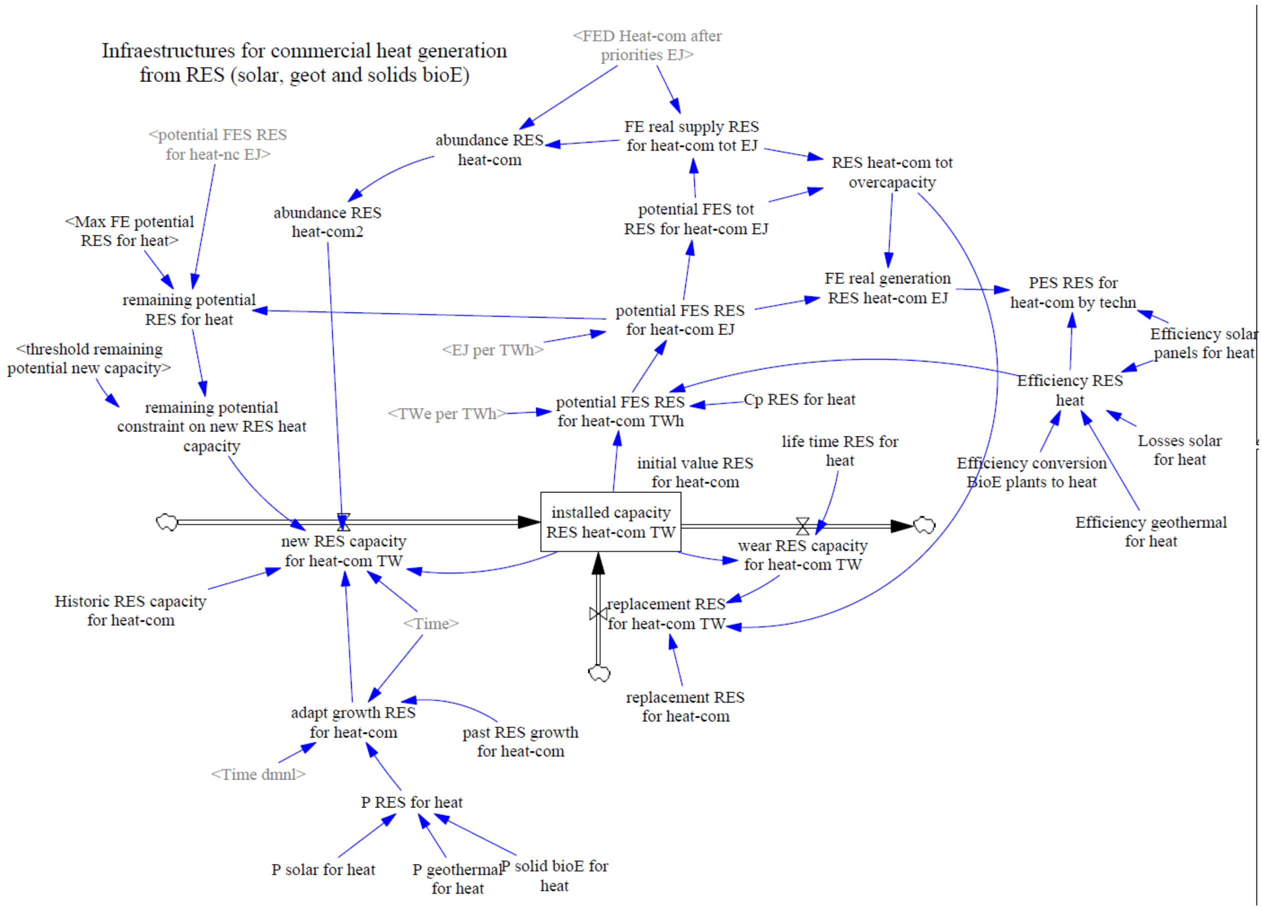

Figure 33: Stock and flow diagram of the extraction of (primary energy) from thermal commercial RES.

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Solar thermal

We use data from (SHC, 2016) for the historical installed capacities (W_{th}). The final energy supply for solar thermal is obtained applying the equation:

$$Final\ energy\ supply_{solar\ thermal}(t) = W_{th}(t) \cdot \chi_{collector} \cdot (1 - Losses)\ \cdot 8760\frac{h}{yr}$$

Where the efficiency of the collector ($\chi_{collector}$) is assumed to be constant (9.5%) as shown by historical data (SHC, 2016), the energy losses (Losses) include the losses in the pipeline (15% estimated by the industry (Nielsen, 2011)), and additional 22% for accounting for the losses due to storage (Capellán-Pérez et al., 2017b). Future great efficiency improvements are not expected since current collectors are very optimized; their low efficiency value is more related to factors dependent on the use of the installation. In fact, solar thermal is highly dependent on seasonal variations, being the demand very uncorrelated with the irradiation levels (more heat tends to be demanded precisely in winter). However, in the current version of MEDEAS the intra-annual variability of the solar thermal is not considered and the installed capacities will tend to be underestimated (the variability of RES technologies for electricity it has been explicitly modelled, see section 0).

Geothermal for heat

We take (de Castro, 2012) as a reference for the techno-ecological potential of total geothermal: 0.6 TWth of primary energy (heat and electricity). This potential represents around 2% of the total Earth dissipation (32 TW) (Hermann, 2006), and > 7% of the thermal exergy of all the emerged lands from the planet (for example in the case of wind we are assuming a harvestable power of 1.25 TW over a total of 1000TW dissipated, see section 0).

For the sake of simplicity, and given that currently a similar level of geothermal for both uses is installed, we assign 50% of the potential for electricity and 50% for electricity. Although the potential for geothermal of low temperature could apparently be higher (e.g. (IEA, 2014)), its EROI is much lower and its profitability from a net energy perspective is uncertain.

Time series of geothermal for heat at global level were not found. Instead, current data, performance parameters (e.g. capacity factor) and growth trends in both installed capacity and energy output from (Lund and Boyd, 2015) were used, which allowed to estimate a time series of the global installed capacity.

Summary

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Table 14 reports the techno-ecological potential of geothermal and solar for heat considered in MEDEAS.

Table 14: Techno-sustainable potential of non-electric renewable sources excluding bioenergy.

	Reference	**Techno-ecological potential (gross power)**
		TW_{th}
Geothermal for heat	(de Castro, 2012)	0.3
Solar for heat	Own estimation (see (Capellán-Pérez et al., 2017b))	0.7
Total		1.0

Thus, combining the data from bioenergy and the gross techno-sustainable potential of thermal RES considered in MEDEAS amounts to ~63 EJ/yr (20 EJ/yr conventional bioenergy, 11.2 bioenergy residues, 9.5 geothermal and 22 solar).

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2.3.4.3. RES for electricity generation other than bioenergy

The most promising electric renewable energies are solar and wind (Smil, 2010). However, recent assessments using a top-down methodology that takes into account real present and foreseeable future efficiencies and surface occupation of technologies find that the potential of their deployment is constrained by technical and sustainable limits (de Castro et al., 2013b, 2011). The evaluation of the global technological onshore wind power potential, acknowledging energy conservation, leads to a potential of 30 EJ/yr (de Castro et al., 2011). In relation to offshore wind, in a back of envelope estimation, assuming a power density of net electricity delivered 1 We/m2 and that 1% of the continental ocean platforms might be occupied by human infrastructures (the density of occupation by human infrastructure in land is 1-2% and entire platforms like Artic and Antarctic are not accessible to human occupation), a rough potential of 0,25 TWe is considered. The estimation of the real and future density power of solar infrastructures including PV and CSP (4-10 times lower than most published studies) leads to a potential of around 65-130 EJ/yr (2-4 TW_e[13]) (de Castro et al., 2013b) in 60-120 MHa.[14]

Hydroelectricity potential is limited by a total gravitational power of rain of 25 TWe (Hermann, 2006). Previous studies have found that the global economic potential is 1-1.5 TWe, being the sustainable potential 50-80% of this range (0.5-1.2 TWe) (EUROELECTRIC, 2000; Gernaat et al., 2017). In the light of these estimations and given the constraints that the variability of RES for electricity impose to the system, we assume an available potential in MEDEAS of 1 TWe.

Sea waves on coasts and tidal resources are limited to a physical dissipation of 3 TW and geothermal renewable resources are limited by a total Earth dissipation of 32 TW (Hermann, 2006). OTEC technology is not considered in MEDEAS given its very low EROI (< 1:1).

Acknowledging their high dispersion and role in the energetic and material fluxes of ecosystems, we estimate that around 1.35 TW_e could be attained in a sustainable way by renewable energies for electricity other than solar, wind and bioenergy.

In relation to electricity generation from bioenergy, as discussed in the precedent section, we assume a shared potential of bioenergy for both heat and electricity. Thus, depending on the

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[13] "TW_e" represents power electric production: 8760 TWh = 1 TWe, i.e. in one year 1 TW of capacity functioning with a 100% capacity factor produces 1 TWe.

[14] The potential in urban areas is greatly limited by the competition with the solar thermal technologies and the fact that the adaptation to the rooftop implies lower efficiencies (Capellán-Pérez et al., 2017a).

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scenario (i.e. final energy demands, policies, etc.), the model will assign a different use for heat and electricity from bioenergy. With the standard assumptions and in the extreme scenario where all the bioenergy potential for heat and electricity would be allocated for electricity production, < 9 EJ/yr (< 0.3 TWe, see Table 13) could be delivered from bioenergy with the standard assumptions in MEDEAS (see section 0). However, it should be noted that the efficiency for heat generation from bioenergy is roughly ~ 4 times bigger than for generating electricity (see caption in Table 13). Accordingly, sustainable policies often give priority to heat generation from biomass (Bermejo, 2014).

Table 15 collates the techno-ecological potential of the different RES technologies for the generation of electricity together with other performance factors (investment costs, lifetime, capacity factor and power density).

Table 15: Data of electric renewable in the model. "TWe" represents the gross annual power electric production: TWh/8760.

	Techno-ecological potential	**Investment cost**			**Lifetime**	**Capacity factor**	**Power density**
	TW_e (gross)	2011$/kW			Years	share	W_e/m^2
		2010	2030	2050			
References	(de Castro et al., 2013b, 2011) and own estimations	(Teske et al., 2011)			(IPCC, 2011) and conventional values	Literature review[b]	(de Castro et al., 2013b; Smil, 2015)
Hydro	1	3,110	3,550	3,800	80	0.42 (2007) – 0.33 (2050)	4
Wind onshore	1	1,740	1,100	1,030	20	0.21	1 (regional level)
Wind offshore	0.25 (1% of ocean platforms)	3,340	1,680	1,500	20	0.315[c]	
Solar PV	2-4 (60-120MHa)	4,310	1,390	1,028[a]	25	0.15	3.3
CSP		8,340	4,900	4,780	25	0.25	
Solid biomass	0 – 0.3	3,240	2,730	2,680	30	0.5	-
Geothermal	0.3	14,310	8,340	5,980	30	0.65	50
Oceanic (Tidal and waves)	0.05	8,300	2,480	2,480[d]	40	0.2	-
Biogas[e]	< 0.01	-	-	-	-	-	-
TOTAL	4.6 – 6.9						

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[a]The investment cost for solar PV after 2030 is set to the same level than wind onshore, since we judge that it is unlikely that solar PV technologies will manage to be less expensive in the future than wind given their higher technological complexity. In fact, in recent years, the price of solar modules has fallen significantly due to efficiency improvements but also to dumping and excess capacity effects in the crisis. [b](Boccard, 2009; BP, 2016; De Castro and Capellán-Pérez, 2018; EIA, 2009; IRENA db, 2017; REN21, 2016). [c]We assume that offshore wind has a +50% higher Cp than onshore wind. [d]The oceanic investment cost is maintained constant after 2030 since we judge too optimistic that these technologies might reach a low cost in the order of the ones of wind offshore. [e]Assuming current final energy use shares and efficiencies (see Table 13); the infrastructure of generation for biogas is not explicitly modelled.

Considering the data presented in Table 15, the aggregated techno-ecological potential of all RES for electricity generation in MEDEAS ranges 4.6-6.9 TWe annually (145-220 EJ/yr) (1.35-1.65 TWe excluding solar and wind). This potential is in the lower range of the literature (see for example (IPCC, 2011; Jacobson and Delucchi, 2011)), given to the consideration of biophysical limits and reinforced sustainability criteria. It should be highlighted that the techno-ecological potential of renewable energies is so far a controversial subject in the literature (see the Supplementary Material in (Capellán-Pérez et al., 2015) for a comparison and discussion).

Still, the considered potential in MEDEAS for RES technologies for electricity generation is large and corresponds with ~45%-70% of the TFEC in 2015. It also should be kept in mind that these are static potentials, i.e. the consideration of time constraints (realistic technologic growth rates) will likely reduce the practical potential in the timeframe of MEDEAS (notably for solar) (Capellán-Pérez et al., 2014; Mediavilla et al., 2013). Moreover, taking into account that most potential is related to variable RES technologies (>80%), the management of intermittency reduces in practice the global theoretical potential estimated in this section (see section 0 “Modelling of intermittency of RES variables”).

We consider the power density of RES in order to estimate their land occupation (although for solar PV and CSP it is the inverse: the land (Mha) dedicated for these technologies is set for each scenario and the annual delivered power estimated subsequently). We apply data based on studies that take into account real present efficiencies and surface occupation of technologies (de Castro et al., 2013b; Smil, 2015). For the capacity factor (Cp) of solar PV and wind, we apply a couple of studies that focus on the estimation of this parameter applying a top-down analysis of real-life systems in large areas rather than usual, laboratory values that happen to substantially overestimate this parameter in working conditions. Thus, Prieto and Hall (2013) estimate the Cp of solar PV in Spain, a country with good insolation and with a significant solar power installed. Boccard (2009) found that, although for more than two decades, the Cp of wind power measuring the average energy

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delivered has been assumed in the 30–35% range of the name plate capacity, the mean realized value for a region as Europe in the period 2003-2007 was below 21%. Arvesen and Hertwich (2012) confirmed the existence of a general tendency of wind power LCAs to assume higher capacity factors than current averages from real-world experiences. An estimation of the real Cp of wind onshore at global level from data from BP (2017) reveals that in the last decade it never surpassed 0.16, thus the extrapolation of the estimation from data from Boccard (2009) for the rest of the world are optimistic (this leaves room in MEDEAS so that the future efficiency could increase ~30%, from 0.16 to 0.21 due to technological improvements). For the rest of sources we apply standard values from the EIA US (2008). Table 15 also shows the energy techno-ecological potential, investment cost (without including O&M), lifetime, capacity factor and power density assumed for each renewable technology for electricity generation.

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2.3.4.4. Summary of RES sustainable potentials considered in MEDEAS

Table 16 shows the total techno-ecological potential of RES for heat and electricity, which ranges 6.3-9.3 TW of energy production by year (~200-300 EJ/yr). This potential amounts 63%-95% of the of the TFEC in 2014.

Table 16: Techno-ecological potential of RES for heat and electricity.

	Techno-ecological potential heat + electricity (gross)
	TW
Bioenergy	0.7-1.7
Geothermal	0.6
Solar (PV, CSP & thermal)	2-4 + 0.7
Wind (onshore + offshore)	1.25
Hydro	1
Marine (Tidal + wave)	0.05
TOTAL	6.3 – 9.3

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2.3.4.5. Modelling of intermittency of RES variables in MEDEAS

The most abundant RES for the generation of electricity, solar and wind (see section 0), are subject to temporal variability. Variable RES are characterized by short-term (e.g., cloudiness, day-night) and seasonal variability (e.g., winter-summer). A renewable mix portfolio allows to partially mitigate the variability of the different RES. For example, in Europe, the annual cycles of wind and PV are partially complementary since the lower solar irradiance in winter is generally balanced by increased wind (and vice versa in the summer). However, this complementarity is far from perfect. In any region there is a certain probability of extreme combinations in the availability of natural resources, such as no wind over large parts of Europe during the winter (Trainer, 2013, 2012). Moreover, there can be large annual variations in the availability of natural resources; for instance, the output of wind turbines in any given area can vary by up to 30% from one year to the next (Brower et al., 2013; Li et al., 2010). It has been estimated that current electricity systems and grids can usually accommodate up to only 20% electricity from renewable sources without a need for dedicated storage facilities (Armaroli and Balzani, 2011; Lenzen, 2010). Thus, a certain level of: (1) storage, (2) grid development (3) overcapacity and/or (4) flexible demand management should then be considered if a high penetration RES electricity system is to be designed. The complexity of the modelling of these systems is illustrated by the conclusions of a recent review which found that modelling exercises to date have failed to adequately represent the full implications of the intermittency on this systems (Heard et al., 2017). In the current version of MEDEAS, we focus on the options 1-3 (see section 0). Finally, section 0 documents the approach to estimate the additional monetary costs.

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2.3.4.5.1. Adaptation of the electric system through storage and overcapacities

Seasonal electric storage faces technical limits (only pumped hydro storage, PHS, is the only large-scale available demonstrated technology for seasonal storage), and that the biophysical potential of PHS is constrained by local conditions and in most cases would not suffice to balance the seasonal variability (Capellán-Pérez et al., 2017a; MacKay, 2013; Trainer, 2012). On the other hand, the required levels of grid developments to balance the variability of the RES are huge and very expensive, which make them extremely low to to deploy (see (F. Wagner, 2014) and the discussion in Capellán-Pérez et al., (Capellán-Pérez et al., 2017a)). Overcapacities are limited by the economic profitability of the power plant (i.e. large overcapacities imply low Cp). From a net energy perspective, overcapacities tend to lower the EROI, which could similarly affect the net energy profitability of the plant. Due to these reasons, in MEDEAS we have decided to combine the first three options to the modelling of the penetration of the RES in the electricity system.

The RES for electricity generation can be classified as "baseload", i.e. those sources that are able to supply a manageable ("dispachtable") load such as hydro,[15] biomass and geothermal, and "variable" generation. The latter are characterized by differing levels of variability and limited predictability over various time scales, and include wind and solar technologies.[16] To cope with their intermittency, MEDEAS incorporates 4 mechanisms:

1. Storage
2. Overcapacities of dispachtable RES power plants,
3. Overcapacities of variable RES power plants,
4. Grid development

The review of the literature showed that while a ~20-35% share of variable RES may require relatively low levels of storage and overcapacity, a system with intermittent RES over 40-50%

[15] Hydroelectricity is not a fully dispatchable RES due to the interanual (e.g. drougths) and seasonal variability and the fact that water is also used for other purposes (irrigation, control floods, human consumption, industrial use, navigability, etc.).

[16] In MEDEAS we model the technology CSP with storage (molten salts) without back-up due to two main reasons: (1) it is the most performant technology, (2) those plants incorporating back-up usually use natural gas; in the case biomass or biogas would be applied it would increase the ecological footprint of the CSP power plants to unsustainable levels. Thus, although CSP with storage allow to mitigate the short-term variability to some extent, it is constrained by large seasonal variations (De Castro and Capellán-Pérez, 2018). For this reasons it is also considered as a variable RES.

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substantially increases these requirements, i.e., there is an exponential relationship when approaching the full intermittent energy mix (Capellán-Pérez et al., 2017a; Delarue and Morris, 2015; Ferroni and Hopkirk, 2016; François et al., 2016; NREL, 2012; REN21, 2017; Weitemeyer et al., 2015).[17] Thus, a realistic 100% RES mix should avoid contributions of variable RES close to the maximum.

On the other hand, the penetration of RES variables tends to increase the distribution losses (see section 2.3.5).

Required level of storage

The storage requirements in MEDEAS are derived from the study (NREL, 2012) which analyses the implications of different levels of RES penetration in USA (from current levels to 90%). Figure 34 represents the share of installed power storage vs. (1) variable RES installed capacity (red curve), and vs. (2) total RES installed capacity (blue curve) as a function of the share of total RES penetration in the electricity mix. We note that the first point relative to the current levels (20% of total RES penetration in the electricity mix) corresponds with the highest level of share of installed power storage. This feature suggests that the storage requirements estimated by this study might be underestimated.

The storage requirements in MEDEAS are estimated from a regression of the share of installed power storage vs variable RES installed capacity as a function of the share of total RES penetration in the electricity mix (discarding the first point relative to 20% penetration levels), see the following equation.

$$\%\frac{storage}{variable}RES = 0.1132 \cdot \%RES + 0.099$$

[17] In particular (Weitemeyer et al., 2015) found that until a 80% contribution of variable RES would require relatively low levels of storage and overcapacity, however the rely on some optimistic assumptions such as assuming no grid limitations, and considering seasonal storage capacities and technologies (such as hydrogen) that are currently not commercially available on the required scale.

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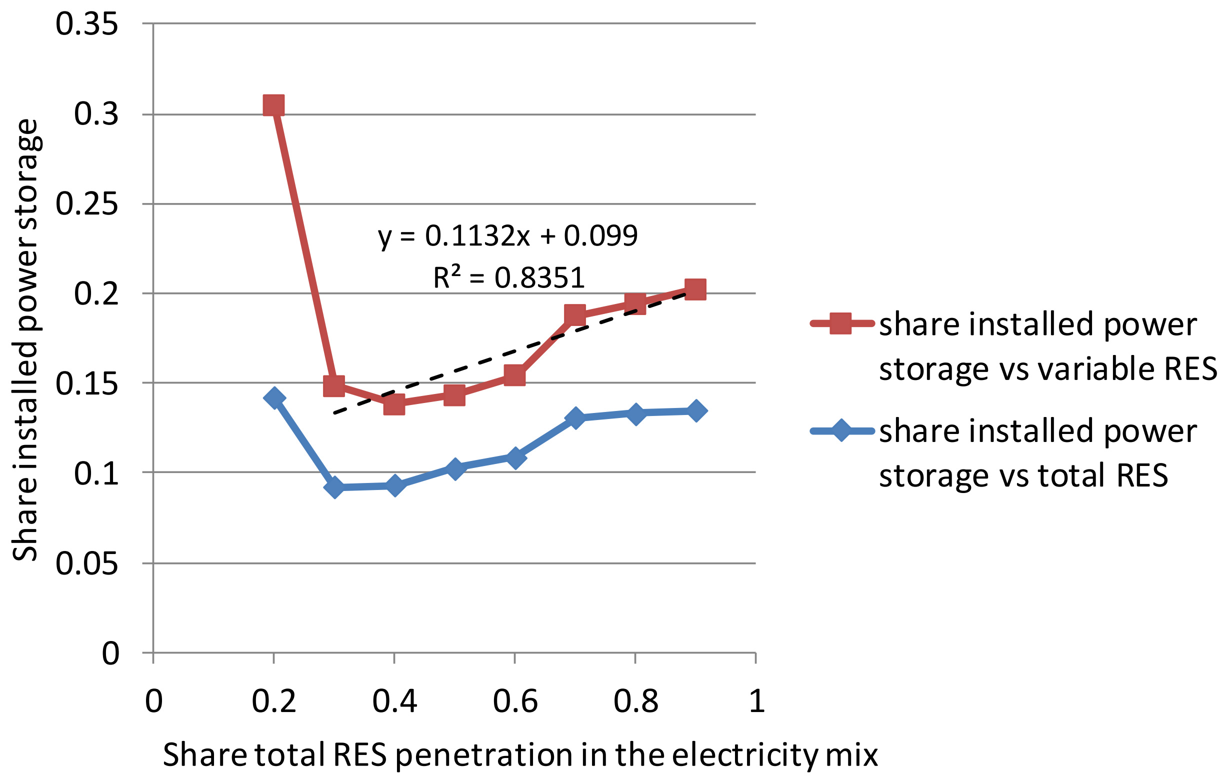

Figure 34: Share of installed power storage vs. (1) variable RES installed capacity (red curve), and vs. (2) total RES installed capacity (blue curve) as a function of the share of total RES penetration in the electricity mix.

It should be highlighted that it may be impossible to achieve the required storage volumes depending on the population density and the local climate and geography conditions (Trainer, 2012). For example, MacKay (2013) estimated that summer/winter balancing for the UK would require lakes for pumped storage occupying 5% of the area of the country, which is physically unfeasible. Wagner (2014) estimated for Germany that the PHS requirements under an optimum 100% RES mix (wind+solar) would reach 660 times the current PHS installed capacity in the country, far from the feasible potential. (Trainer, 2013) estimated for Europe that generation from PHS would have to be scaled up by a factor approaching 20, which is again higher than the estimated theoretical potential for PHS (Gimeno-Gutiérrez and Lacal-Arántegui, 2015).[18] Note that the storage requirements estimated by each study depends on the area of the region studied and on the consideration (or not) of other mechanisms to adapt to variability.

[18] However, the identified total technical potential for hydropower in Europe only doubles current installed capacity (IPCC, 2011).

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PHS is the main storage technology in MEDEAS given that it is currently the best solution due to its demonstrated functioning, competitive cost, high efficiency, long storage times (up to years) and fast response (Armaroli and Balzani, 2011). Although not all hydroelectric plants can host a PHS, the PHS installed in the remaining could have larger installed capacity than usual hydroelectricity plant. We assume the global potential of PHS to be 25% of the conventional hydropower (i.e. 0.25 TWe) following the estimation of (Gimeno-Gutiérrez and Lacal-Arántegui, 2015) for the EU27. For the sake of simplicity we assume in this model version that the storage requirements are not limited by the potential dynamic constraints to the installation of PHS infrastructure.

Electric batteries might also address the short-term variability. MEDEAS assumes that non electric batteries are exclusively dedicated to the storage of electricity, instead, we assume that batteries from electric cars will be available as storage devices. In fact, the IEA (IEA, 2016) estimates that "125,000 cars could be equivalent to 300 MW of flexibility – a medium size pump storage plant or a successful stationary demand side response program". Given that the ESOI of PHS is higher than EV batteries for most of the potential of PHS, the current version of MEDEAS assigns priority to the electric storage of PHS. In the case that more storage is required the EV batteries could then be used. However, an extensive use of EV batteries for electricity storing would wear very fast the batteries, effectively reducing its lifetime. For example, increasing their Cp 10x would translate into 20,000 cycles. Thus, in MEDEAS we assume that the electric batteries for EV can be used for electricity storage at a same Cp than for driving, i.e. that each battery would be able to function 10 years without wear (4,000 cycles) (more details in section 2.4).

In the case that the electric storage capacity available cannot sustain the penetration of variable RES, the growth of these RES variable technologies is constrained.

Overcapacities of RES power plants

The mechanisms 2 and 3 operate similarly: we assume that an increasing level of overcapacity of both dispatchable and variable RES is required when the variable RES increase their generation share in the electricity sector. A literature review of studies analysing the implications of RES intermittency for the overcapacities of the system was performed (Capellán-Pérez et al., 2017a; Delarue and Morris, 2015; NREL, 2012; Schlachtberger et al., 2016; F. Wagner, 2014; Weitemeyer et al., 2015). The followed approach consists on estimating the reduction of the Cp of the RES power plants as a function of the penetration of variable RES in the electricity generation.

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We estimate the overcapacity of dispatchable RES taking as reference again the study (NREL, 2012) which analyses the implications of different levels of RES penetration in USA (from current levels to 90%). Figure 35 shows the reduction in the Cp of the dispatchable RES as a function of the penetration of variable RES. We extended these scenarios until 100% RES penetration levels with two methods (lineal and polynomial order 2), considering that at 100% penetration level of intermittent generation the Cp of baseloads plants would fall to zero. The polynomial curve provides a better fit and is therefore introduced in the model. For the sake of simplicity, in this model version the same reduction factor for all baseload plants is applied equally.[19]

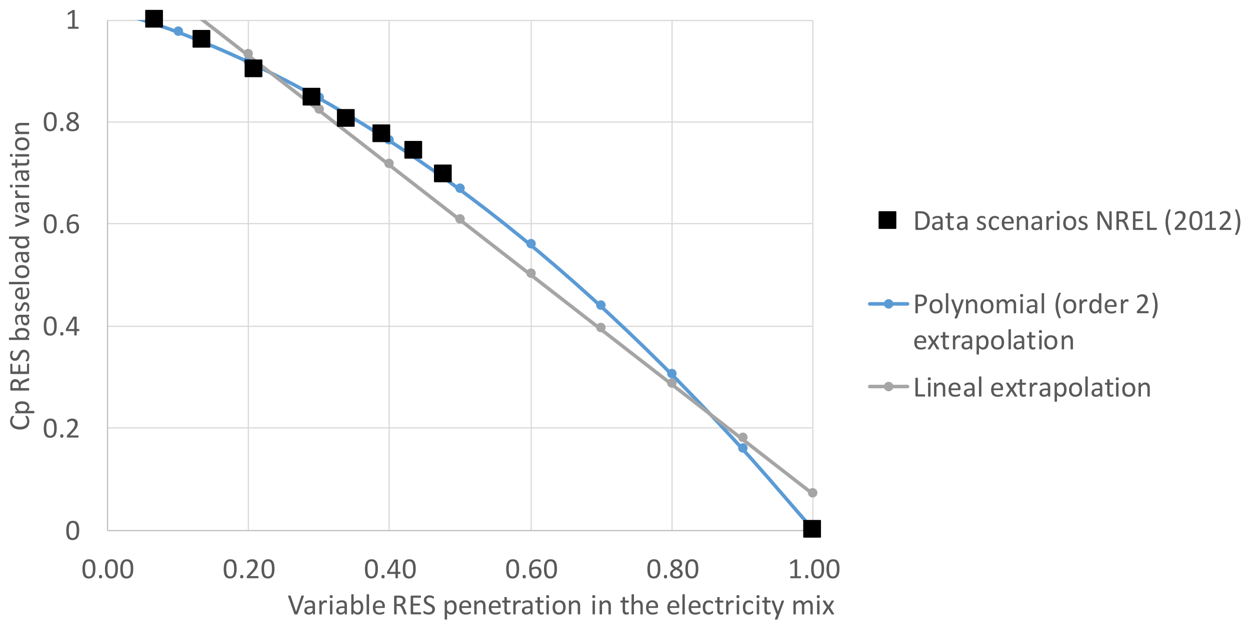

Figure 35: Capacity factor reduction of baseload plants (including RES and non-RES power plants) in relation to the initial point of "negligible" variable RES penetration as a function of the increasing level of penetration of the electricity generation of RES variables. Source: own calculations from NREL (2012) data (Figure 2-2), and polynomial and lineal extrapolation until 100% (Cp baseload=0%).

We estimate the overcapacity of variable RES following the study from (Delarue and Morris, 2015). NREL (2012) study could not be applied for this estimation since several shortcomings were identified in the methodology, such as the unrealistic assumption that key characteristics of the energy system remain constant with the increase in the penetration of RES technologies in the electricity mix (such as the Cp of the variable RES), or the consideration of CSP as dispatchable source

[19] This was explicitely modelled only for dispathable RES sources and nuclear, since capacity for electricity generation from fossil fuel resources is not modelled in this model version.

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of electricity (CSP has in fact a higher seasonal variability than solar PV (De Castro and Capellán-Pérez, 2018)).

Figure 36a shows the overcapacities of variable RES as a function of the variable RES penetration in the electricity mix from (Delarue and Morris, 2015) and the exponential fit. Figure 36b shows the correspondent reduction in the Cp of the variable RES power plants and interpolation assuming that Cp=1/(1+overcapacity). Hence, we assume that in the case the variable RES would cover 100% of the electricity generation, an overcapacity of almost +200% (3 times) would be required for those power plants running on variable RES technologies, equivalent to a reduction of almost 3 times in their Cp. Weitemeyer et al., (2015) reach a similar conclusion for Germany assuming PHS requirements of more than 30 times the current installed capacity (in combination with 200% overcapacity).

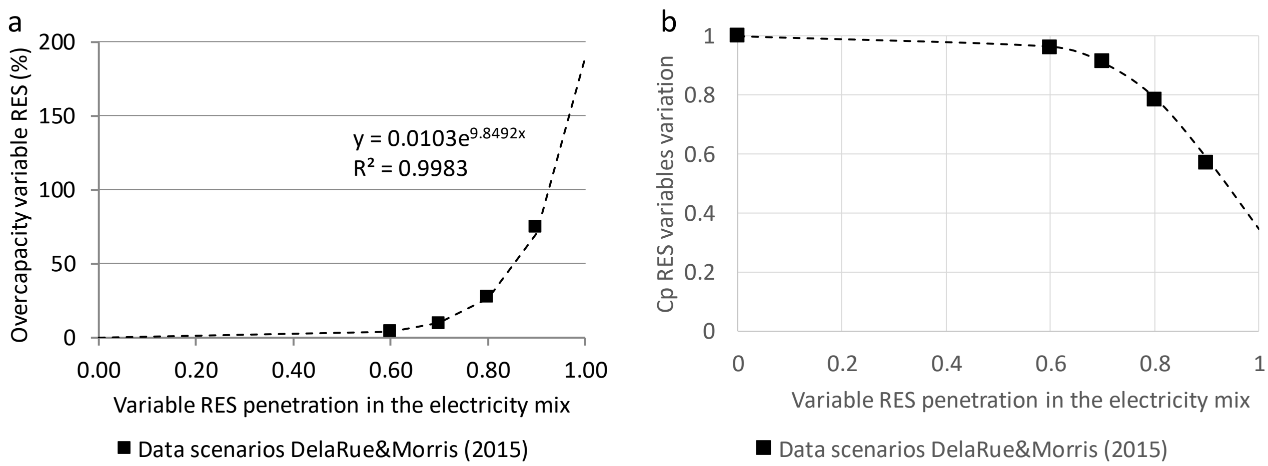

Figure 36: Overcapacities of RES variables: (a) Overcapacities of variable RES as a function of the variable RES penetration in the electricity mix from (Delarue and Morris, 2015) and exponential fit; (b) Reduction in the Cp of the variable RES power plants and interpolation.

To avoid unrealistically low values of Cp that would imply that power plants would be running unprofitably (and/or with negative net energy return to the system), we set a minimum Cp per technology.

Grid development

MEDEAS-World does not explicitely model electricity grids given that these infraestructure are regional/national by definition. However, an estimation of the additional grids per MW of variable RES (overgrids and inter-regional grids) to be constructed to integrate the renewable variable

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electricity generation is performed (see section 2.4.4). Thereafter the additional material requirements associated to these grid developments is computed, which affects the EROI of the RES variables for electricity generation.

Finally, it should be highlighted that this combined approach is subject to high uncertainties given that the variability of RES is dependent on the local geographic conditions and its analysis at global level can only be performed qualitatively, expecting to capture the magnitude order of the involved phenomena.

There is also generally a trade-off between the installation of additional generation capacities and storage capacities to balance the intermittence of resources (Armaroli and Balzani, 2011; François et al., 2016; F. Wagner, 2014; Weitemeyer et al., 2015). Other sources of variability that have not been considered would increase the requirements of storage, overcapacities and grid developments, such as low rain years; by taking yearly average electricity demands, we are not accounting for neither seasonal and short-term variability (i.e., over hours, days, weeks). Finally, we have not allowed for the fact that demand peaks at certain times of day at levels much higher than the average, conservative estimates of these peaks being +30%, while other studies have yielded estimates several times higher.

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2.3.4.5.2. Additional monetary costs

The monetary investment for building new plants up to 2050 is computed following (Teske et al., 2011). We assign the same cost to new and repowering plants in order to be sure not to underestimate that cost, since the costs when replacing an old power plant are usually lower. Slight adjustments are made to represent the costs in 2011 US$ (2005-2011 consumer price index of 1.15 from http://www.measuringworth.com/uscompare/), and to represent it as a function of the delivered electricity instead of installed capacity through the capacity factor (see Table 15). Since solar FV investments cost have declined faster than projected by (Teske et al., 2011), we fitted their learning curve to actual developments.

The additional costs related to the variability of RES (increase of operating costs[20]) and the need of grid development (renewable energies are often located in remote areas) are modelled taking into account studies for wind. Grid reinforcement costs are, by nature, dependent on the existing grid. We use the median value calculated in (Mills et al., 2012) for 40 transmission studies for wind energy in the USA, which is, in fact, on the upper side of the comprehensive study made by (Holttinen et al., 2011): 300 $ 2011US/kW of wind installed. Assuming a capacity factor of 21% for wind (the mean value for Europe between 2003 and 2007):

$$300\,\frac{\$}{kW} = 300\,\frac{T\$}{10^3\cdot TW}\cdot\frac{1\,TW}{8760\,TWh\cdot CF}\cdot\frac{8760\,TWh}{1\,TWe} = 1.43\,\frac{\$}{We}$$

Other monetary costs, such as balancing costs, are also introduced into the model: (Holttinen et al., 2011) also concludes that at wind penetrations of up to 20% of gross demand (energy), the system operating cost increases arising from wind variability and uncertainty amounted to about 1–4 €/MWh of wind power produced. We assume here similar costs for the combined variable renewable producers -solar and wind-, extrapolating the cost until it reaches a maximum of 8 euros/MWh (7.6 US 1995$/MWh) at 50% of total electricity share (see

[20] Increase in reserve requirements is not computed since the investments for non-renewable electricity production are not modeled.

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Table 17). This cost is assigned to the wind production, assuming that solar technologies might have more capacity to store energy in the future (e.g. CSP with thermal storage). Since there exist no real experiences of countries with such a level of RES variable penetration, the balancing costs at high penetration levels is uncertain. However, this is a conservative estimate.

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Table 17: Integration cost adapted from (Holttinen et al., 2011).

Combined variable RES electricity generation share	**Balancing cost** [$ 199US/MWh produced]
0 %	0
10 %	1.52
20 %	3.03
30 %	4.55
40 %	6.07
> = 50 %	7.58

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2.3.4.6. Employment factors of RES technologies

MEDEAS estimates the number of jobs dedicated to manufacture, construct, install, operate and maintain RES power plants for both electricity and heating generation. While these factors are fairly well documented, the labour intensity of system integration is still unclear and is not included in the publicly available statistics (REN21, 2017). Table 18 shows the technology-specific employment factors considered from (Greenpeace et al., 2015). These factors are usually from OECD countries, as this is wherethere is most data. In peripheral countries it typically means more jobs per unit of electricity because those countries have more labour intensive practices. On the other hand, we do not take into account "learning adjustments or 'decline factors'". We assume that the evolution of both factors in long-term will cancell out.

Table 18: Employment factors considered in MEDEAS. Source: (Greenpeace et al., 2015).*For CSP, the original data from Energy [R]evolution report seems to low (2.2 jobs/MW for manufacturing, construction and installation, and in this case data for this technology from (REN21, 2017) was used instead.

	C+I+M	O&M
	job year/MW	job year/MW
RES elec		
hydro		
geot-elec	16.6	0.4
solid bioE-elec	16.9	1.5
oceanic	20.4	0.6
wind onshore	7.9	0.3
wind offshore	23.6	0.2
solar PV	19.7	0.7
CSP*	9.3	0.6
RES heat		
solar-heat	8.4	0
geot-heat	6.9	0
solid bioE-heat	16.9	1.5

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2.3.5. Electricity generation

Distribution losses must be added to the estimated final electricity demand in order to compute the electricity generation demand. An analysis of the period 1980-2010 reveals that these losses were approximatively 9.5% of the electricity consumed (US EIA db, 2015) (Figure 37). When checking this relation for the past years an error inferior to 1% was obtained.

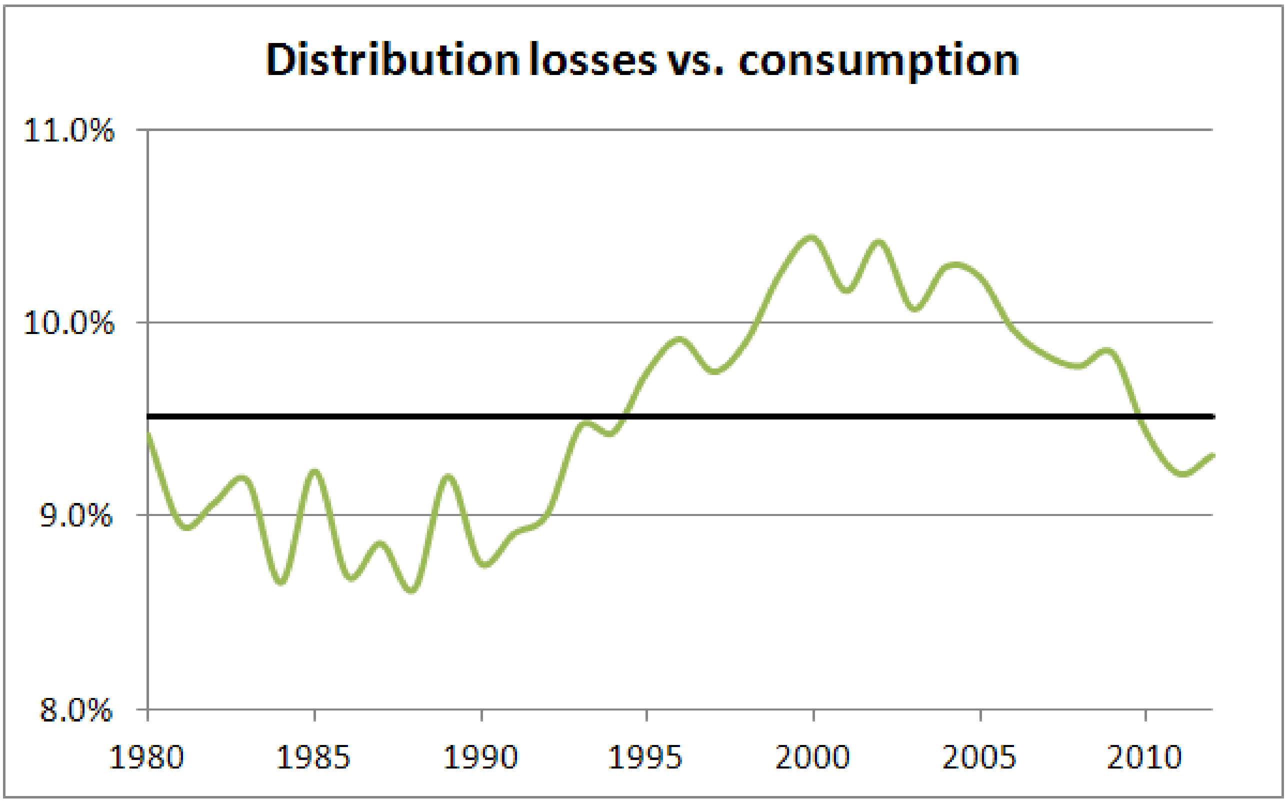

Figure 37: Distribution losses vs. consumption at global level (1980-2012) (US EIA db, 2015).

The level of penetration of RES variables must be also taken into account in the estimation of the electricity generation since a higher share in the electricity mix would increase the transmission and distribution losses of the whole system (increase of volume of electricity transported and distance, round-trips for electricity storage, etc.). As a reference, we take the study from (NREL, 2012) and estimate the variation of transmission and distribution losses in relation to baseline scenario as a function of the share of RES in the electricity mix (see Figure 38):

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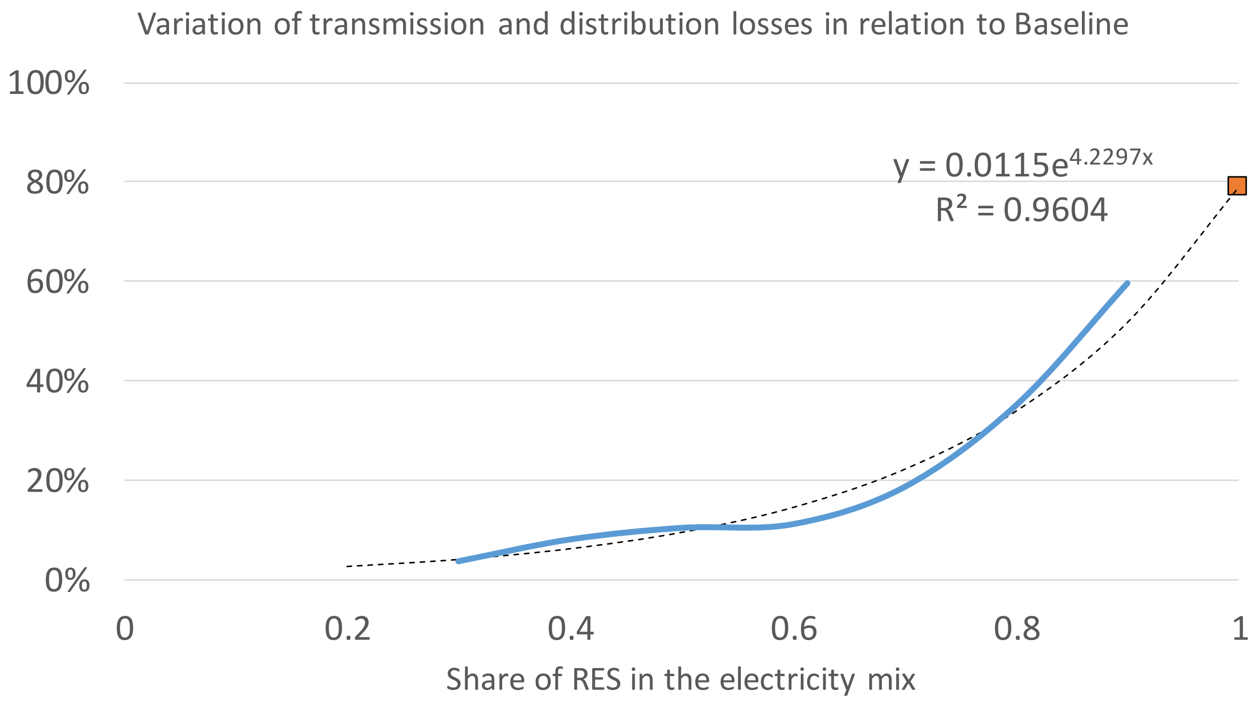

Figure 38: Variation of electricity transmission and distribution losses as a function of the share of RES in the electricity mix. Source: own work from (NREL, 2012).

Thus, the electricity generation taken into account these dynamics is estimated applying the following equation.

$$E_{elec}^{gen} = E_{elec}^{cons} \cdot \left(1 + 0.095 + 0.0115 \cdot e^{4.2297 \cdot share\ RES\ in\ elec\ mix}\right)$$

The model also accounts for the additional energy due to the electrification of transportation (see section 0). The modelling of electricity generation in MEDEAS is as following: priority is given to the evolution of exogenously variables (in this order: RES, oil waste-to-energy, CHP plants and nuclear); the remaining is distributed equally between coal and gas following their share in 2014 (70% and 30% respectively). The following efficiencies are applied for the non-renewable electricity generation following the IEA Balances (IEA, 2018):

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Table 19: Assumptions for the efficiency of fossil and nuclear power plants.

Fuel	Efficiency of power plant	Comment
Nuclear	33%	Constant in the IEA balances
Coal	35.3%	Stable trend between 1971 and 2014, average of the period.
Oil	36.1%	Stable trend between 1971 and 2014, average of the period.
Natural gas	5% annual improvement growth from current values with an asymptote in 60%.	There has been a constant improvement in the efficiency of natural gas power plants, from 35% in 1990 to 44.3% in 2014.

The generation of electricity from RES, waste-to-energy CHP, oil and nuclear are exogenously projected depending on the scenarios modelled.

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2.3.5.1. Electricity generation from RES

In MEDEAS, RES have priority in the fulfilment of the electricity demand. Their share in the electricity mix is allocated as a function of EROI (see section 2.4.5). Among the renewable energies, hydroelectricity continues to be the largest contributor due to its early historical deployment; however the new renewable energies show a strong growth in the last decades (e.g. solar +44%, wind +30%, see Table 20), while reaching (or close to) grid-parity costs in many locations (REN21, 2014).

Table 20: Historical installed capacity growth of RES technologies for electricity generation (annual averaged growth over the period).

	Reference (See (MEDEAS, 2016a)**)**	**Annual averaged capacity growth over the period**	
		Historic trends	Recent trends (2012-2015)
Hydro	(US EIA db, 2015) & (IRENA db, 2017) and own estimation	+2.8% (1995-2015)	+3.8%
Wind onshore	(IRENA db, 2017) and own estimation	+25.1% (1995-2015)	+14.9%
Wind offshore	(IRENA db, 2017) and own estimation	+41.0% (2000-2015)	+29.4%
Solar PV	(IRENA db, 2017) and own estimation	+45.3% (2000-2015)	+30.4%
CSP	Own elaboration based on SolarPACES data	+29.5% (2005-2015)	+22.8%
Geothermal	(IRENA db, 2017) and own estimation	+2.4% (1995-2015)	+4.2%
Solid biofuels	(IEA, 2018) (IRENA db, 2017) and own estimation	+7.2% (1995-2015)	+7.8%
Oceanic	(IRENA db, 2017)	+4.8% (2000-2015)	+0.4%

However, still the new renewable energies reached less than 4.5% of the world electric generation in 2011 (US EIA db, 2015). In 2007, over 95% of the power generation capacity under construction worldwide was for fossil fuel and hydro power production (WEO, 2008, fig. 6.4). But the in less than a decade the trend has radically changed: the capacity additions of renewable technologies in 2013 reached the same level than for the rest of technologies (Liebreich, 2014). Since the Cp of RES

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technologies are generally lower than those of NRE power plants, the electricity delivered by the new RES is still lower than those of the NRE power plants.

Below we represent the equations and Stock and flow diagram (Figure 39) of the infrastructure of RES technologies for electricity generation (vectorial programming).

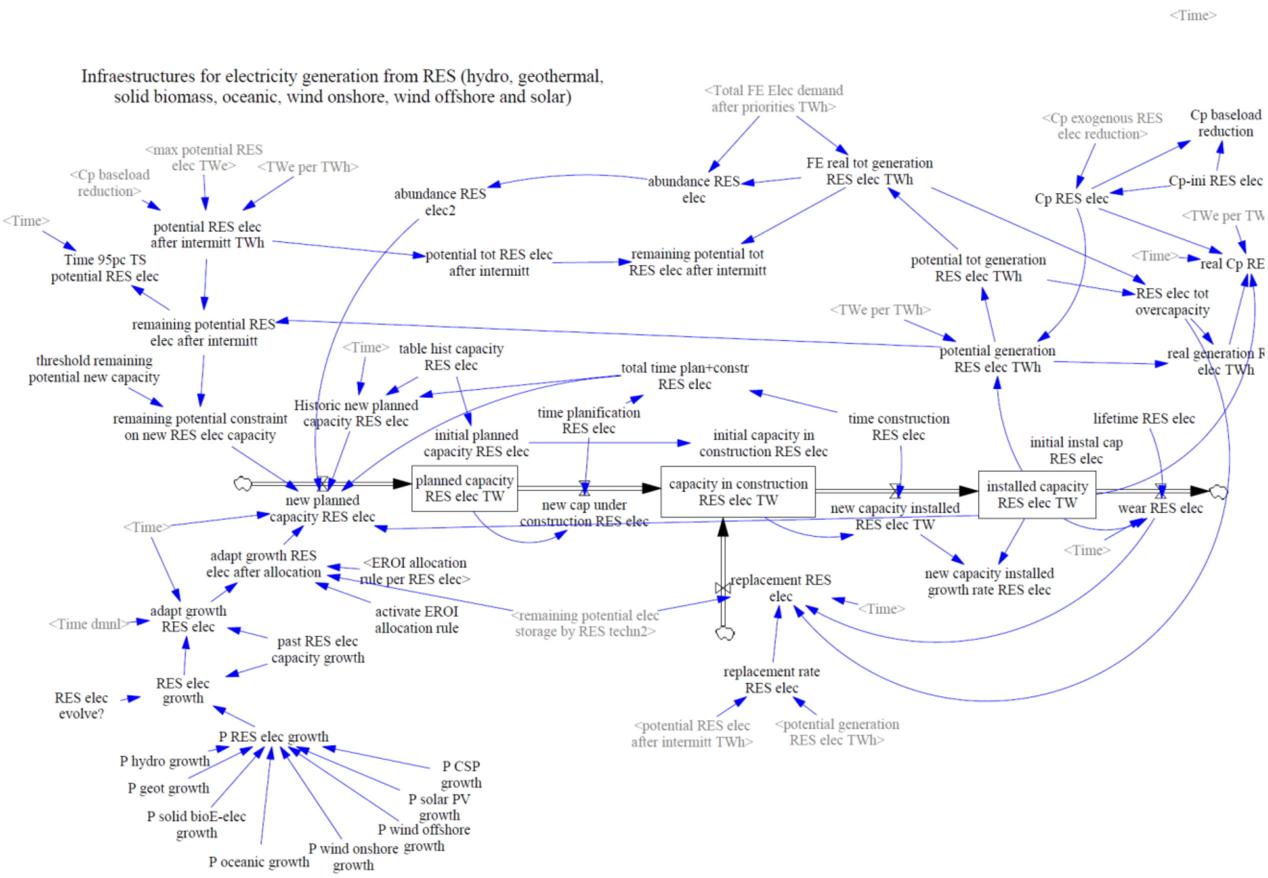

Figure 39: Infrastructure of RES technologies for the generation of electricity (vectorial programming).

P1_solar represents the annual growth considered in each scenario (*past_solar* represents the past trends and *Adapt_growth_solar* models a soft transition between both during a period of 5 years). However, this growth is adjusted to a function that introduces diminishing returns on the new solar power (*new_solar_TWe*) depending on the proximity to the potential (*max_solar_TWe*, that in the case of solar comes from the potential land dedicated to solar power plants *max_solar_Mha*) reducing the exogenous growth initially set. We apply a logistic curve (Höök et al., 2011):

$$New_{solar_{TWe(t)}} = Adapt_{growth_{solar(t)}} \cdot \left(\frac{\max\_solar\_TWe - solar\_TWe(t)}{\max\_solar\_TWe}\right) \cdot solar_{TWe(t)}$$

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Solar_TWe accounts for the level of solar power accumulated, balanced between the new power installed (*new_solar_TWe*), the wear of infrastructure (*wear_solar*) and the replaced infrastructure (*replacement_solar*):

$$\frac{d(solar_{TWe})}{dt} = new_{solar_{TWe}} + wear_{solar_{TWe}} + replacement_{solar_{TWe}}$$

Figure 40 shows the dynamics of the with an example to illustrate the behaviour of exponential growth constrained by an exogenous limit (upper panel, annual variation of electric solar production; lower panel, total electricity generation from solar). Thus, MEDEAS dynamically accounts for the electrical production, the land occupied and the required monetary investment needed.

It should be however highlighted that continued exponential growth trends might be an optimistic assumption in the light of real developments. For example, an analysis of a set of countries with high PV production reveals that when its share in the electricity mix surpasses 2-3% the exponential trend is not maintained, and from 4-5% in many cases a lineal growth trend cannot even be maintained (see also Table 20 in section 0).

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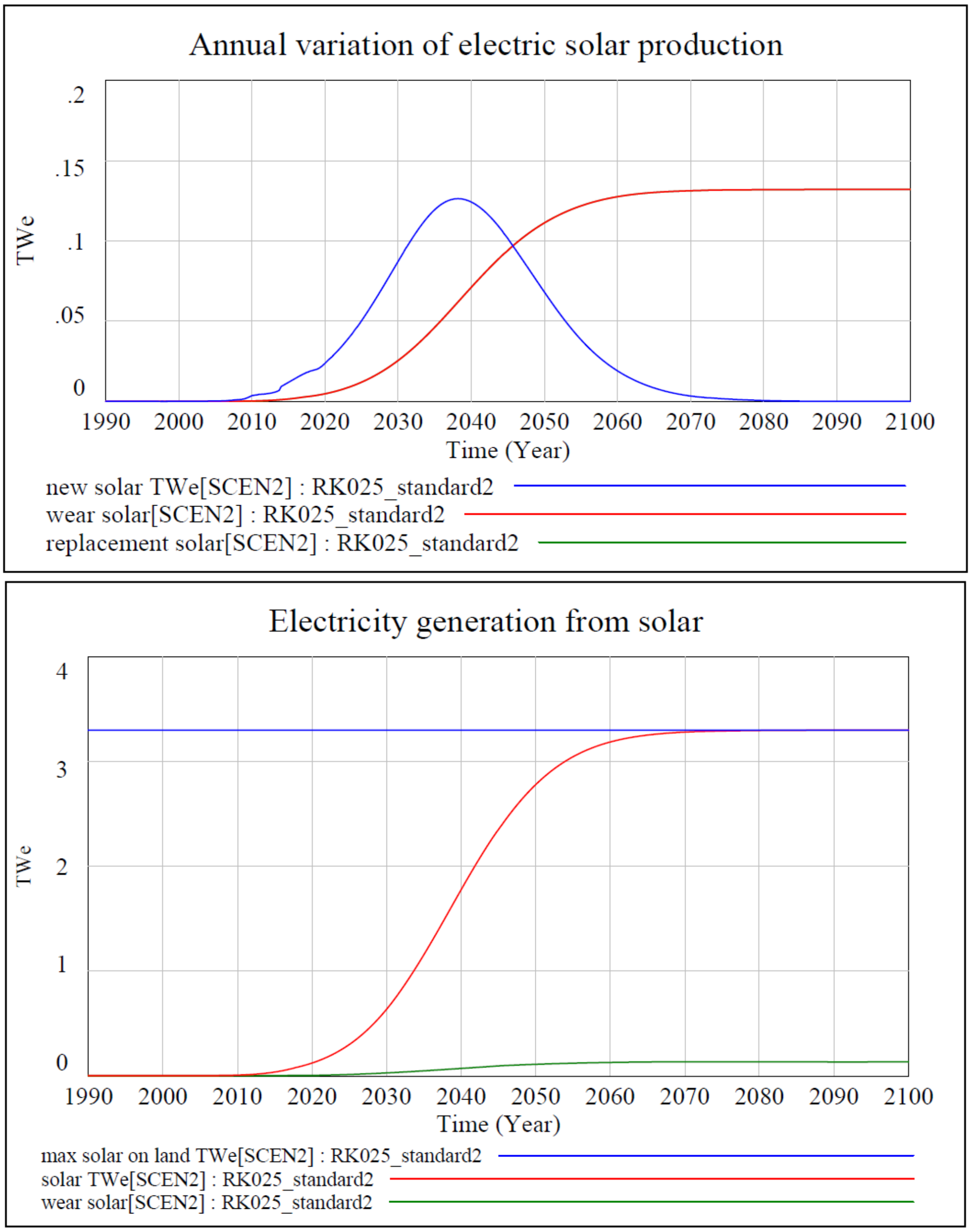

Figure 40: Total electric solar production (TWe). In this figure we represent the dynamics of the previous equation considering a very rapid growth of solar (+19%, as in scenario 1). While being far from the potential limit, exponential growth drives the growth of new solar power. As the total solar power installed increases, the depreciation of infrastructures becomes significant. Finally, just 15 years after reaching the maximum installation rate, 95% of the potential is achieved in 2065.

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2.3.5.2. Electricity generation from oil

The current generation of electricity is dominated by fossil fuels (75% in 2010 (WEO, 2012)), dominated by coal (46%) and gas (23%)). The contribution of oil is declining since the 70s and currently represents around 4%. We implement the policy to linearly extrapolate past trends assuming that oil, due to its high quality and increasing scarcity in the future, will be driven out from the electricity generation around 2025 to be used in more specific applications (see Figure 41). However, it should be highlighted that oil is often used in isolated areas and as a back-up fuel in many installations (e.g. hospitals, airports, etc.).

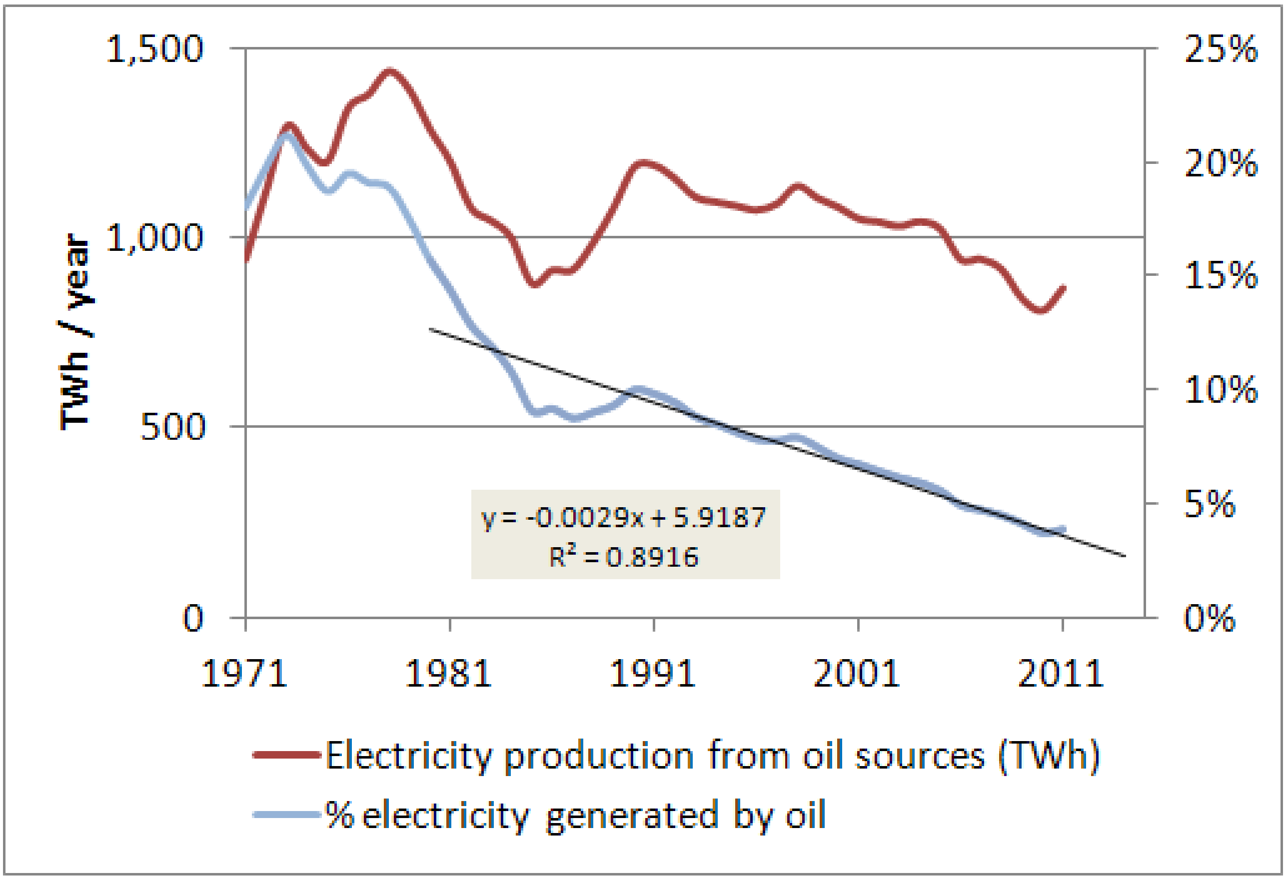

Figure 41 (own analysis from (World Bank database, 2018)): Electricity production from oil sources (TWh) and as percentage of the total electricity production.

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2.3.5.3. Nuclear power scenarios

Due to the uncertainty in future nuclear deployment, we consider 4 possibilities in relation to nuclear fission power capacity:

1. Constant power at current levels (optimistic realist as argued by Schneider et al., (2012),
2. No more nuclear capacity installed, current capacity depreciates,
3. Growth of nuclear power installed capacity,
4. Phase-out of nuclear power.

Global nuclear power plant capacity is explicitly represented in MEDEAS. Since nuclear power plants require a depletable input to operate (uranium), the electricity produced by uranium is modelled by three structures for representing: the exogenous demand of each scenario (TWh), the installed capacity (GW) and a submodule of uranium extraction similar to the ones for other non-renewable energy extraction (see Figure 27). Ultimately, the electricity generation is the minimum between the available uranium and the existing infrastructure.

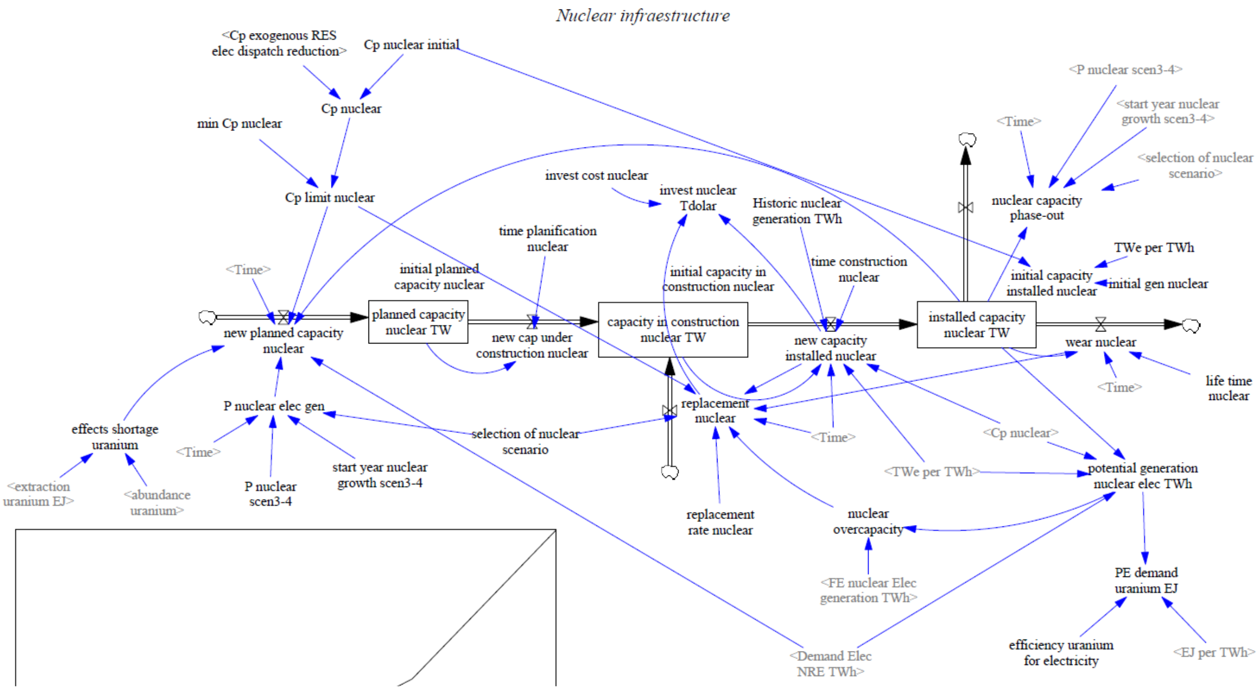

Figure 42: Stock and flow diagram of electric generation from nuclear power.

As a result, in those scenarios where the nuclear capacity is expanded, uranium availability might constraint supply, eventually generating transitory problems of overcapacity. It is assumed that there are not new nuclear capacity additions when the demand of uranium exceeds its availability.

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For the sake of simplicity, in this model version it is assumed that decommissioned power is always replaced. Under this modeling, capacity constraints do not operate. However, as a result of the penetration of the electric intermittent RES the Cp of the nuclear plants falls which ultimately causes the decrease in the annual average output per installed capacity. A Cp minimum of 60% is set due to the specific characteristics of nuclear power plants which cannot operate a low Cp levels.

In relation to construction times, although most constructors assume a 5-year construction period, real data shows that this is an underestimate. For example, (Schneider and Froggatt, 2016) calculate that the average construction time of the 10 units that started up in 2015—eight Chinese, one Korean and one Russian that took almost 31 years to complete—was 8.2 years. The actual lead time for nuclear plant projects includes not only the construction itself but also lengthy licensing procedures in most countries, complex financing negotiations, and site preparation. Thus, MEDEAS assumes 1 year of planification and 8 years of construction for nuclear power plants.

Since the costs of nuclear have continuously upscaled since the deployment of this technology (Grubler, 2010), we take a conservative approach considering that future reactors would require the same investment as the recent Hinkley Point C nuclear power station in UK of 8,000 US$/kW (Schneider and Froggatt, 2014).

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2.3.5.4. Electricity generation from CHP plants

The modelling of CHP plants is explained in detail in section 0. The development of these plants is estimated as a function of the remaining commercial heat demand that is not covered by renewables sources. Tendencies are maintained. Once commercial heat produced in CHP plants is estimated to cover the demand, CHP plants efficiencies are used to obtain the electricity produced in each of these plants.

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2.3.6. Heat generation

Due to the variety of energy sources and end uses, heat can be produced and consumed at many scales, ranging from very small domestic applications at the local level to large-scale use in industrial processes and district heating networks. One important characteristic of heat is that it can be produced from different fuels and be provided at different temperature levels. In the following descriptions, heat-temperature ranges will be 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 enduse sectors (IEA, 2014).

Energy for heating currently represents over 40% of total final energy demand – a greater share than the entire power sector. But heating does not feature as high on the agenda in energy debates. Compared to renewable power generation which continues to enjoy double-digit growth rates, renewable heating and cooling technologies have grown at a much slower pace. (REN21, 2017) partly attributes this to the fact that due to the decentralised and technical diversity of heating applications, but also to the multitude of decision-making processes – primarily at the customer level. More complex and therefore fewer renewable energy support policies have also hindered growth in this sector.

Commercial heat is defined in IEA statistics as heat that is produced and sold to a different end user. The heat is produced through co-generation or heat plants and is often distributed through district heating networks. The heat can also be bought and sold, for instance between neighbouring industrial complexes. The transaction associated with purchased heat produces a reliable data point for national administrations to collect in a consistent manner, hence the category “heat” is reserved for these quantities in IEA statistics. Most heat is not sold, however, because it is produced and consumed directly on-site, through space heating for homes or industrial processes on a manufacturing site. Due to the variety of end uses, useful heat outputs are rarely measured unless there is a commercial need or financial incentive to invest in measuring the useful heat outputs at the end-user level (IEA, 2014). Due to this discrepancy, a correction is introduced in MEDEAS to estimate the heat demand of non-commercial applications (see section 0).

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In order to account for the heat generation demand, distribution losses must be added to the heat consumption trends. An analysis of the period 1990-2014 reveals that these losses were approximatively 6.15% of the commercial heat consumed (Figure 43). We assume the same losses for non-commercial heat due to the lack of available data.

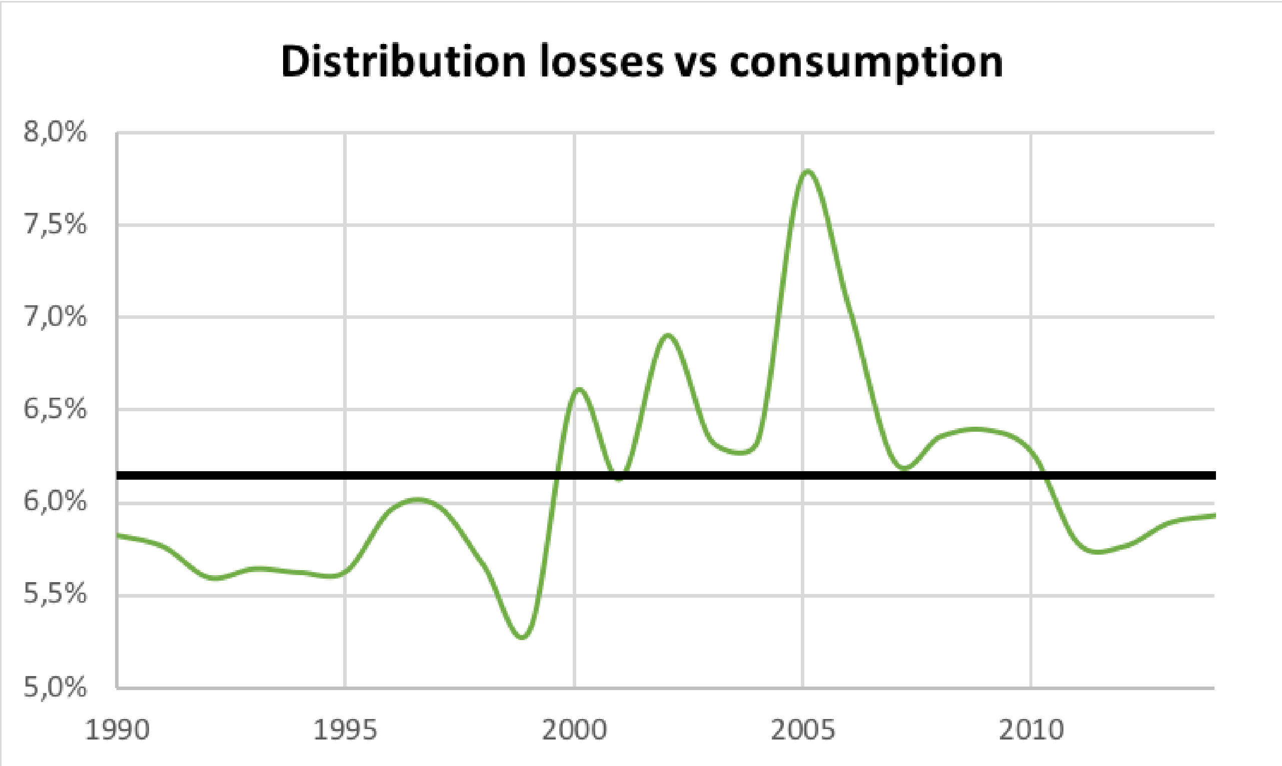

Figure 43: Distribution losses vs. consumption at global level for commercial heat (1990-2014) (IEA, 2018).

The heat generation is estimated applying the following equation.

$$E_{heat}^{gen} = E_{heat}^{cons} \cdot (1 + 0.0615)$$

The modelling of heat generation in MEDEAS is as following: priority is given to the evolution of exogenously variables (liquids, CHP and RES); the remaining is distributed equally between coal and gas following their share in 2014 (62% and 38% respectively).

The efficiencies are applied for the non-renewable heat generation following the IEA Balances (IEA, 2018). The efficiency in 2014 remains constant in the next decades.

The generation of heat from RES, CHP and liquids are exogenously projected depending on the scenarios modelled.

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2.3.6.1. Heat generation from liquids

The current generation of heat is dominated by fossil fuels. The contribution of liquids is declining since the 70s and currently represents around 4%. We implement the policy to linearly extrapolate past trends assuming that oil might be driven out from the heat generation around 2025 to be used in other applications (see Figure 44). However, it should be highlighted that oil is often used in isolated areas and as a back-up fuel in many installations (e.g. hospitals, airports, etc.).

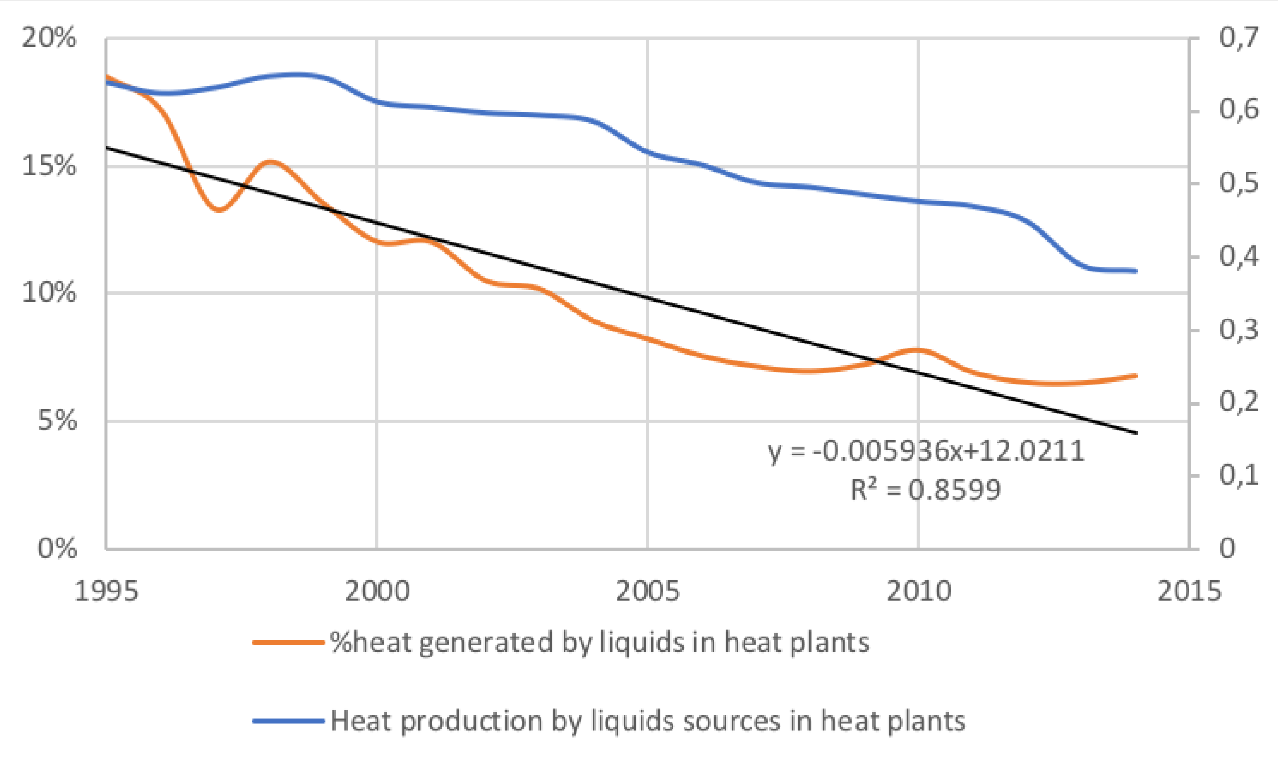

Figure 44: Heat production from oil sources (TWh) and as percentage of the total heat production (own analysis from (World Bank database, 2018)).

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2.3.6.2. Heat generation from RES

In MEDEAS, RES have priority in the fulfilment of the heat demand. Solar heat is the fastest growing RES technology for heat in the last years, although its growth does not reach the speed of RES for electricity such as solar or wind (see Table 25).

In relation to the potential of these resources to fulfil the whole heat demand, a study reported that 58% of the experts interviewed agreed that thermal renewable heating technologies such as solar thermal collectors, geothermal and bio energy will remain the backbone of (process-) heating supply for the coming decades, 7% disagreed, and 35% were undecided (REN21, 2017).

Table 21: Historical installed capacity growth of RES technologies for heat generation (annual averaged growth over the period), commercial and non-commercial uses aggregated.

Technology	**Reference** **(See** (MEDEAS, 2016a)**)**	**Annual averaged capacity growth over the period**	
		Historic trends (2000-2014)	Recent trends (2012-2015)
Solid biofuels	(IEA, 2018) and own estimation	+3.6%	+11.5%
Solar heat	(IEA, 2018), (SHC, 2016) and own estimation	+14.4%	+12.7%
Geothermal heat	(IEA, 2018), (Lund and Boyd, 2015) and own estimation	+7.4%	+7.6%

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2.3.6.3. Heat generation from CHP plants

Cogeneration Heat and Power (CHP) plants are a type of plants that generate at the same time electricity and heat. These plants can use RES and NRE.

In MEDEAS, the use of CHP plants is related to the demand of heat for non renewable sources. This happen because in heat demand the priority is given to RES sources. The demand not covered by RES sources is covered by fossil fuel Heat plants and CHP plants. Among these plants, the priority is given to CHP plants because their efficiency is better than only heat/electricity plants

Then, heat production in CHP plants depends of heat demand for NRE. Historic data shown that arround 46.5% of the heat demand not covered by renewable sources is covered by CHP plants (Figure 45):

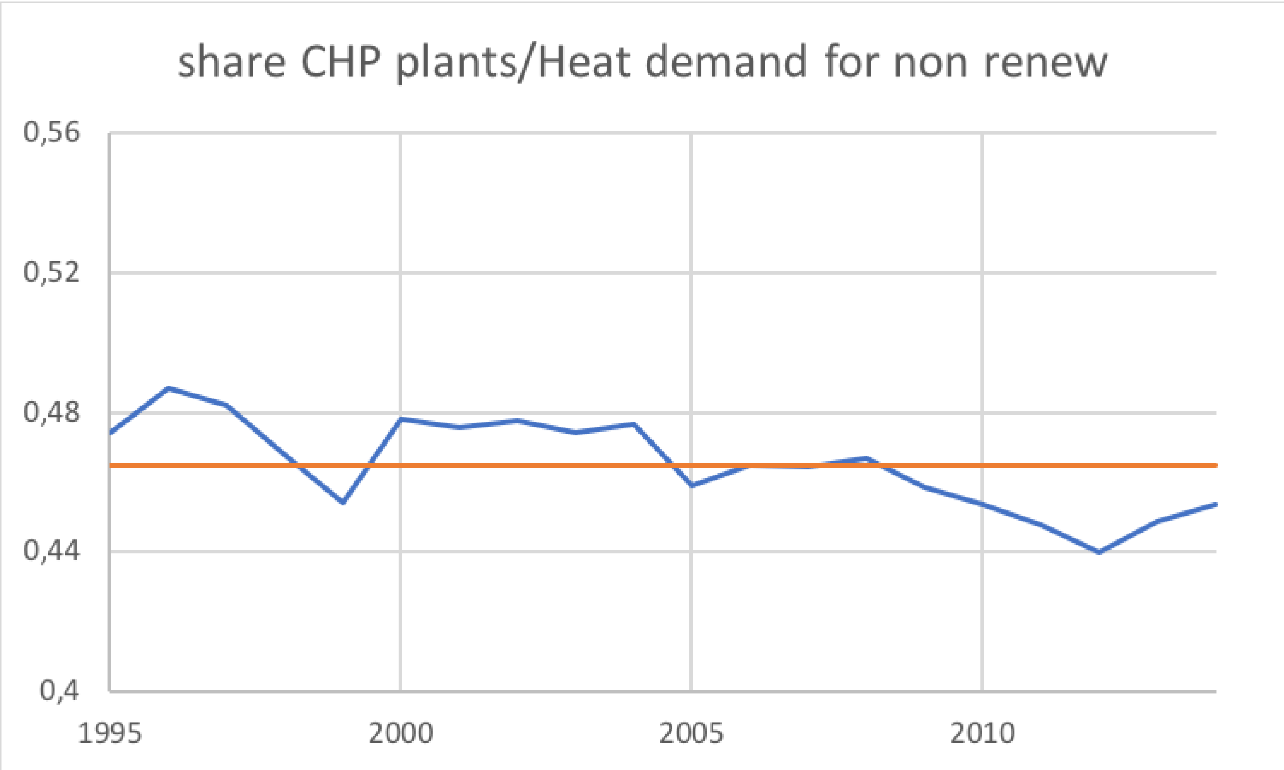

Figure 45: share of Heat demand without RES sources covered by CHP plants

Once the demand that CHP plants have to cover is estimated, the procedure is similar to the method used for electricity and heat plants. RES have priority in the fulfillment of the supply and the remaining is covered by the fossil fuels. Like for other types of plants, it has been observed that there is a decreasing trend in the use of oil for CHP plant in the last years. So, we introduce a lineal

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decreasing trend in order to reach cero around 2050. The remaining heat demand is thereafter covered by coal and gas. As we know historical data, we assume as a first approximation that coal and gas share will remain constant.

At the same time, CHP plants produce electricity. The following efficiencies derived from (IEA, 2018) are used to calculate the electricity produced in each plant.

Table 22. CHP plants efficiencies for heat for the 2014: Own elaboration from (IEA, 2018).

	GAS	**COAL**	**OIL**
Efficiency elec CHP plants	0.33	0.31	0.33
Efficiency heat CHP plants	0.28	0.26	0.26

It also exists some co-production in nuclear plants. It is considered that the heat produced in nuclear plants is a fixed share of the total electricity produced.

In this way, CHP plants are estimated in MEDEAS through tendencies and always as a function of the remaining commercial heat demand that is not covered by renewables sources. Further work could include CHP development policies.

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2.3.7. Transportation

Consumption in transport covers all transport activity (in mobile engines) regardless of the economic sector to which it is contributing including: road (passenger and freight), aviation, rail, marine bunkers and domestic navigation and pipeline transport. Transportation largely relies (95%) on liquid fuels; and 55% of the world total liquid fuels are dedicated to the Transportation sector. Transportation is a key sector, which has a strong dependency on oil and is essential for most industrial processes and services, and increasingly also for the food sector (Lassaletta et al., 2014). The lack of energy for transportation is expected to have an impact on all of the other sectors, especially in a strongly globalized economy.

As much of the global vehicle market is already covered by fuel-economy standards, the need for additional abatement from the transport sector is comparatively lower than for the power and industry sectors (WEO, 2014).

The most immediate technological substitutes for the consumption of oil in transport are biofuels, electric and hybrid cars and natural gas vehicles (NGVs), as these are technologies that are already being utilised. Greater efficiency may also be expected, through improvements in the engines and the change to lighter vehicles. This is similar to the introduction of hybrid vehicles, as it simply represents a smaller consumption per vehicle. Cars using hydrogen, synthetic fuel and similar alternatives are not introduced in the model as they are still in a developmental stage. Other ways of saving energy, such as railways and changes in mobility patterns require more profound social transformations and costly infrastructures (and for the moment are not included in the model).

Energy for transportation is consumed in different economic sectors and in private households activity. In MEDEAS, the economic sectors linked to transportation are Inland Transport, Water Transport, Air Transport and Other Supporting Transport Activities Activities of Travel Agencies, these include (passenger and freight), aviation, rail, marine bunkers and domestic navigation and pipeline transport. Another important transport activity is the one related to households private transportation, whose energy requirement is an important percentage of the total transportation energy.

55% of the world total liquid fuels are dedicated to transportation, and the transportation, as well, largely relies on liquid fuels (95%). The most immediate technological substitutes for the consumption of liquid fuels in transport are electric cars and natural gas vehicles (NGVs), as these are technologies that are already being utilised. Greater efficiency may also be expected, through improvements in the engines, hybrid vehicles and the change to lighter vehicles. Cars using

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hydrogen, synthetic fuel and similar alternatives are not introduced in the model as they are still in a developmental stage. Other ways of saving energy in transportation include the shift from private to public transportation, the substitution of four wheel vehicles by two wheelers and the shift to non-motorized modes of transportation in cities. The shift to alternative energy sources for transportation needs a shift to different vehicles or a modification (in the case of gas). This shift is already taking place (at a very slow pace) in household, two wheelers and light vehicles, but at present is not noticeable in heavy vehicles, marine or air transportation.

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2.3.7.1. Methodology

MEDEAS modelling of the transport sectors is based on two main dynamics: a general improvement of liquid based vehicles due to improvements in motor efficiency -which is relatively low since vehicle market is already covered by fuel economy standards (WEO, 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.

Household vehicles are organized into six types: liquid, electric, hybrid and gas 4 wheelers and liquid and electric 2 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. Some of the categories of vehicles have not been considered because they do not seem to be realistic such as gas 2 wheelers or trains and electric heavy vehicles. The basis of the model is the change in the energy intensity of transport sectors and households due to the change of vehicles or in the general efficiency.

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2.3.7.1.1. Households intensity variation

Households intensities are the relation between their economic demand and the energy of each type consumed. This energy consumption could be separated into transport and non-transport related energy, therefore household intensities might be expressed as:

$$IH_{liq} = \frac{L_{Ht} + L_{H\,no\,t}}{DH} \qquad IH_{elec} = \frac{E_{Ht} + E_{H\,no\,t}}{DH} \qquad IH_{gas} = \frac{G + G_{H\,no\,t}}{DH}$$

Where IH_{liq} IH_{elec} IH_{gas} are the households intensities for liquids, electricity and gas *DH* is the households economic demand, $L_{Ht}, L_{H\,no\,t}$ are the liquids consumed by households in transport and in non transport activities, $E_{Ht}, E_{H\,no\,t}$ is the electricity and $G_{Ht}, G_{H\,no\,t}$ the gas (heat and solid fuels are not considered for transportation).

The derivatives of these intensities can be separated into a term related to transportation and a term related to other uses. Assuming that other changes are kept constant and only the energy related to transportation is modified, we might relate the change of household intensities to the percentage of each type of vehicle, since, for liquid vehicles:

$$\frac{dIH_{liq}}{dt} = \frac{d}{dt}\left(\frac{H \cdot \%H_{liq4w} \cdot use_{H4w} \cdot EF_{liq4w}}{DH}\right) + \frac{d}{dt}\left(\frac{H \cdot \%H_{hyb4w} \cdot use_{H4w} \cdot EF_{hyb4w}}{DH}\right) + \frac{d}{dt}\left(\frac{H \cdot \%H_{liq2w} \cdot use_{H2w} \cdot EF_{liq2w}}{DH}\right)$$

Being H the total number of household vehicles (2 wheelers plus 4 wheelers), $\%H_{liq4w}, \%H_{hyb4w}, \%H_{liq2w}$ the percentages of liquid 4 wheelers, hybrid 4 wheelers and liquid 2 wheelers, $use_{H4w,} use_{H2w}$ the average use of 4 wheels and 3 wheels vehicles done by household uses measured in terms of Km/year vehicle, EF_{liq4w} , EF_{hyb4w} EF_{liq2w} the technical efficiencies of vehicles expressed in terms of the energy per Km.

Technical efficiencies can be expressed as relative to the efficiency of liquid vehicles using what we call saving ratios:

$$EF_{hyb4w} = EF_{liq4w} \cdot sr_{hyb}$$

Since the purpose of this modelling is finding out the effect of the change of vehicle sharing in households intensities we can assume that the number and use of household vehicles divided by households demand is a constant, this means that the relation between transportation use and economic demand is constant.

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Therefore we might define the following constants:

$$A_1 = \left(\frac{H \cdot use_{H4w} \cdot EF_{liq4w}}{DH}\right) \qquad A_2 = \left(\frac{H \cdot use_{H2w} \cdot EF_{liq2w}}{DH}\right)$$

And express the variation of the intensity as a function of the variations of percent of different vehicles.

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

A similar approach might be used for electricity, since:

$$\frac{dIH_{elec}}{dt} = \frac{d}{dt}\left(\frac{H \cdot \%H_{elec4w} \cdot use_{H4w} \cdot EF_{elec4w}}{DH}\right) + \frac{d}{dt}\left(\frac{H \cdot \%H_{elec2w} \cdot use_{H2w} \cdot EF_{elec2w}}{DH}\right)$$

If

$$EF_{elec4w} = EF_{liq4w} \cdot sr_{elec4w} \qquad EF_{elec2w} = EF_{liq2w} \cdot sr_{elec2w}$$

$$\frac{dIH_{elec}}{dt} = \frac{d}{dt}\left(\frac{H \cdot \%H_{elec4w} \cdot use_{H4w} \cdot sr_{elec4w} \cdot EF_{liq4w}}{DH}\right) + \frac{d}{dt}\left(\frac{H \cdot \%H_{elec2w} \cdot use_{H2w} \cdot sr_{elec2w} \cdot EF_{liq2w}}{DH}\right)$$

And:

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

In a similar way, for gas vehicles:

$$EF_{gas4w} = EF_{liq4w} \cdot sr_{gas4w}$$

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

Parameters A_1 and A_2 are estimated using the values of the initial calibrating year (t0, T hist H transp, default 2015) since we can assume that all the energy used by 4 wheels vehicles is liquids and all the electricity is due to 2 wheelers. Since we know the energy used by electric and liquids 2 wheelers and 4 wheelers the following equations can be set:

$$IH_{liq} = A_1 \cdot \%H_{liq4w} + A_2 \cdot \%H_{liq2w} = \frac{líquids\ 4w + 2w\ households(t0)}{demand\ households(t0)}$$

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$$IH_{elec} = A_2 \cdot \%H_{elec2w} = \frac{electricity\ 2w\ households(t0)}{demand\ households(t0)}$$

Which enable the calculation of A_1 and A_2 constants.

Using the previous equations the model is defined in the diagram of

Figure 46. The percentages of vehicles of each type (vector percent H vehicles) are the drivers of the subsystem and vary according to the desired policies. The change of these percentages (*var percent H vehicles*) modifies the variation of energy intensities of households transport.

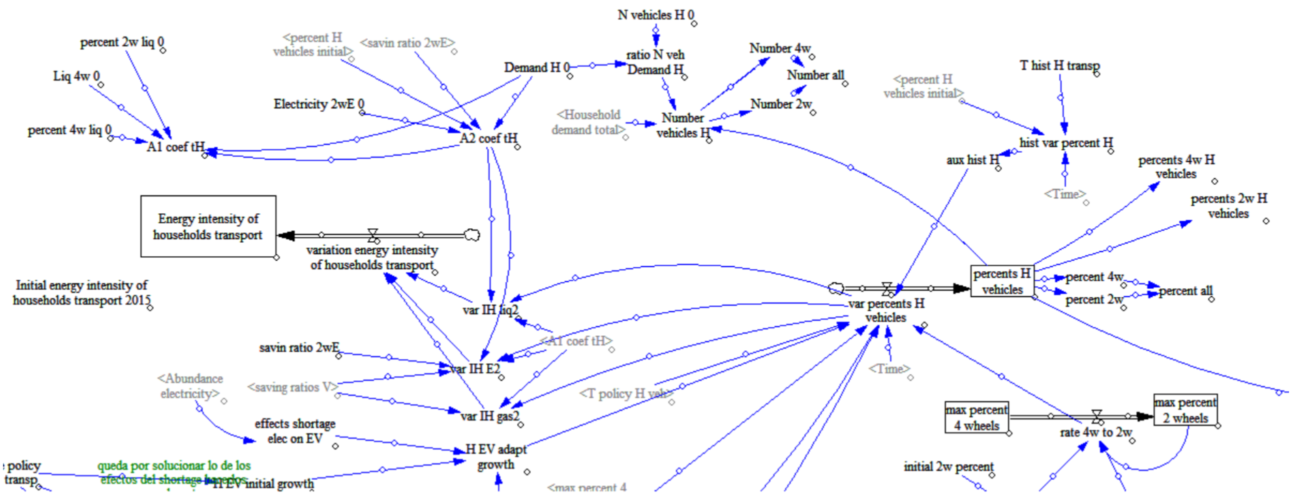

Figure 46: Stock and flow diagram of the household transport subsystem.

The number of vehicles is estimated approximately using the ratio, calculated in the year of calibration (*T hist H transp* ,default 2015)

$$ratio\ N\ veh\ demand\ H = \frac{Number\ household\ vehicles\ (t0)}{Household\ Demand\ (t0)}$$

And assuming this ratio in constant though the simulation, therefore

$$Number\ of\ vehicles\ tipe\ i\ (t) = Household\ Demand(t) \cdot ratio\ N\ veh\ demand\ H \cdot percent\ vehicle\ type\ i(t)$$

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The percent of each type of vehicle is limited to the maximum of 4 wheelers and 2 wheelers, which is also a used-defined policy which can evolve in time due to the two stocks (max percent 2 wheels, max percent 4 wheels).

2.3.7.1.2. Inland transport intensity variation

The methodology used for Inland Transport intensity is similar to the one used for Households. 13 types of vehicles are defined: HV_{liq}, HV_{hyb}, HV_{gas} for heavy vehicles of different fuels, HV_{liq} HV_{elec} ,HV_{hyb},HV_{gas} for light cargo vehicles, bus_{liq}, $bus_{elec}, bus_{hyb}, bus_{gas}$ for buses of different types (in this case electric buses are included, since they are already used…cita??) and trains $train_{liq}, train_{elec}$.

Inland Transport intensities are expressed for each type of energy as the energy of that type used divided by the economic activity of Inland Transport economic sector:

$$I_{liq\ t\ inland} = \frac{liquids_{HV} + \ liquids_{LV} + \ liquids_{bus} + liquids_{train} + liquids_{HVhyb} + liquids_{LVhyb}}{X\ t\ inland}$$

$$I_{elec\ t\ inland} = \frac{elec_{LV} + \ elec_{bus} + elec_{train} + liquids}{X\ t\ inland}$$

$$I_{gas\ t\ inland} = \frac{gas_{HV} + \ gas_{LV} + \ gas_{bus}}{X\ t\ inland}$$

Assuming that the only change in transport habits is due to the change of only type of vehicle to another, the change in these intensities would be given by:

$$\frac{dI_{liq\ inland\ t}}{dt} = \frac{d}{dt}\left(\frac{HV \cdot \%HV_{liq} \cdot use_{HV} \cdot EF_{HVliq}}{X_{t\ in}}\right) + \frac{d}{dt}\left(\frac{LV \cdot \%LV_{liq} \cdot use_{LV} \cdot EF_{LVliq}}{X_{t\ in}}\right) + \frac{d}{dt}\left(\frac{Bus \cdot \%bus_{liq} \cdot use_{bus} \cdot EF_{bus\ liq}}{X_{t\ in}}\right) + \frac{d}{dt}\left(\frac{Train \cdot \%train_{liq} \cdot use_{train} \cdot EF_{train\ liq}}{X_{t\ in}}\right)$$

Being HV the total number of heavy vehicles, LV the total number of light cargo vehicles, Bus the number of buses, and Train the number of trains. $\%HV_{liq4w}, \%LV_{liq}$, $\%bus_{liq}$ and $\%train_{liq}$ are the percentages of liquid vehicles of each type; $use_{HV}, use_{LV}, use_{bus}, use_{train}$, the average use of each vehicle in terms of Km/(year· vehicle) and $EF_{HV\ liq}$, $EF_{LV\ liq}, EF_{bus\ liq}, EF_{train\ liq}$ the technical efficiencies of vehicles expressed in terms of the energy per Km.

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We assume that the use and the number of vehicles per unit of economic activity $X_{t\ in}$ is kept constant and the only change is the variation of the type of vehicle, therefore, we can assume that the following are constant and can be estimated via the initial values of number of vehicles of each type in the initial year:

$$CX_{HV} = \left(\frac{HV \cdot use_{HV} \cdot EF_{HVliq}}{X_{t\ in}}\right); \quad CX_{LV} = \left(\frac{LV \cdot use_{LV} \cdot EF_{LVliq}}{X_{t\ in}}\right) \ ;$$

$$CX_{bus} = \left(\frac{Bus \cdot use_{bus} \cdot EF_{bus\ liq}}{X_{t\ in}}\right); \quad CX_{train} = \left(\frac{Train \cdot use_{train} \cdot EF_{train\ liq}}{X_{t\ in}}\right)$$

Technical efficiencies can be expressed as relative to the efficiency of liquid vehicles using what we call saving ratios:

$$EF_{HV\ hyb} = EF_{HV\ liq} \cdot sr_{hyb\ HV}$$

$$EF_{HV\ gas} = EF_{HV\ liq} \cdot sr_{gas\ HV}$$

$$EF_{LV\ elec} = EF_{LV\ liq} \cdot sr_{elec\ LV}$$

$$EF_{LV\ hyb} = EF_{LV\ liq} \cdot sr_{hyb\ LV}$$

$$EF_{LV\ gas} = EF_{LV\ gas} \cdot sr_{gasLV}$$

$$EF_{bus\ elec} = EF_{bus\ liq} \cdot sr_{elec\ bus}$$

$$EF_{bus\ gas} = EF_{HV\ liq} \cdot sr_{bus\ gas}$$

$$EF_{train\ elec} = EF_{train\ liq} \cdot sr_{elec\ train}$$

Therefore, changes in the intensities are related to the changes in percent of vehicles using the following formulas:

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

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

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

Constants CX might be calculated using the initial values of vehicles, since, for each constant

$$CX_{j\ vehicle} = \frac{liquids\ of\ vehicle\ j\ (t0)}{X_{t\ inland\ (to)}}$$

The model is defined in the diagram of Figure 47. The percentages of vehicles of each type (vector percent T vehicles) are the drivers of the subsystem and vary according to the desired policies. The change of these percentages (var percent T vehicles) modifies the variation of energy intensities of Inland Transport.

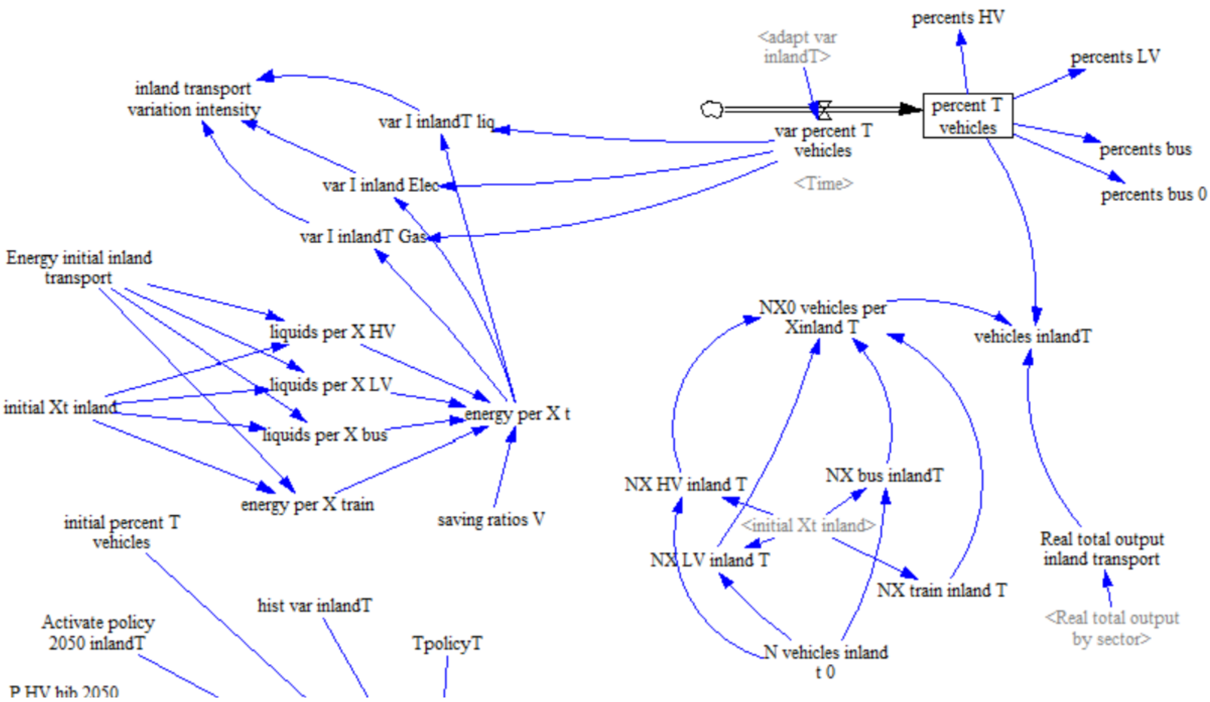

Figure 47: Stock and flow diagram of the household transport subsystem.

The number of vehicles is estimated approximately using the ratio, calculated in the year of calibration (T hist H transp ,default 2015), as described for the households vehicles.

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2.3.7.1.3. Batteries for electric vehicles methodology

Batteries are an important component of the transport systems since they might pose a restriction on material and they might be used as a storage for the electric network. Since the number of vehicles is already estimated the number of batteries can be calculated quite straight forward. Figure 48 shows the diagram of the *TRANSP total vehicles and batteries* submodule. In this module the total number of electric vehicles of each type is calculated adding Households and Inland Transport sector. The desired number of batteries is calculated by assuming a standard battery of 21KWh (average for pure electric light vehicles) and using batteries ratios for hybrid vehicles, heavy vehicles and two wheelers, since those vehicles require smaller or bigger batteries depending on their weight and the fact that hybrids have a much smaller battery than pure electric vehicles. Since batteries age and must be replaced, a stock of batteries is used. This stock has got a discard ratio (based on batteries lifetime) and a new batteries ratio, which adjust logistically to the desired number of batteries. While the stock *batteries EV+hib+2wE* is calculated in terms of the number of standard batteries the variable *EV batteries TW* calculates them in terms of energy storage in TWatts and the variable *new batteries* shows the new sales of batteries that should be needed.

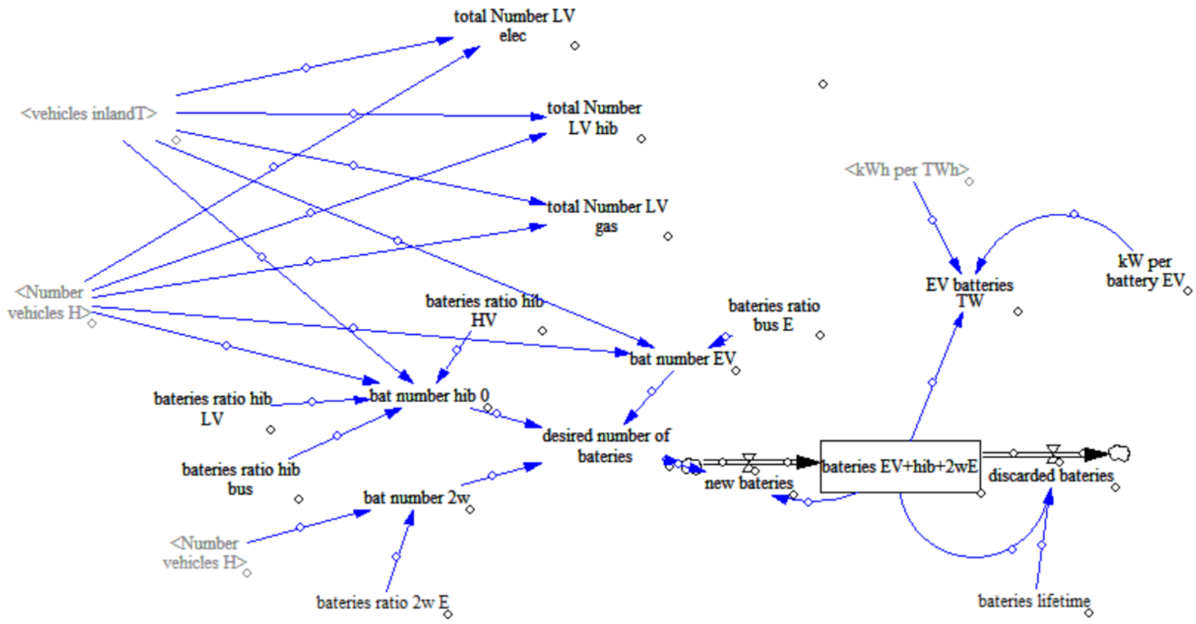

Figure 48: Diagram of the batteries submodule.

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2.3.7.1.4. Transport Policies Methodology

The implementation of transport policies in the model is based on the growth ratios of percent of vehicles. In the sub model of Households transport (see Figure 49) the variable *var percent H vehicles* is calculated using variables *H EV adapt growth, H hib adapt growth, H gas adapt growth, H 2wE adapt growth* which are calculated via the policies elected by the user in different scenarios (*P EV 2050, P hib 2050, P gas 2050, P 2wE 2050*). By default the growth of vehicles percent increases linearly with time and gets moderated when reaching the limit (all available 4 wheels percent already transformed, for example) and when the alternative fuels get scarce (*effects of shortage* variables). The growth of liquid fuels vehicles adapts to the growth of others (decrease).

For the Inland Transport vehicles (see Figure 50) *adapt var inland T* is the variation of the stock of *var percent T vehicles* and is governed by policies *P H hib, P HV gas*…etc. By default the growth of vehicles percent increases linearly with time and gets moderated when reaching the limits and when the alternative fuels get scarce (*effects of shortage* variables). The growth of liquid fuels vehicles adapts to the growth of others (decrease).

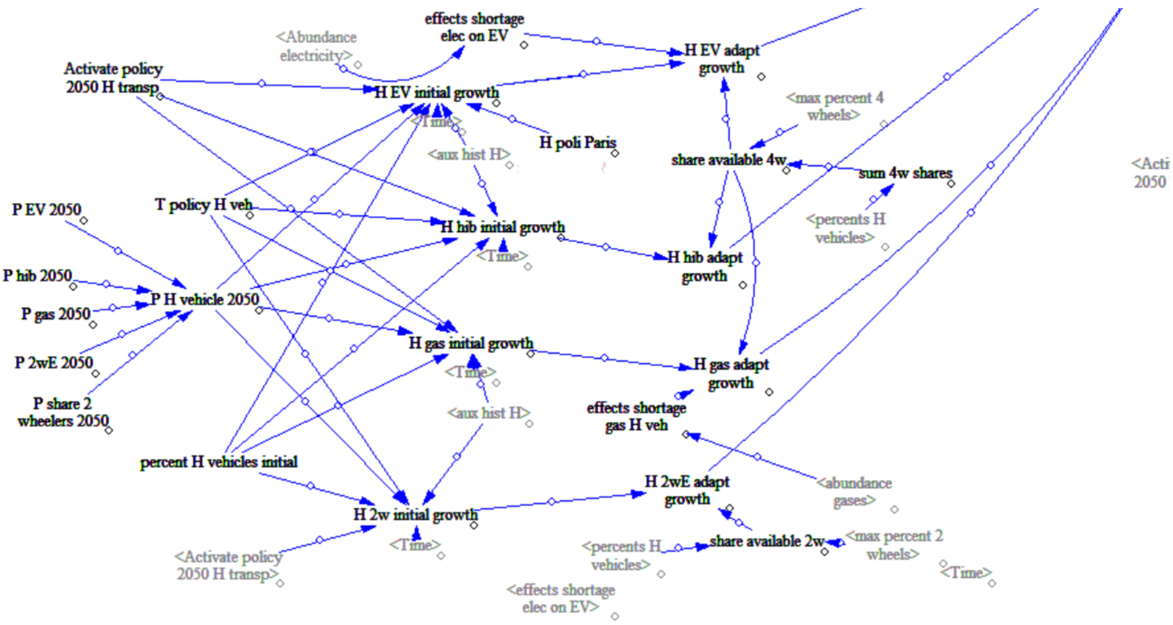

Figure 49: Diagram of the policies of Households Transport subsystem

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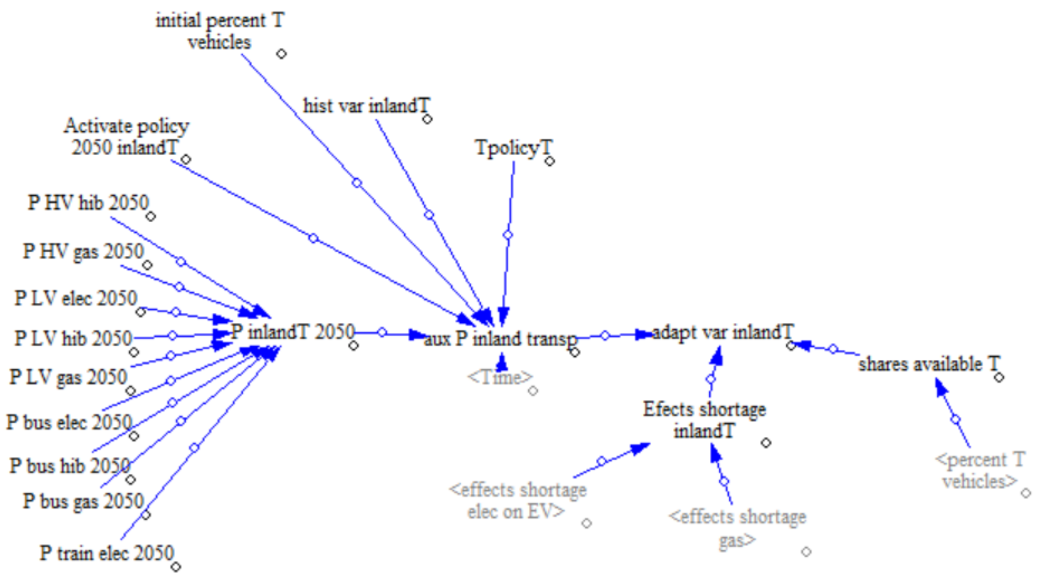

Figure 50: Diagram of the policies of Inland Transport subsystem

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2.3.7.2. Data and parameters of the transportation submodels

This section shows the data and parameters used for the methodology described in section 0.

2.3.7.2.1. Electric vehicles data

In spite of the promising forecasts done in previous decade, the global electric car stock in 2015 is stille very low compared to the global amount of vehicles (see figure 5.6 for historical values). In their 2009 report (IEA 2009), the International Energy Agency proposed a "Blue EV Success" scenario which foreseed 7 million of EV and plug-in hybrid vehicles by 2020, and the EVI (EVI IEA, 2013) set a target of 20 million EVs on the road 2013by 2020, while the stock of those vehicles in 2015 was 2,4 million (1 million battery electric), a 0,1% of the light passenger vehicles in the World (IEA ETP, 2016).

The prospects for electric vehicles (EVs) 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. MEDEAS considers BEV (battery electric vehicles) and PHEV (plug-in hybrid vehicle) that are the types of electric vehicles that represent the bulk of the electric transportation for light duty vehicles (IEA, 2016). One of the most important limitations of electric cars is their low functionality in terms of the capacity of accumulation of energy: 15 times less storage, according to (FTF, 2011), even taking into account the greater efficiency of electric motors and battery technology that can be expected in the next decade. This is an important limitation and, probably, the main cause of its poor development in this decade.

IEA report (IEA, 2016) forecasts between 20 and 150 million electric cars in 2030, seting 100 million as the target of Paris agreements, which represents a strong growth from present values (see

Figure 51). This value could be stablished as an optimistic policy for households and light cargo EV growth.

Although some prototypes of electric buses are being tested and used in some cities (Wikipedia, 2017a) their number is neglictive in the statistics wich makes forecast very uncertain. A delay in the aplication of the policies of electric buses would probable be a realistic approach since these vehicles will need time in order to grow as an alternative.

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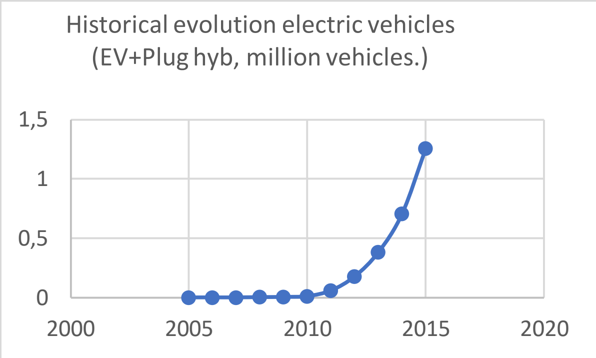

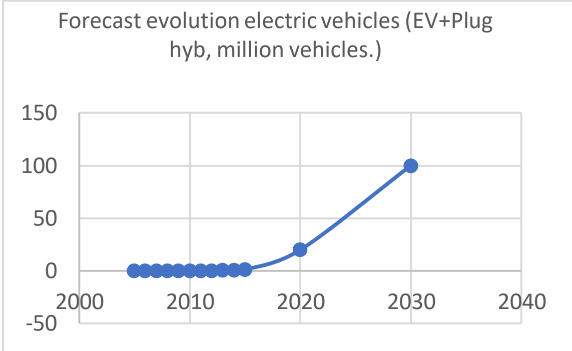

Figure 51: Historical evolution of EV+PHEV vehicles. (Own elaboration based on data from (IEA, 2016))

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2.3.7.2.2. Hybrid vehicles data

Hybrid non plug vehicles represent an energy-saving technology compared to equivalent gasoline vehicles but cannot be considered electric vehicles. The evolution of hybrid vehicles in this decade has reached 4 million vehicles (see Figure 52) in a constant pace of growth that can be considered linear in time. Hybrid vehicles in 2015 where 0,14% of the household vehicles and 0,04% of the heavy vehicles (IEA, 2016) therefore its evolution in heavy vehicles is slower than in light ones and it could be realistic to apply policies with an initial delay.

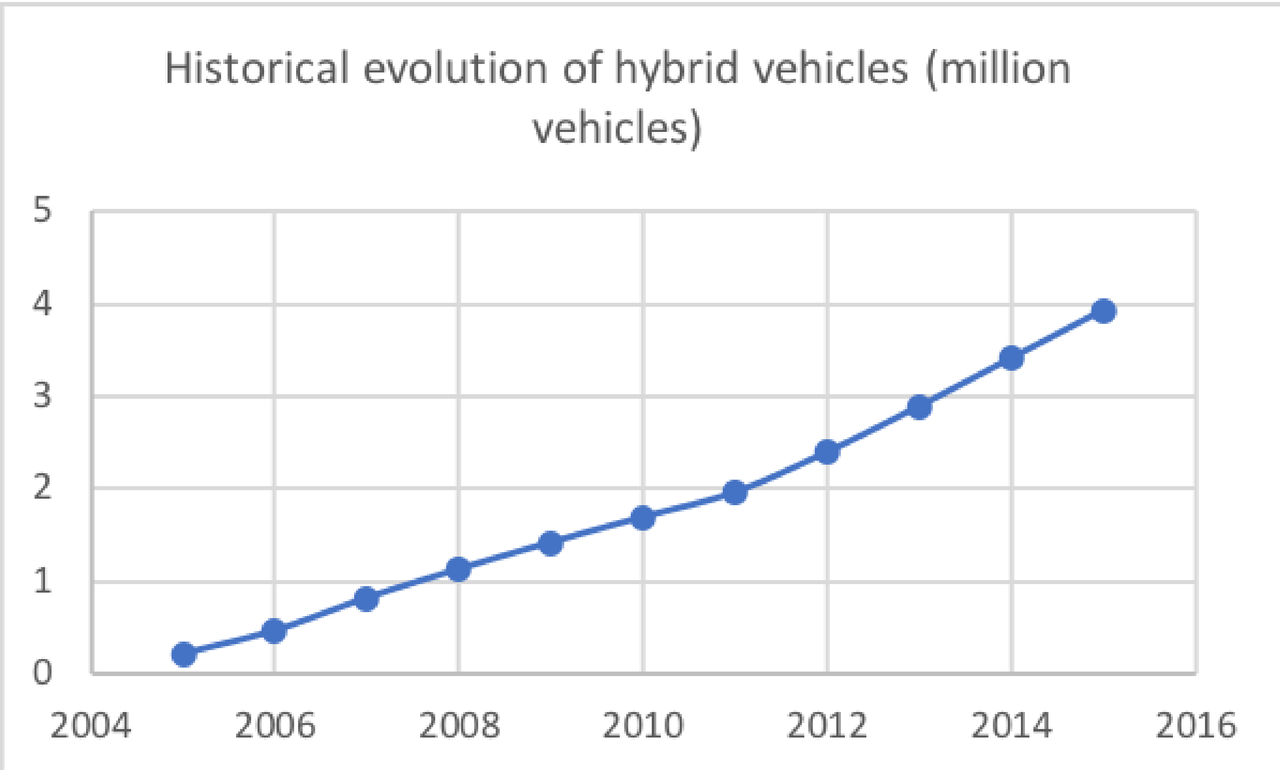

Figure 52: Historical evolution of hybrid vehicles worldwide (own elaboration based on data from (IEA, 2016))

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2.3.7.2.3. Gas vehicles data

Differently to BEV&HEV, natural gas can cover almost the whole spectrum of vehicles. Natural gas can be used in a compressed (CNG) or liquid (LNG)[21] state in several modes of transport, including road transportation, off-road, rail, marine and aviation (IEA, 2010). Generally, CNG is more commonly used for light duty vehicles, while heavy duty vehicles require more energy to run and tend to use LNG to maintain an acceptable range (IEA, 2010). Due to the strong growth in the past decade (+22% per year in number of vehicles, +17% share growth per year), by 2015 there were 59,4 million NGVs (IEA ETP, 2016). Still, this number pales in comparison the total 2800 million of vehicles (all types) and represents a 2,1% of the vehicles worldwide.

The world gas consumption in transport is expected to increase from 20 bcm in 2010 up to 40-45 bcm in 2030 (IGU & UN ECE, 2012). (WEO, 2014) projects that an expansion of 5.1% per year in gas energy use for transportation, from 40 bcm in 2012 to 160 bcm in 2040. Economic analysis indicate that natural gas can compete with gasoline in all scenarios where gas transmission and distribution grids are present (IEA, 2010). Especially, this growth is expected to remain strongest in the regions that are also currently leading in NGV market development (Asia-Pacific and Latin America). Also, due to the foreseen liquids scarcity along the first half of the century, it seems plausible to expect a high growth in the order of the past decade (+20% per year) of NGVs in the coming years.

The NGVs in MEDEAS are modelled in a similar way to the BEV&HEV by an exogenous growth driven by the market penetration level assumed to be reached in the future. The development cost of retail infrastructure, that is estimated to be significant (WEO, 2012), is not modelled for the sake of simplicity.

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[21] At atmospheric pressure and temperature, natural gas has an energy content of around 40 MJ/m3 or 50 MJ/kg, as compared to gasoline (35 MJ/L) and diesel (39 MJ/L). In order to reach an acceptable range, gas needs to be stored in a way that increases the energy density. There are currently three technologies for this. The most common are CNG and LNG. CNG is gas that is compressed to a pressure of usually 200 bar, after which it is stored in cylinders. LNG is gas that has been liquefied by cooling it to below its boiling point of -163 °C (at atmospheric pressure) and subsequently stored. There are two standards for dispensing LNG: saturated LNG (8 bar and -130 °C) or cold LNG (3 bar - 150 °C) (IEA, 2010).

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2.3.7.2.4. Electric two wheelers data

The evolution of electric two wheelers has been very fast in this decade driven by China's policies banning conventional motorcycles in cities. Data from (IEA, 2016) (see

Figure 53) show that 173 million electric two (ant three) wheelers are in stock in 2015 (the large majority of them in China), which is 21% of total two wheelers.

The Paris Declaration on Electro-Mobility and Climate Change and Call to Action sets a global deployment target for electric 2- and 3-wheelers in 2030 exceeding 400 million units (UNFCCC, 2015). A linear evolution of present trends in two wheelers growth would lead to 500 million units by that date, a value even higher that those targets. Since the historical evolution shows a linear profile and an exponential burst does not seem realistic due to the stagnation of the Chinese market, a lineal growth policy seems realistic for BAU MEDEAS scenarios.

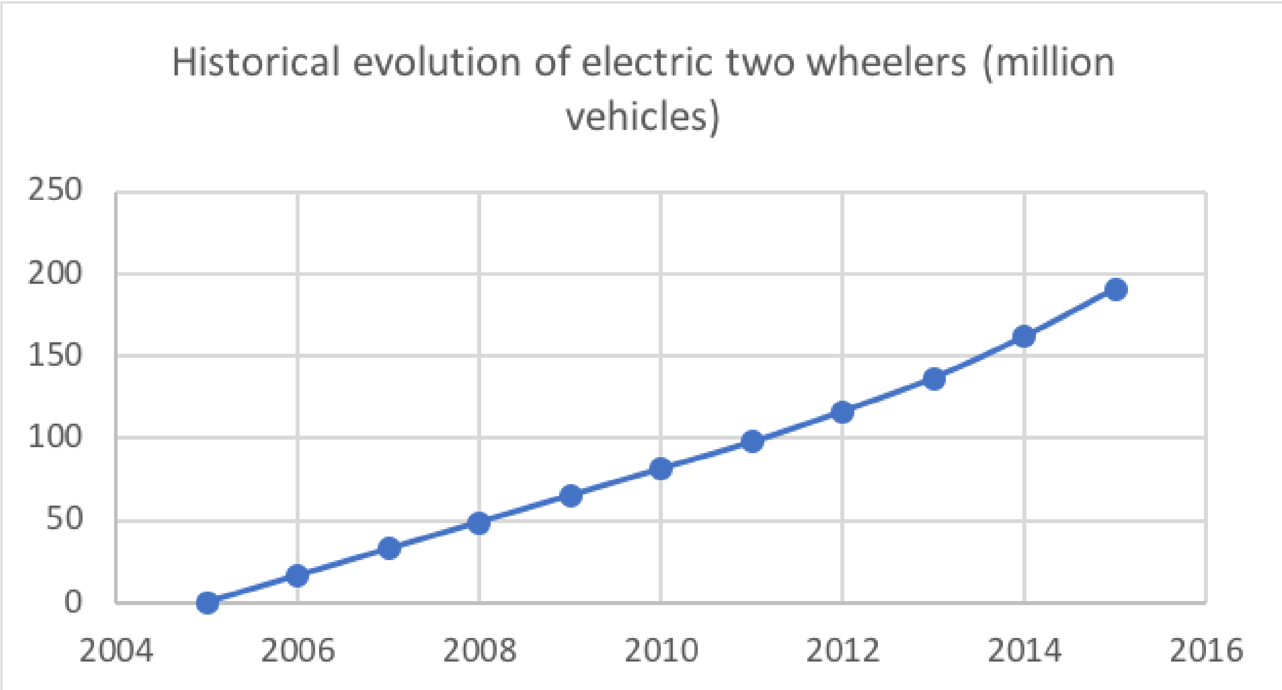

Figure 53: Evolution of the stock of electrical two wheelers worldwide. Own calculations based on data from (IEA, 2016).

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2.3.7.3. Saving ratios

In order to stablish the energy requirements of alternative modes of transportation MEDEAS model defines the saving ratios of different types of vehicles. Saving ratios are defined as the ratio of energy consumption of a give vehicle compared to the liquids-based equivalent vehicle.

For electrical four wheels vehicles EABEV gives a ratio of 0,33 (EABEV, 2008), while (Toyota, 2017) gives 0,4 and (Murphy, 2011) data give an average ratio of 0,3.

For electrical buses Irizar in its case study find a ratio of 0,5 comparing tank to wheel efficiency of their electrical buses to diesel ones (IRIZAR, 2015).

In (Guerra and Artavia, 2016), the average consumption of small electrical two wheelers, such as the ones widely used in Souther Asia is set from 2 kWh/100 km to 8 kWh/100 km with an average of 5 kWh/100km, while the equivalent gasoline 30-250cc scooter would spend an average 2,32 liters gasoil/100 km (Sanz et al., 2014). These values set a ratio of 0,21 for electrical two wheelers.

Hybrid vehicles saving ratio is set to 0,7 according to the data in (Murphy, 2011), while Toyota Prius models (Toyota, 2017) estimate a consumption of 0,66 of similar models. We assume this value can be applied to all kinds of hybrid vehicles.

Gas vehicle efficiency is similar to the one of liquid based vehicles. In (Hekkert et al., 2005) the tank to wheel efficiencies of gasoline and natural gas vehicles are set in the range 16%-25% for both, therefore the saving ratio of NGV is 1. In (Pelkmans et al., 2001), a similar conclusion is reached for gas buses operated in a case study of real traffic conditions. We assume that the same ratio can be applied to other types of gas vehicles.

For electrical trains the average consumption of railways is set for Spanish railways (Sanz et al., 2014) as 2,090 Kep passenger/Km for electricity and 3,035Kep passenger/Km for gasoil, while the ratio is 0,903 electric/1,674 gasoil for freight. These values give saving ratios 0,68 for passenger and 0,54 for freight. A ratio of 0,6 is assumed as average.

A summary of the values estimated for saving ratios is shown in

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Table 23.

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Table 23: 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	0,5	0,6	1
Two wheelers	0,21		
trains	0,6		

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2.3.7.4. Batteries for electrical vehicles

One of the limiting factors regarding electric mobility is the number of batteries. The most promising batteries at the moment are lithium-ion batteries, as an average, each electric vehicle needs between 9 and 15kg of lithium mineral per vehicle. Electric batteries might also address the short-term variability of renewable energy sources, since electric cars may act as storage devices. The IEA (IEA, 2016) estimates that "125,000 cars could be equivalent to 300 MW of flexibility – a medium size pump storage plant or a successful stationary demand side response program". The number of batteries is stimated in MEDEAS using the number of electrical vehicles calculated as described in sections 0 and 2.3.7.1.2.

An average value for purely electric cars batteries could be stablished in 21,3 KWh (such as the one of the Leaf EV, (Dunn et al., 2012)). Hybrid vehicles need much smaller batteries, and overview of the main hybrid models in (Wikipedia, 2017b) shows an average battery for hybrid light vehicles of 1,43 KWh .

Heavy vehicles, buses and two wheelers need batteries relative to their respective weights. According to (Sanz et al., 2014) the average weight of vehicles is 1276 kg for households four wheelers, 1545 Kg for light cargo duty plus an average of 500 kg of load, 380 kg for motorbikes, 12507 Kg for bus and 5327 Kg for trucks plus 10600 Kg of load.

All these data give an estimation of the ratio of batteries wheight needed froe each vehicle compared to the standard battery of electric light household cars shown in Table 24.

Table 24: Ratios of battery size relative to light purely electric vehicles.

	Electric	**Hybrid**
Household LV	1	0,10
Cargo LV	1,52	0,15
Heavy vehicles		0,83
buses	9,8	0,65
Two wheelers	0,29	

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2.3.8. Non-energy use consumption

The demand for fossil fuels for non-energy purposes such as production of bulk chemicals is poorly understood (Daioglou et al., 2014). Thus, a detailed modelling of non-energy demand use at global level is beyond the scope of MEDEAS. Following Daioglou et al., (2014), we assume a relationship between each final fuel demand i (liquids, gases and solids) and historic GDP. For the sake of simplification, we assume a lineal relationship:

$$Final\ fuel\ demand(t)_i^{non-energy\ use} = a_i \cdot GDP(t) + b_i$$

Table 25 reports the values of the parameters a and b for each final fuel.

Table 25: Results of regressions of final fuel non-energy use demand as a function of GDP.

Final fuel	a	b	r^2
Liquids	0.461	4.916	0.943
Gases	0.124	0.101	0.964
Solids	0.080	-1.673	0.896

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2.4. Materials module

The materials module in MEDEAS explicitly represents the required flows of materials by the global economy, with an emphasis on the material requirements of the key technologies for the transition to low-carbon energy systems. In fact, there is a tight link between energy and materials given that energy is required to extract, process and concentrate materials. For example, the mining industry is one of the most energy-intensive industrial sectors globally. According to the International Energy Agency, between 8 and 10% of the world total energy consumption is dedicated to the extraction of materials that the society demands, and that number does not take into account metallurgical processes, transport and other mining related activities (Task 2.2.c.2. from (MEDEAS, 2016b)). This dependence is especially relevant for renewable systems, especially for PV systems (EC, 2010; Elshkaki and Graedel, 2013; García-Olivares et al., 2012). Moreover, although metal recycling and technological change may contribute to future supply, mining will likely have to continue growing for the foreseeable future to ensure that such minerals remain available to industry (Ali et al., 2017; UNEP, 2013a). Hence, the main objective of the materials module in MEDEAS is (1) to assess the implications that mineral depletion may exert on this transition in relation to potential mineral supply constraints, and (2) allow the estimation of EROI of a set of key alternative energy technologies.

Most existing models of material demand and supply in the literature focus on a specific mineral given the specificities of the life-cycle of each mineral, including the interdependencies with other mineral extraction (Verhoef et al., 2004), e.g. (Mohr et al., 2012; Ragnarsdóttir et al., 2011; Sverdrup et al., 2017, 2014), although general frameworks also exist (Ragnarsdóttir et al., 2012). Additionally, there are large uncertainties in relation to the future availability of minerals, the usual reserves and resources estimates being even more problematic than those of fossil fuels (see section 0). Estimates of RURR in the literature to date are scarce and limited to few minerals (e.g. (Mohr et al., 2012; Northey et al., 2014)). In fact, although the concept of "peak oil" and other fossil fuels has been explored and debated extensively within the literature, there has been comparatively little research examining the concept of "peak minerals" (Bardi, 2014; Bardi and Pagani, 2007). From the demand-side, since the material intensity per sector is not available from WIOD database (being its estimation beyond the scope of this project), the approach followed for the estimation of energy demand by fuel cannot be replicated.

Given the existing uncertainties in reserves and resources data and the objective of the materials module within the MEDEAS framework, we followed the ensuing approach. On the one hand, MEDEAS estimates the materials demand for a set of 6 key technologies for the energy transition

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(solar PV, solar CSP, wind onshore, wind offshore, electric vehicle batteries and grids). Hence, the demand of 58 materials (of which 19 minerals) associated to each scenario are calculated. On the other hand, the demand of minerals the rest of the economy is roughly estimated as a function of GDP from historical data. Finally, after accounting for recycling rates, the demand of minerals is compared with their current estimated level of geological availability (reserves and resources) for qualitative detection of risks of material supply. In this model version, potential mineral scarcity is not feed-backed and do not affect the rest of the model (i.e. mineral consumption always fulfils demand).

The cumulative energy demand (CED) of the 6 aforementioned key technologies is estimated after a literature review of the energy consumption per unit of material consumption, which allows endogenizing the estimation of their EROI. Subsequently, the EROI of each renewable technology for producing electricity is used for to drive the allocation of technologies in the electricity mix. A policy in this module is the level of recycling of these materials.

This section is structured as follows: section 0 describes the methodology to derive the demand of materials, which in turn is divided in two subsections: 2.4.1.1 describes the demand of materials for key technologies for the transition to RES and 2.4.1.2 explains how the demand of the rest of the economy is modelled in MEDEAS. Section 0 describes the rationale and the approach to represent the supply of minerals in the model. Section 0 describes the modelling of recycling policies. The last three sections of this paragraph are related to EROI: section 0 documents the EROI estimation per electricity generation technology, section 0 describes the EROI-based criteria for the allocation of RES technologies in the electricity mix and section 2.4.6 explains how the EROI is feed-backed to the rest of the system.

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2.4.1. Demand of materials

2.4.1.1. Demand of materials for key technologies for the transition to RES

A literature review was performed in order to identify the materials required by 6 key technologies: solar PV, solar CSP, wind onshore, wind offshore, electric vehicle batteries and electric grids. Both new installed capacity and operation and maintenance activities are considered to estimate the material requirements.

For the first 5 technologies, the literature was comprehensively reviewed in order to collate the most complete and accurate data about material requirements for each technology. This approach differs from published meta-analyses which tend to select the average values of the range of parameters found in the literature REF. In the cases where no published data for an element/phase of the manufacture/installation of the technology was found, the material requirements have conservatively been estimated from available data from other technologies (instead of being assumed 0 as most common in the literature). For example, since no data about the material requirements for fences for CSP were found, the data estimated by Prieto and Hall (2013) for fences for PV were considered; similarly, since no data about ground removal for PV were found, so we applied data for ground removal for CSP (De Castro and Capellán-Pérez, 2018; Pihl et al., 2012), etc. In relation to the electric grids, the additional requirement of grids (i.e. "overgrids") were estimated considering that the RES reach a high penetration in the electric mix, the losses due to Joule effect and the maintenance of grids. In relation to the electric vehicle batteries we also estimate the energy requirements to maintain the vehicle fleet. All considered data are energy data, i.e. no energy values were derived from monetary costs. Additionally, in the case of uncertainty about potential double accounting, material requirements were not included. Hence, our estimations can be considered conservative/optimistic.

For each technology, a "representative" technology has been selected taking into account the present and foreseen most efficient and showing a better performance:

- CSP with molten-salt storage without back-up: most efficient and used technology. We do not consider back-up since it is usually powered by non-renewable fuels such as natural gas.
- Fixed-tilt silicon PV: better performance in terms of CED and EROI and subject to less mineral availability constraints.

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- 2MW onshore wind turbines: currently the average wind onshore turbine capacity is ~1.2 MW.
- 3.6MW offshore wind turbines:
- $LiMn_2O_4$ electric vehicle batteries: although they are less efficient than other alternatives (e.g. $LiCoO_2$), the embodied energy for their fabrication is substantially lower and Mn is subject to less mineral availability constraints than Co.

Table 26 summarizes the applied methodology for each RES variable electricity generation technology:

Table 26: Material requirements per RES variable electricity generation technologies considered in MEDEAS.

Name in MEDEAS (representative technology)	Reference(s) and comments
CSP (CSP with molten-salt storage without back-up)	Main reference: (De Castro and Capellán-Pérez, 2018). Realistic Cp of 0.25 and a lifetime of 25 years. Mirrors coated with a silver reflective layer despite (despite the potential scarcity of this mineral in the future). If considering aluminium mirrors instead, the CED would increase by ~8% (De Castro and Capellán-Pérez, 2018) and the efficiency of the system (equivalent Cp) would decrease by ~14% (García-Olivares, 2016), which would lead to a lower EROI ~80% lower ($EROI_{CSP}(Al) = EROI_{CSP}(Ag)*0,86/1,08$). For the data: diesel, evacuation lines, gravel (roads, protection…) and heavy machinery data from PV have been considered. Given that the density of material requirements (kg/m2) of CSP are ~2x comparing to PV, this approximation is thus conservative. +1.5% of additional losses has been conservatively considered as Joule effect to account for small devices (pumps, valves, etc.) which other authors have estimated in 2.5% of the CED of the construction phase.
Solar PV (Fixed-tilt silicon PV)	Main reference: (Prieto and Hall, 2013); completed with (MEDEAS, 2016a) Annex 9 and other sources. Material data have been extracted and re-calculated from Prieto and Hall (2013) excluding data indirectly estimated from economic parameters (which could eventually be considered in a calculation of $EROI_{ext}$).

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	For those materials not available in Prieto and Hall (2013), the lower estimates from MEDEAS (MEDEAS, 2016a) have been considered. For the remaining of materials not available from these sources, a conservative estimation from CSP data (25%) has been carried out taking into account that the density of material requirements of PV is 25-35% that of CSP and that the surface power density of both technologies is similar. For "heavy machinery", the depreciation of the heavy machinery is estimated as a function of the mileage of trucks estimated by Prieto and Hall (2013) following (DGTT, 2016) (since other vehicles than trucks such as tractors, etc. are not considered the approximation is conservative). For the data of "site preparation" we have considered 1/3 in relation to CSP values' given that the PV power plants can be installed in steeper slope terrains (e.g. (Deng et al., 2015)). For the data of "silicon wafer", we take as reference Alsema and Wild-Scholten (2006), who report a thickness of 300 µm (0.7kg/m2 accounting for the density of silicon), 6,400 m2/MW, i.e. 4,475 kg/MW. However, instead we consider the performance parameters from Latunussa et al., (2016) for more recent technologies of 200 µm (0.5kg/m2 accounting for the density of silicon). MEDEAS (MEDEAS, 2016a) literature review identifies the range 3,653-9,000 Kg/MW. For other technologies such as a-Si and thin-films, the wafer requires less materials and is energetically less costly, however its efficiency decreases significantly, around half (MEDEAS, 2016a) Annex 9). In the case of thin-films, material scarcity may appear (Cd, Te, Ga, In and Ge, see (MEDEAS, 2016a) Annex 9).
Wind onshore (2MW turbines)	Main reference: (GAMESA, 2013), completed with MEDEAS (MEDEAS, 2016a) and other sources. Although wind onshore turbines of higher capacity currently exist at commercial level (up to 8MW), the average current installed capacity is just ~1.2 MW. Thus, the increase in the average installed capacity will require time to surpass our "middle" estimate of 2MW. Moreover, (GAMESA, 2013) was the most complete study found in the literature. In any case, other sources referring to higher capacity turbines were found and used (prorating to obtain values of kg/MW). Material requirements of Cu, Ni, Dy and Nd have been collated from MEDEAS (MEDEAS, 2016a). In the case of Dy

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		and Nd, likely scarce in the future, their influence in the CED and EROI is reduced. Thus, from an EROI perspective its utilization is worth of given that they increase the efficiency of the turbine. In the case of scarcity, the estimations presented here would be thus too low. However, from a socio-environmental perspective, it would be better not to use them given the high impacts of their mining (Martinez-Alier, 2003; UNEP, 2013b). For the estimation of diesel requirements the methodology applied by Prieto and Hall (2013) has been applied considering the material requirements of (GAMESA, 2013). “Heavy machinery” requirements have been estimated proportionally to the required diesel. For the O&M, we have followed the replacements of the components of the turbines following (Haapala and Prempreeda, 2014; Ribrant and Bertling, 2007).
Wind offshore	3,6MW (LondonArray)	Main reference: (LondonArray, 2016). Complemented with (SMart Wind, 2013) project data and with wind (conservative) onshore specifications when data not available for wind offshore. London Array is the largest offshore wind plant in the world, and it is considered as a paradigmatic example of this technology. Data from this farm (LondonArray, 2016) have been verified with data from the Hornsea Offshore Wind Farm Project (SMart Wind, 2013) with information for turbines between 3.6 and 8MW, taking data for 8MW which usually required less materials per capacity. The latter is a wind farm far away from the coast and with projected turbines of higher size. For the case of carbon and glass fibers, we assume a 50% share for each MW installed (which is a higher share of carbon fiber than the one considered by (GAMESA, 2013) given the higher use of carbon fiber in wind offshore). For “site preparation”, we assume that the energy required per kg is twice that of wind onshore (i.e. twice amount of materials to maintain the same value of MJ/kg). We judge that the estimation is conservative given that the result is lower than that for CSP.

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Electric vehicle batteries (LiMn2O4 bateries)	Main references: data from components of the battery of Nissan Leaf, and data of its composition from (ALIVE, 2016; Dunn et al., 2012; Li et al., 2013). Batteries use graphite, phosphorus and fluor which are not included in the list of 58 materials of Table 28. These have been added in the category "wires" since their energy requirements are approximately equivalent. The grid correction factor (Joule effect) has been set to 1.1 accounting for the losses during the processes of charging and discharging the batteries. No O&M considered, no wear. The charged battery delivers 21.3 kWh which would allow to cover 117 km. Assuming a lifetime of 10 years, 2,000 cycles (equivalent to almost 150,000 km for a battery of 80kW and 210kg of weight (i.e. 12.5 batteries per MW)). Thus, the equivalent Cp is 0.0055 (80KW*10years*31.5E6sec/year). The energy output in the lifetime is 138.24GJ (including 10% of losses over the whole lifetime since the capacity is reduced after 2,000 cycles), which delivers an average electric power per battery of 439W assuming a Cp of 0.0055 (80KW*0,0055=439W). In relation to their use as ellectric storage devices, in principle they could be used the rest of the time when the EV is not being used (i.e. 1-0.0055), which could be a significant potential. However, their extensive use would wear the batteries, effectively reducing its lifetime. For example, increasing their Cp 10x would translate into 20,000 cycles. Thus, in MEDEAS we assume that the electric batteries for EV can be used for electricity storage at a same Cp than for driving, i.e. that each battery would be able to function 10 years without wear (4,000 cycles).

Additionally, the material requirements for the additional grids to be constructed to integrate the renewable variable electricity generation as well as for the O&M of the grid are estimated. For the sake of simplification, in this model version we estimate the material requirements for grids as a function of the installed power of renewable variable electricity generation technologies (CSP, solar PV, wind onshore and wind offshore). The materials required for new grids are thus assigned to

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these RES variable electricity generation technologies (O&M material requirements of both the existing and new grids are not considered). Specifically, we consider:

- Overgrids high power for variable RES for electricity generation: estimation of the additional high power grids (and associated transformers) to integrate the variable generation of electricity from renewables.
- Inter-regional grids (HVDCs)

Table 27 documents the assumptions followed to estimate the material requirements of the electric grids in MEDEAS:

Table 27 : Material requirements for electric grids related to the RES variable electricity generation technologies

Electric grid	Modelling assumptions
Overgrids high power for variable RES	The additional high power grids (and associated transformers) to integrate the variable generation of electricity from renewables is estimated. The penetration of variable renewables in the electricity generation mix requires a relative increasing construction of electric grids. For example, NREL (2012) reports 20% more grids with a RES penetration of 50% in relation to current levels (i.e., 0.725 km/MW of new installed power). This number increases to 1.09 km/MW with a penetration of 80% (+60% grids), and to 1.77 km/MW with a penetration of 90%. For the sake of simplicity, in MEDEAS we consider this factor constant at 1 km/MW of new high power aerial lines and an additional 10% (0,1km/MW) of new high power underground lines (both of 150 KV), as well as some of their infrastructures and associated costs. We believe it is a conservative estimation for at least 2 reasons: (1) high power grids are usually a minor part of the total number of grids (for example, in Europe grids over >100KV represent only 3% of the total (EUROELECTRIC, 2013)); (2) there are many more components associated to the functioning of high power lines that we are not considering such as switches, switchgears, etc. In relation to the required additional transformers, we use data from (US DOE, 2014, 2012) to estimate the number of transformers per installed MW in the USA, and extrapolate to the world. Following (US DOE, 2014), there are 450,000 miles of high power lines in the country, with an installed capacity of 1,000 GW (6,000 power plants), i.e. 0.725km/MW. Following (US DOE, 2012), there are 30,000 LP Transformers of >100MVA and a similar number of >60 y <100MVA. This represents around 5 transformers per power plant or 30 transformers of each type per installed

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	GW (0.03 transformers/MW). Since there are 725,000 km of high power grids, the ratio is 24 km/transformer (i.e. 0.042 transformers/km grid). We compare the above estimations with the European case in 2003. In that year, the electric grid in EU-26 was 9.25 million km and distributed ~2,700TWh. With a Cp of the grid of ~0.3, this would mean around 1,000 GW of installed power, i.e. 10km grids/MW. Since more than 4 million of transformers of low and medium voltage exist, this means a ratio of ~4 transformers/MW of installed power (EUROELECTRIC, 2013). Summarizing, we consider 1 km/MW of aerial lines 150 KV, 0.1 km/MW of underground 150 KV lines, 0,03 transformers of 63MVA and 0,03 transformers of 250MVA per MW of variable RES for electricity generation. Material requirements are derived applying (Jorge et al., 2012a, 2012b).
Inter-regional grids (HVDCs)	We roughly estimate the material requirements of new HVDCs lines to integrate the variable electricity generation from renewables. We estimate the total length of HVDC grids and their material requirements per installed MW of renewables for electricity (11.5TW dominated by CSP, solar PV and wind) from García-Olivares et al., (García-Olivares et al., 2012): 0.82 meters/MW submarine and 2.9 meters/MW aerial. Losses depend on the length of each HVDC line, however we take the average of ~7.5%. Applying this methodology, we observe that the material requirements of HVDCs are generally below 10% of those related to high power overgrids.

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Thus, the materials requirements for a total of 58 materials were estimated for each technology. Additionally, the water requirements for solar PV and CSP were also estimated. See Table 28 below for the detailed results.

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Table 28: Material requirements (kg) per new MW installed. Source : own compilation.

	Material intensity of technologies						
	kg/new MW	kg/new MW	kg/new MW	kg/new MW	kg/new MW	kg/new MW of each RES var elec techn	kg/new MW of each RES var elec techn
	CSP	**PV**	**wind onshore**	**wind offshore**	**Li bateries**	**material overgrid high power**	**Inter-regional grids (HVDC)**
Construction phase							
Adhesive	0	0	0.74	0.74	0	0	0
Aluminium (Al)	740	16000	2030	9400	500	7362	100
Aluminium mirrors	3280	0	0	0	0	0	0
Cadmium (Cd)	0	6.1	0	0	0	0	0
Carbon fiber	0	0	1500	3800	0	0	0
Cement	250000	75000	561600	24000	0	48	0
Chromium (Cr)	2200	550	0	0	0	0	0
Copper (Cu)	3200	2200	2700	22200	289	2044	125
Diesel	15600	15600	5700	18080.88818	0	6200	0
Dysprosium (Dy)	0	0	4.86	14.58	0	0	0
Electric/electronic components	0	0	450	450	0	0	0
Evacuation lines (KM)	150	150	0	0	0	0	0
Fiberglass	310	0	6090	3800	0	1140	0
Foam glass	2500	0	0	0	0	0	0
Galium (Ga)	0	0.3	0	0	0	0	0
Glass	130000	640000	0	0	0	562	0
Glass reinforcing plastic (GRP)	0	0	950	950	0	0	0
gravel (roads, protection…)	500000	500000	11900	900000	0	0	0
Indium (In)	0	4.5	0	0	0	0	0
Iron (Fe)	650000	162500	22000	0	0	29683	435
KNO3 mined	220000	0	0	0	0	0	0
Asphalt	0	0	0	0	0	7500	0
Lime	11000	0	0	0	0	0	0
Limestone	170000	0	0	0	0	0	0
Lithium (Li)	0	0	0	0	34.4	0	0
Lubricant	0	0	640	640	0	0	0
Magnesium (Mg)	3000	53.5	0	0	0	0	0
Manganese (Mn)	2000	500	0	0	1631	0	0
Heavy machinery (depreciation and reposition)	100	100	36.5	115.9	0	40	0
Concrete	0	0	0	0	0	130000	1160
Molybdenum (Mo)	200	50	0	0	0	0	0
NaNO3 mined	340000	0	0	0	0	0	0
NaNO3 synthetic	340000	0	0	0	0	0	0
Neodymium (Nd)	0	0	61	183	0	0	0
Nickel (Ni)	940	235	111	111	0	0	0
Over grid (15%)	0	0	0	0	0	0	0
Over grid (5%)	0	0	0	0	0	0	0
Paint	0	0	670	670	0	11	0
Lead (Pb)	0	21.2	0	0	0	1390	112
Plastics	0	5760	1940	9200	125	970	0
Polypropylene	500	0	0	0	0	190	15
Rock	1.30E+06	0	0	0	0	0	0
Rock wool	4700	0	0	0	0	0	0
Sand	1900	0	16560	16560	0	160000	0
Silicon sand	92000	0	0	0	0	0	0
Sillicon wafer modules	0	3200	0	0	0	0	0
Silver (Ag)	13	46.7	0	0	0	0	0
Site preparation (soil works), etc.	1.80E+07	6.00E+06	1.50E+06	1.20E+07	0	0	0
Tin (Sn)	0	463	0	0	0	64	0
Soda ash	18000	0	0	0	0	0	0
Steel	240000	2000	126100	400000	0	2651	200
Syntethic oil	44000	0	0	0	0	2544	7
Tellurium (Te)	0	4.7	0	0	0	0	0
Titanium (Ti)	25	6.25	0	0	0	0	0
Titanium dioxide	11.5	0	0	0	0	0	0
Vanadium (V)	1.9	0.475	0	0	0	0	0
Wires	0	0	640	640	0	0	0
Zinc (Zn)	650	162.5	0	0	0	200	0
Total construction phase					0		
grid correction factor (A34+A41)	0.075	0.06	0.06	0.06	0.1		
Operation and maintenance (yearly)	kg/installed MW	kg/installed MW	kg/installed MW	kg/installed MW			
Aluminium (Al)	0.78	0	10.8	10.8			
Carbon fiber	0	0	29.8	59.6			
Copper (Cu)	0	0	5.8	5.8			
Diesel	3450	1294	65	356			
Fiberglass	0	0	122	122			
Glass	140	0	0	0			
Glass reinforcing plastic (GRP)	0	0	19	19			
Lime	11	0	0	0			
Lubricant	0	0	25.6	25.6			
Magnesium (Mg)	3.2	0	0	0			
Plastics	0	0	9.2	9.2			
Silicon sand	98	0	0	0			
sillicon wafer	0	2.56	0	0			
Silver (Ag)	0.014	0.04	0	0			
synthetic oil	2000	0	0	0			
Clean, pumped Water	1.20E+07	0	0	0			
Distilled, deionized water	500000	20000	0	0			

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2.4.1.2. Demand of the rest of the economy of key materials for the transition to RES

The demand of minerals of the rest of the economy is roughly estimated as a function of GDP from historical data (1994-2015) (USGS, 2017). Data for Te and Nd are not available from the source at global level and could then not be projected. Current recycling rates are assumed constant over the period given the lack of historical data at global level (see section 0). Thus, for each mineral i, given its recycling rate (RR), its demand and extraction in mines are related as follows:

$$Demand_i(t) = \frac{Extraction_i(t)}{(1 - RR_i)}$$

For each mineral, the extraction level is assumed to follow a lineal function of GDP:

$$Extraction_i(t) = a_i \cdot GDP(t) + b_i$$

This approach of mineral extraction estimation presents evident limits given that the demand of minerals is estimated from an aggregated variable such as GDP instead of being derived from the requirements by sector. As aforementioned, the material intensity per sector is not available from WIOD database and its estimation is beyond the scope of this project. However, we believe that the adopted approach allows to roughly estimate the order magnitude of the mineral demands. In any case, since the potential mineral scarcity is not feed-backed, potential errors in this estimation do not affect the rest of the model (see next section).

Forthcoming scheduled work from the UNEP "Future Demand Scenarios for Metals" (Report 4) could be applied in further versions of MEDEAS (UNEP, 2013a).

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2.4.2. Supply of minerals

2.4.2.1. Analysis of the potential importance of minerals scarcity

One of the objectives of MEDEAS project is to analyse the potential importance of scarcity of minerals in the transition to a sustainable and renewable energy system. The followed approach consisted on analysing the expected increase in energy consumption for the extraction and refining of a set of minerals, since it has been showed that cumulative extraction drives the exploitation of mines with lower ore. In fact, the analysis of historic trends has shown that, although technology improvements allow to consume a lower amount of energy per kg extracted of material, the reduction of the exploited ore forces the extraction of more material to obtain the same amount of mineral. This makes that the energy required in the mining and refining process increases (non-linearly) faster than the decrease in ore grade (Calvo et al., 2016; Mudd, 2010).

However, for most minerals, the energy consumption in the mining process is relatively small in relation to the total energy consumption to make available the mineral to the society (LCA from cradle to grave). For example, for the case of Cr, Co, Fe, Li, Ni and Zn, the smelting and refining process are more than 10 times energy consuming that the mining and concentration process. Additionally, there are also some other energetic costs from the refining to the dismantling (grave) (Calvo, 2016). Hence, despite the mining process will increase the energy requirements faster than the rest of processes, its influence in the total energy requirements for most minerals is expected to remain limited. Comparing the required exergy in the mining process with the LCA cradle to point of use from the set of minerals considered in MEDEAS from (Hammond and Jones, 2011), the share of the mining process is only significant for few minerals such as Cd and Cu (although still representing less than 50% of the total exergy), and only for one mineral from our list this share represents over 50% (Ag).

To investigate the eventual importance of scarcity of minerals in the future, we analysed the full set of minerals required for the 6 key technologies described in previous section. Table 29 reports the 19 minerals analysed as well as their currently estimated level of reserves, resources and end-of-life-cycle recovery rate (EOL-RR). This set includes most of the minerals considered in (EC, 2010).

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Table 29: Reserves and resources information (source: Task 2.2.c.2. from (MEDEAS, 2016b)) and end-of-lifecycle recycling rate (EOL-RR) for the minerals modeled in MEDEAS (source: (UNEP, 2011)).

Mineral	**Symbol**	**Reserves (tonnes)**	**Resources (tonnes)**	**EOL-RR (%)**
Source		**Task 2.2.c.2.** (MEDEAS, 2016b)		**(UNEP, 2011)**
Aluminium	Al	28,000,000,000	75,000,000,000	42-70
Cadmium	Cd	500,000	6,000,000	15
Chromium	Cr	480,000,000	12,000,000,000	87-93
Copper	Cu	720,000,000	2,100,000,000	43-53
Gallium	Ga	5,200	1,000,000	<1
Indium	In	11,000	47,100	<1
Iron ore	Fe	160,000,000,000	800,000,000,000	52-90
Lead	Pb	87,000,000	2,000,000,000	52-95
Lithium	Li	13,500,000	39,500,000	<1
Magnesium	Mg	2,400,000,000	12,000,000,000	39
Manganese	Mn	570,000,000	1,030,000,000	53
Molybdenum	Mo	11,000,000	14,000,000	30
Nickel (sulphides)	Ni	32,400,000	52,000,000	57-63
Nickel (laterites)		48,600,000	78,000,000	
Silver	Ag	530,000	1,308,000	30-97
Tellurium	Te	11,080	25,000	<1
Tin	Sn	4,800,000	76,200,000	75
Titanium (ilmenite)	Ti	740,000,000	1,840,000,000	91
Titanium (rutile)		54,000,000	160,000,000	
Vanadium	V	15,000,000	63,000,000	<1
Zinc	Zn	230,000,000	1,900,000,000	19-60

Revising the depletion curves in the literature, those minerals which may reach a peak supply in the next decades were analysed (Source: Task 2.2.c.2. from (MEDEAS, 2016b), (Calvo et al., 2017) and (L.D. Roper, 2017)). Subsequently we followed the following criteria:

Potentially scarce minerals which could be relatively easily replaced by other minerals have not been considered (e.g. gallium used in some semiconductors used for PV thin-films could be replaced by silicon in the same PV industry).

For those minerals whose energy consumption for its extraction and refining is less than 10% of their full LCA, the potential influence in energy requirements increase due to ore decrease when approaching the level of reserves has been omitted.

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For the remaining minerals of the set, i.e. those minerals that may be more difficult to be replaced and whose energy consumption for its extraction and refining is over 10% of their full LCA (Cu, Zn, Sn, Ni, Mn, Mo, Ag, Mg, Co, Cr, Li, NaNO2 and KNO3), we have analysed the impact of increasing the energy consumption for its extraction and refining 3-fold on the total energy cost of the energy plant (i.e. CED of the $EROI_{st}$, see section 0). After this, just three minerals emerge from the set as potentially problematic: copper, sodium nitrates ($NaNO_3$) and potassium nitrates (KNO_3). Thus, this 3-fold increase in the energy consumption for the extraction of copper would translate into an overcharge of +6.6% in the CED of the batteries and +4% in the CED of wind offshore (the technologies more affected). For the sodium and potassium nitrates, if mineral reserves would be depleted they could be obtained from organic sources with an overcharge in the CED of the CSP of at least +18%.[22]

As a consequence of the results obtained in these analyses, it was decided to take a conservative approach and not to include the impact of the potential increase in energy requirements due to ore decrease of minerals. Hence, the demand of minerals is always fulfilled in the model and it does not represent a limitation for the deployment of alternative energy systems neither for the whole economy. However, it should be kept in mind that in the real world social and political constraints add to geological constraints, which are particularly important in the case of mineral exploitation given their large environmental and social impacts (Martinez-Alier, 2003; UNEP, 2013b).

[22] For the CSP, silver limitations could have significant implications in terms of reduction of EROI. In the case of eventual scarcity of silver, it could be replaced by alumium. However, due to the lower reflectivity of the latter (14%), for obtaining the same net energy the CSP power plant should be scaled up in the same amount, thus reducing its EROIst. Due to the allocation rule implemented in MEDEAS this would reduce the deployment of CSP.

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2.4.2.2. Implementation in MEDEAS

The demand of materials of the 6 energy systems and the rest of the economy (see section 0) allows to estimate the energy requirements to extract and refine these minerals. The cumulative demand of each mineral is dynamically compared with the current level of reserves and resources (see

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Table 30).

Although potential supply scarcities do not affect the demand of minerals in the model, MEDEAS generates two types of warnings; in the case that:

1. the cumulative demand of a mineral surpasses the current level of reserves,
2. the cumulative demand of a mineral surpasses the current level of resources.

The user can modify the level of reserves and/or resources for each mineral. We assume that reserves represent a minimum estimate, economic and technologically reasonable and as a consequence likely to be increased by new/better technologies, decreasing extraction costs and increasing prices. Thus, it is allowed that the cumulative consumption surpasses the level of reserves for all minerals. In that case, the user will be warned that the energy system using this mineral will lose efficiency and thus will counteract the trends of technological improvement. On the other hand, it is considered that the level of mineral resources represents a maximum in the timeframe of MEDEAS. Hence, if the cumulative demand of a mineral surpasses the level of resources it would be an indication that it should be replaced. Note that this will not be explicitly modelled in MEDEAS, remaining as a qualitative result. In that case, the model could be run in 2 steps, e.g. 1st run: we obtain a scenario where there is copper scarcity; 2nd run: in this simulation we replace copper by aluminium obtaining systems with a lower energy efficiency (more Joule effect), more CED, etc.

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2.4.3. Modelling of recycling policies in MEDEAS

Recycling polices have the potential to reduce the extraction of minerals from mines, thus effectively expanding its availability and reducing the harmful related environmental impacts, as well as reducing the energy consumption dedicated to the extraction of materials that the society demands, given that the energy consumption of metal recovery from recycled sources is usually less than that of primary production (UNEP, 2013a). However, recycling policies depend on choices made during design, which have a lasting effect on material and product life cycles. They drive the demand for specific metals and influence the effectiveness of the recycling chain during end-of-life. The end-of-life recycling rate is strongly influenced by the least efficiency link in the recycling chain, which is typically the initial collection activity (UNEP, 2011).

Recycling rates can be defined in many different ways, from different perspectives (product; metal; metal in product) and for many different life stages; sometimes the term is even left undefined. In MEDEAS we apply the End-of-Life-Recycling Rate (EOL-RR), i.e. the percentage of a metal in discards that is actually recycled. Figure 54 reports the roughly estimated values of EOL-RR for all the elements of the periodic table at global level (UNEP, 2011).

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Table 30 reports the values used in MEDEAS for the minerals considered.

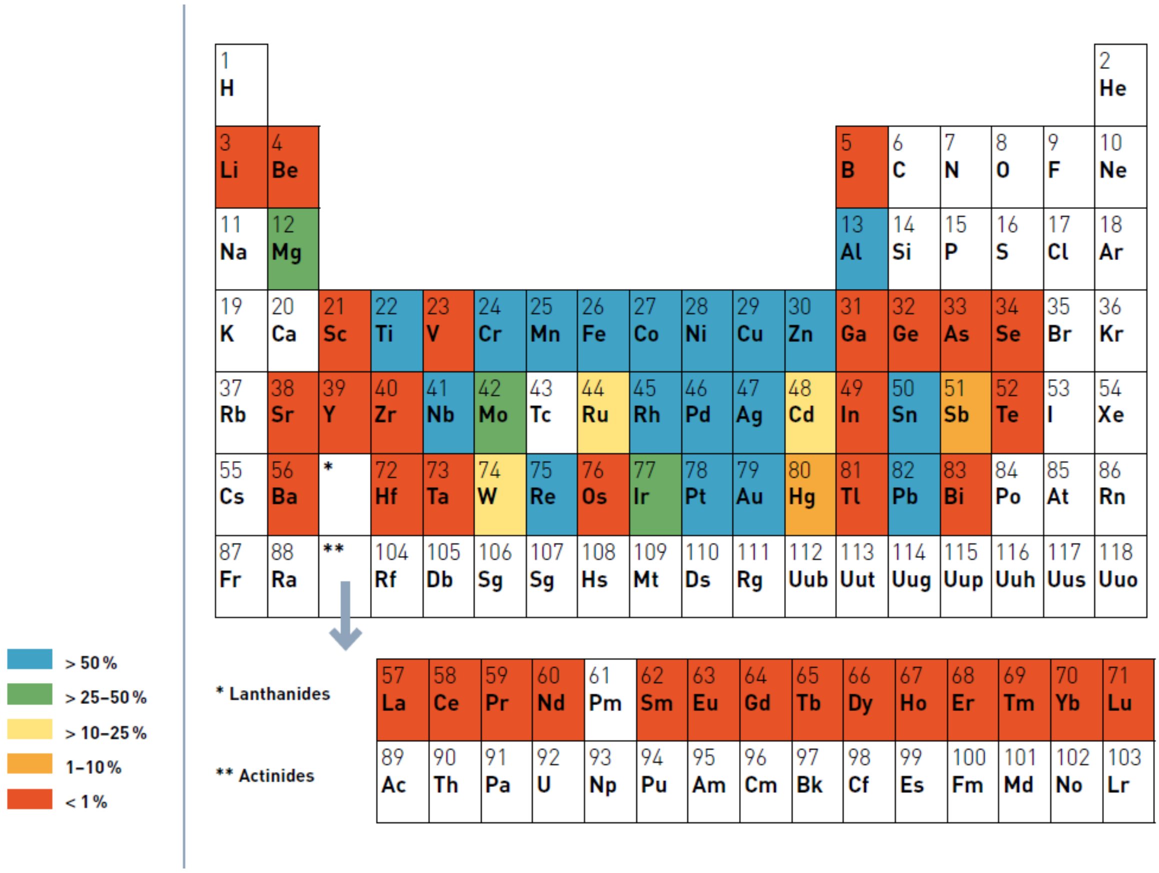

Figure 54 (UNEP, 2011): EOL-RR for sixty metals.

Where relatively high EOL-RR are derived, the impression might be given that the metals in question are being used more efficiently than those with lower rates. In reality, rates tend to reflect the degree to which materials are used in large amounts in easily recoverable applications (e.g. lead in batteris, steel in automobiles), or where high value is present (e.g. gold in electronics). In contrast, where materials are used in small quantities in complex products (e.g. tantalum in electronics) or where the economic value is at present not very high, recycling is technically much more challenging (UNEP, 2011). Apart from produc design, other constraints and limits to mineral recycling rates improvement include a high mobility of products due to international trade, a generally low awareness about a loss of resources or lack of an appropiate infraestructure for end-of-life management of complex products. Recycling is becoming increasingly difficult due to the rising complexity of products, mixing almost any imaginable metal or other material. This makes that without the appropiate policies, recycling rates could even worse if the share of complex products continues to increase over the total (UNEP, 2013a, 2011).

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MEDEAS allows to explore the implications for mineral availability and energy consumption of recycling policies selected by the user. The user can select the annual improvement in the rate of recycling for the 19 minerals considered from current values (see

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Table 30) during the timeframe of the simulations for the 6 RES key technologies and the rest of the economy. By default, an absolute maximum of 95% for all minerals is considered to take into account biophysical limits (following the scenario 4 from (Ragnarsdóttir et al., 2012)), in a way that the recycling rates follow a logistic curve. Data for the energy consumption per unit of material consumption recycled is constant and from Hammond and Jones (2011) for the following minerals: Al, Cu, Fe, Pb and Ti. When data for recycled minerals was not available (which was the case for most minerals) the energy consumption for virgin minerals was assumed.

For the initial rate of recycling of minerals, and due to the aforementioned reasons, MEDEAS distinguishes between the modern RES technologies and the rest of the economy:

Current values of EOL-RR for minerals of the rest of the economy are taken from (UNEP, 2011). Data at global data are scarce and subject to many uncertainties for most minerals. The years for which figures reported by UNEP (2011) are available vary, but many apply to the 2000-2005 time period; in most cases the statistics change slowly from year to year. For this reason we consider these rates constant in MEDEAS for the period 1995-2015. When a range is given (see

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- Table 30), the mean of the minimum and maximum is used.
- Given the lack of data for the reycling rates of the variable RES technologies at global level, and acknowledging that these modern technologies have likely a lower recycling rate due to the aforementioned reasons, we set the initial (current) EOL-RR rates for minerals for these technologies as been 1/3 of those of the aggregated economy.

Moreover, it should be highlighted that in the process of recycling the utility of metals is maintained through the addition of high primary (virgin) metals, bringing the concentration of the recycled metals to desired levels. This mixing with high-grade primary metals keeps these recycled metals in the cycle. Long term, this practice of dilution of the undesired substances prevents a closure of the material cycles, whereas recovery without dilution reduces the quality (or quantity) of recycled metals (Verhoef et al., 2004). Thus, if applications requiring an extremely high purity (e.g. aluminium mirrors from CSP, electronic devices, etc.) substantially increase their share in the global economy, this would limit the practical recycling rates to well below the 95% considered by default in MEDEAS. Moreover, another phenomenon not taken into account in the model is that higher recycling rates imply higher energy consumption.

Figure 55 shows the loop diagram of this policy:

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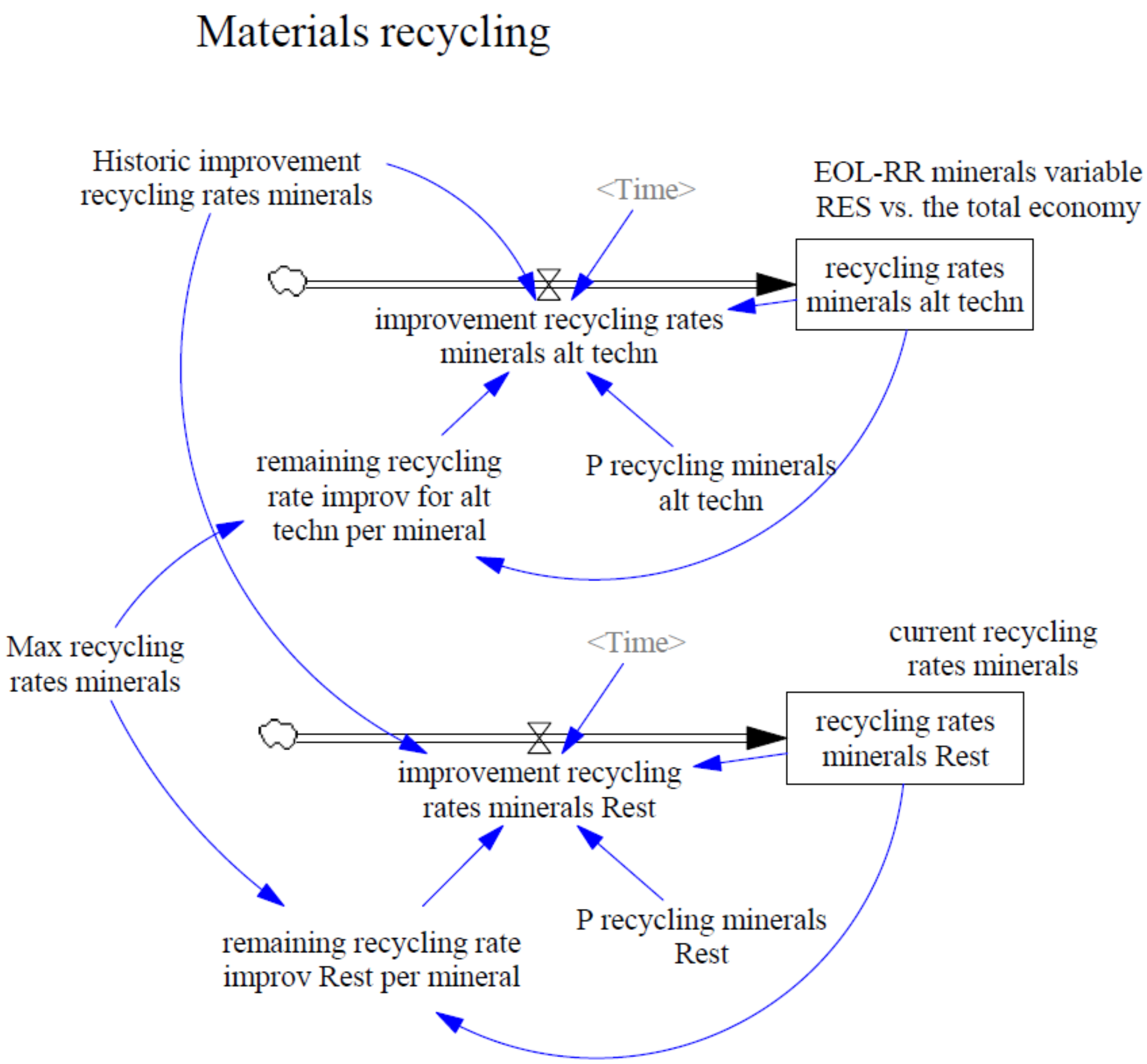

Figure 55 : Loop diagram of the mineral recycling policy in MEDEAS.

Ultimately, the improvement of mineral recycling policies has two impacts in MEDEAS model:

- Reduce the demand of minerals to be mined from the earth crust,
- Improves the EROI of the 6 RES technologies considered.

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2.4.4. EROI estimation per electricity generation technology

Given data availability, two methods are used to estimate the EROI of the electricity generation from RES technologies:

- Static approach for RES dispatchables since their material requirements have not been estimated (section 0),
- Dynamic approach for RES variables since we do have their disaggregated material requirements (section 0). The EROI from a static approach is also computed for the sake of comparison and in order to integrate the allocation function (see section 0).

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2.4.4.1. EROI of RES dispatchables for electricity generation

To estimate the EROI of RES dispatchables for electricity generation we apply the classic definition of standard EROI (Hall et al., 2014). For an electricity technology i, the EROI over the whole lifetime of the infrastructure is defined from a "static" perspective:

$$EROI_i = \frac{Annual\ elec\ output_i \cdot lifetime_i}{\left(CED_i^{New\ cap} + CED_i^{Decom\ wear\ cap} + CED_i^{GCF} + CED_i^{O\&M} \cdot lifetime_i\right) \cdot g + Annual\ elec\ output_i \cdot lifetime \cdot SC_i}$$

$$== \frac{Annual\ elec\ output_i \cdot lifetime_i}{\left(CED_i^{New\ cap} \cdot (1 + Decomm + GCF_i) + CED_i^{O\&M} \cdot lifetime_i\right) \cdot g + Annual\ elec\ output_i \cdot lifetime \cdot SC_i}$$

$$Annual\ elec\ output_i = Cp_i \cdot Installed\ new\ cap_i \cdot 8760 \frac{h}{yr}$$

i: electricity generation technology.

Annual elec output: Annual electricity output.

Cp: capacity factor.

Installed new cap: installed new capacity.

Lifetime: lifetime of the installed infrastructure.

$CED^{New\ cap}$: cumulative energy demand of the new installed capacity.

$CED^{Decom\ wear\ cap}$: cumulative energy demand for decommissioning those infrastructures that have ended their lifetime. We assume a fixed share in relation to the CED of the energy required for the construction of each power plant of 10% following (Hertwich et al., 2015), i.e. Decomm=0.1.

CED^{GCF}: cumulative energy demand to consider the losses due to the effect Joule of each power plant (grid-correction factor). Depending on the power plant a different share of the CED of the energy required for the construction of each power plant is assumed.

$CED^{O\&M}$: annual cumulative energy demand of the operation and maintenance.

g: quality factor of the electricity.

SC: electricity self-consumption of the power plant as a share of the electricity output.

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The above equation can be simplified removing the annual installed electricity capacity and expressing the CEDs as EJ per installed capacity:

$$EROI_i = \frac{Cp_i \cdot 8760\frac{h}{yr} \cdot lifetime_i}{\left(CED_i^{New\,cap}\ per\ TW \cdot (1 + Decomm + GCF_i) + CED_i^{O\&M}\ per\ TW \cdot lifetime_i\right) \cdot g + Cp_i \cdot 8760\frac{h}{yr} \cdot lifetime \cdot SC_i}$$

The previous equation can be directly applied for those technologies of electricity generation for which the material requirements for both new installed capacities and O&M are explicitly modelled (which correspond with the RES variables: solar PV, solar CSP, wind onshore and wind offshore) since MEDEAS dynamically estimates the $CED^{New\ cap}$ and $CED^{O\&M}$. For the rest of RES electricity technologies for which the CEDs are not endogenously calculated (which correspond with the dispatchable technologies: hydroelectricity, geothermal, biomass&waste and oceanic[23]), we assume that the operation and maintenance are independent of the Cp and the self-consumption losses are negligible. The current total CED per capacity (EJ/TW) per technology over the lifetime of the infrastructure ("Static EROI over lifetime") can be then derived as follows:

$$Total\ CED_i\ per\ TW\ over\ lifetime = \frac{Cp_i^{initial} \cdot lifetime_i \cdot 8760\frac{h}{yr} \cdot EJ\ per\ TWh}{EROI_i^{initial} \cdot g}$$

$Cp^{initial}$ refers to the initial (current) capacity factor for each technology (without accounting for decreases due to overcapacities).

$EROI^{initial}$ is the initial (current) EROI level associated to the initial (current) capacity factor (without accounting for decreases due to overcapacities).

[23] A great diversity of marine technologies exist, and some of them could be considered as dispatchable (e.g. OTEC) while others are subject to variability (e.g. tidal & wave). For example, the wave plant of Mutriku (Spain) presents a factor of almost 5 in its seasonal variability comparing summer and winter (Torre-Enciso et al., 2009). For the sake of simplicity and thus from a conservative point of view, we assume that all oceanic power is dispatchable. Moreover its importance in the model is reduced given its low potential and low EROI (see section 0).

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Thus, once estimated the current total CED per TW for each technology, and assuming that its value will remain constant during the timeframe of MEDEAS, the evolution of EROI over time of the dispatchable electricity generation sources can be expressed as follows:

$$EROI_i = \frac{Cp_i \cdot lifetime_i \cdot 8760\frac{h}{yr} \cdot EJ\ per\ TWh}{Total\ CED_i\ per\ TW\ over\ lifetime \cdot g}$$

(the term Installed new $cap_i(t)$ cancels out in the numerator and denominator).

Both previous equations applying the "static" approach can still evolve over time considering the dynamic evolution of the capacity factor of each technology $Cp_i(t)$ and the quality factor of the electricity g(t). And for the case of RES variables, CED can also vary depending on the recycling policies (see section 0).

- RES dispatchables:

$$EROI_i(t) = \frac{Cp_i(t) \cdot lifetime_i \cdot 8760\frac{h}{yr} \cdot EJ\ per\ TWh}{Total\ CED_i\ per\ TW\ over\ lifetime \cdot g(t)}$$

- RES variables:

$$EROI_i(t) =$$
$$= \frac{Cp_i(t) \cdot 8760\frac{h}{yr} \cdot lifetime_i}{\left(CED_i^{overgrids} per\ TW + CED_i^{New\ cap}\ per\ TW(t) \cdot (1 + Decomm + GCF_i) + CED_i^{O\&M}\ per\ TW(t) \cdot lifetime_i\right) \cdot g(t) + Cp_i(t) \cdot 8760\frac{h}{yr} \cdot lifetime \cdot SC_i}$$

$CED^{overgrids}$: cumulative energy demand of overgrids high power and inter-regional grids (HVDCs).

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2.4.4.2. EROI of RES variables for electricity generation

For those technologies of electricity generation for which the material requirements for both new installed capacities and O&M are explicitly modelled (which correspond with the RES variables: solar PV, solar CSP, wind onshore and wind offshore), the EROI can be endogenously estimated dynamically in the model for each time period t (i.e. independently of the lifetime of the infrastructure):

$$EROI_i(t) = \frac{Annual\ elec\ output_i(t) \cdot EJ\ per\ TWh}{(CED_i^{overgrids}(t) + CED_i^{New\ cap}(t) \cdot (1 + GCF_i) + CED_i^{decom\ wear\ cap}(t) + CED_i^{O\&M}(t)) \cdot g(t) + Annual\ elec\ output_i(t) \cdot SC_i}$$

$$Annual\ elec\ output_i(t) = Cp_i(t) \cdot Installed\ new\ cap_i(t) \cdot 8760 \frac{h}{yr}$$

Cp(t) depends on the level of overcapacity.

$CED^{New\ cap}(t)$ and $CED_{O\&M}(t)$ depend on the recycling rates of the minerals (check consistency between numerator and denominator to be both in EJ). This parameter would capture the increasing energy cost of the decreasing ore grade of minerals in the case of having been included (see section 0).

$CED^{decom\ wear\ cap}$: assuming that the cumulative energy demand for decommissioning electricity plants is 10% of the energy required for its construction (Hertwich et al., 2015), the dynamic expression of the CED for decommissioning power plants would thus be:

$$CED_i^{decom\ wear\ cap}(t) = 10\% \cdot \frac{wear\ cap_i(t)}{Instaled\ new\ cap_i(t)} \cdot CED_i^{Installed\ new\ cap}(t)$$

g(t) depends on the evolution of the quality factor of the electricity within the model

Since this expression is not averaged over the whole lifetime and considers the dynamic evolution of all parameters, we refer to this metric as "Dynamic EROI", similarly to other studies (Kessides and Wade, 2011; Neumeyer and Goldston, 2016).

Finally, a correction has to be introduced in the EROI computation of the RES variables to account for energy losses when storing electricity. MEDEAS incorporates two options for electricity storage: pumped hydro storage (PHS) and batteries from electric vehicles:

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- PHS: ESOI values reported in the literature reach 700:1 (Barnhart et al., 2013). However, these values do not seem realistic given that the PHS technology is very similar to conventional hydro (although usually requiring more infrastructure) and it is between 2 and 10 times more expensive for current projects which are moreover built located in the best locations (Hearps et al., 2014). Thus, the CED of PHS is probably higher than for conventional hydro for the same level of output. On the other hand, the Cp of the PHS is currently around 10% (in fact declining from 13% in 2000 to 8.5% in 2014 (IRENA db, 2017)). Thus, (optimistically) assuming that the CED of PHS corresponds with the CED of conventional hydro, the initial level of ESOI of the PHS could be expressed as:

$$ESOI_{PHS}^{initial} = EROI_{hydro}^{initial} \cdot \frac{Cp_{PHS}^{initial}}{Cp_{hydro}^{initial}}$$

  Assuming that the initial EROI of hydro is 50:1 and its initial Cp 39.2%, the initial ESOI of PHS would be 12.7:1. We assume that the ESOI of the PHS decreases linearly until 5:1 when its maximum potential is reached (0.25 TWe, see section 0):

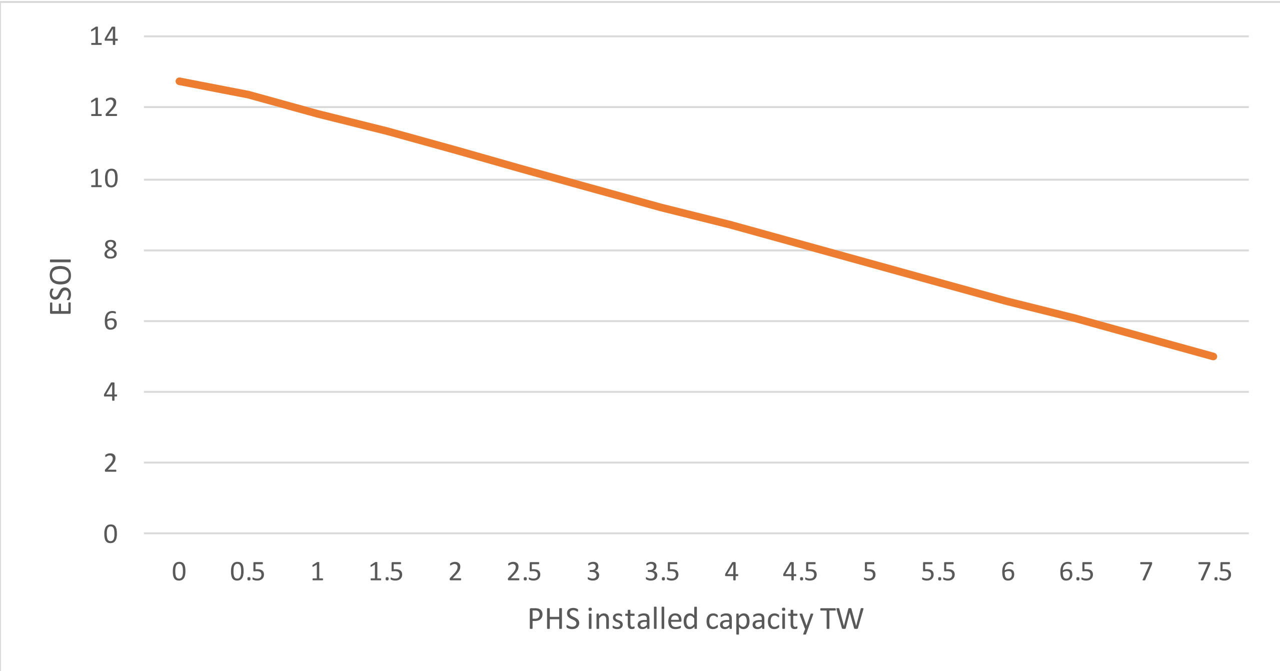

Figure 56: ESOI of PHS as a function of the installed capacity.

- EV batteries. ESOI=6.1 (own estimation, see section 0).

Given that the ESOI of PHS is higher than EV batteries for most of the potential of PHS (see Figure 56), the current version of MEDEAS assigns priority to the electric storage of PHS. In the case that

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more storage is required the EV batteries could then be used. Further developments could however allocate the share as a function of the relative ESOI, as it is currently done for the electricity (see 0).

The resulting EROI of each RES variable technology ($EROI_{st}^{grid}$) is then decreased as a function of the following equation from (Barnhart et al., 2013):

$$EROIst_i^{grid} = \frac{1 - \varphi_i + \varphi_i \eta_c}{\frac{1}{EROIst_i} + \frac{\varphi_i \eta_c}{ESOI_c}}$$

Where ϕ represents the faction of electricity stored, η_c represents the combined storage efficiency of PHS and EV batteries and $ESOI_c$ represents the combined energy stored on electrical energy invested of PHS and EV batteries.

Finally, it must be highlighted that the energy costs related to the construction and O&M of the full electricity grid have not been taken into account, which would increase the EROI of all electricity technologies.

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2.4.4.3. Cumulative energy demand for new installed capacity and O&M per technology of RES variables

The cumulative energy demand (CED) for new installed capacity and operation and maintenance activities (O&M) for each RES variable technology for which the material requirements are explicitly modelled (solar PV, solar CSP, wind onshore, wind offshore) is estimated for virgin and recycled materials from a LCA (Hammond and Jones, 2011). This part of their CED is estimated multiplying the material intensity of each technology (constant) by the energy consumption per unit of material consumption (MJ per kg), whose current values constitute a starting point for the dynamic analysis (see

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Table 30). Values of Hammond and Jones (2011) are cradle to gate or at most to point of use. The change of recycling rate makes them evolve dynamically. Thus, the CED of each technology i evolves endogenously for each material j:

$$CED_i(t) = Material\ intensity_i^j \left[\frac{kg}{MW}\right] \cdot Energy\ consumption\ per\ unit\ of\ material\ consumption^j [\frac{MJ}{kg}](t)$$

In the case of RES variables, the material intensity includes also the additional requirements in terms of overgrids high power and inter-regional grids required by the penetration of these technologies in the electricity mix (see section 0).

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Table 30 : Energy consumption per unit of material consumption for virgin and recycled materials.

Initial energy consumption per unit of material consumption (virgin)	Initial energy consumption per unit of material consumption (recycled)
MJ/kg	MJ/Kg
100	0
218	29
0	0
264	0
200	0
4.5	0
83	0
57	16.5
38.5	0
384.2	0
2000	0
120	0
28	0
28	0
610000	0
15	0
100	0
0.083	0
3320	0
25	9.4
21.5	0
3	0
5.3	0
0.85	0
853	0
100	0
220	0
57.6	0
2000	0
0.95	0
378	0
21.5	0
0	0
384.2	0
164	0
0	0
0	0
70	0
49	10
80.5	0
95.4	0
1	0
16.6	0
0.081	0
0.1	0
2000	0
1580	0
0.45	0
250	0
0	0
56.7	0
207	0
589000	0
400	258
60	0
3710	0
36	0
72	9

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Figure 57 shows the contribution of each of the 58 materials to the $CED^{New\ cap}$ and $CED^{O\&M}$ of each RES variable technology (assuming current mineral recycling rates). It can be observed that the main materials are: steel, cement, Al, electric/electronic components, Fe and site preparation for wind onshore (>80%); steel, site preparation and Al for wind offshore (>80%); glass, silicon wafer modules, Te, Fe, Al and diesel for solar PV (>90%); and synthetic oil, steel, Fe, site preparation and mined NaNO3 (>75%).

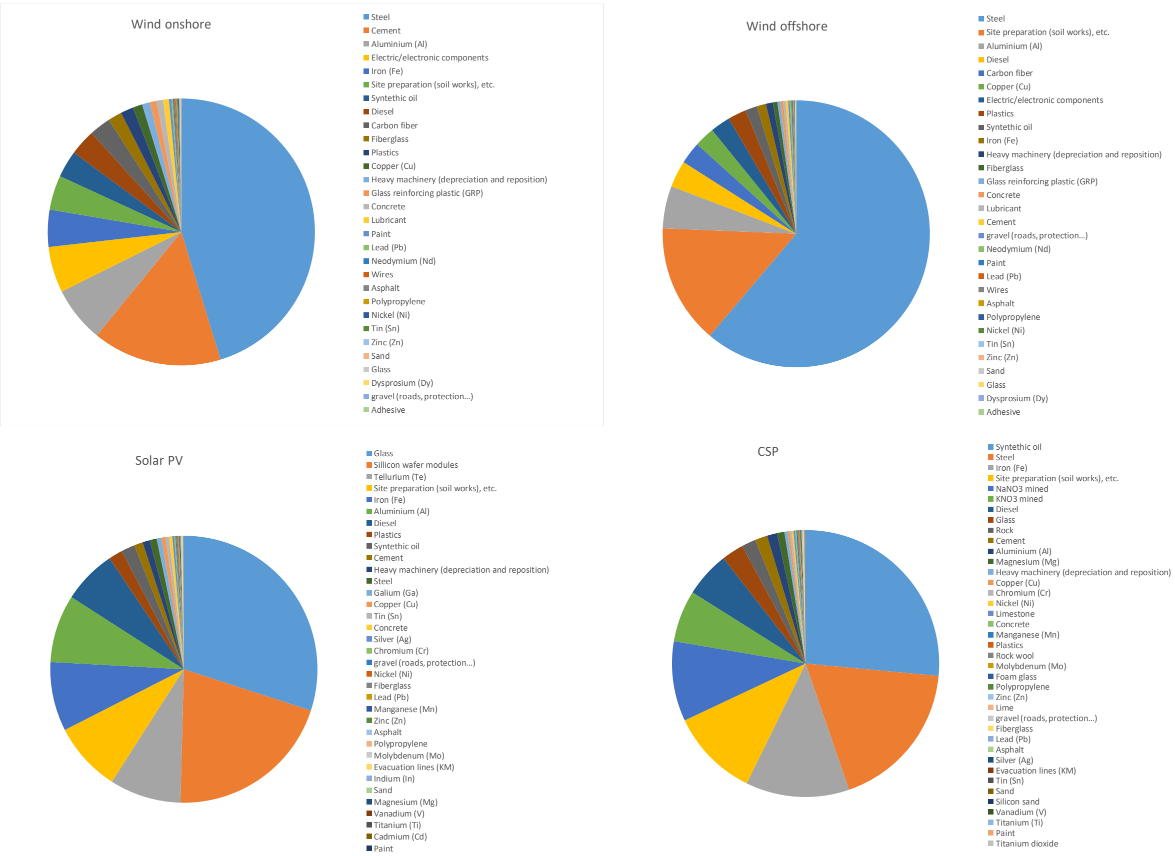

Figure 57 : CED for new installed capacity and operation and maintenance activities (O&M) per material and RES technology. If a material is not used then it is not showed in the legend. In the case of RES variables, it also includes also the material requirements for overgrids high power and inter-regional grids.

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2.4.4.4. Summary of results

Table 31 reports the value of the EROI over lifetime (i.e. static definition) for the different electricity generation technologies considered in MEDEAS. Two considerations:

- **Parameter « g », quality factor of the electricity:** Different authors use different criteria to set this parameter (e.g. (Carbajales-Dale et al., 2015; Ferroni and Hopkirk, 2016; Prieto and Hall, 2013; Raugei et al., 2017)). Under the rationale that electricity is a type of energy of higher quality than others such as thermal, most analysis take g<1, typically g≈0.35 considering g as the average efficiency in the transformation of primary energy to electricity (which depends on the electricity mix of each country/region). However, it could also be argued that despite the electricity is indeed a type of energy of higher quality than others, globally just ~¼ of the TFEC is supplied by electricity, being the rest supplied by sources of energy which could well be over g=1 such as the case of heat (~30% of TFEC). In the words of Prieto and Hall (2013, p. 116) for the case of solar PV : « Most of the inputs to the production of the PV system are fossil fueled, and the output is high-quality electricity. If we assume that electricity is worth three times what fossil energy is (and assuming that it is used for high-quality functions such as lights and compueters and not space heating), then we might conclude that the quality-corrected EROI is 7.35 [x3 estimated]. But this is adouble edged argument. It assumes that PV systems replace already existing electricity generated by fossil or nuclear fuels. The world consumes 59EJ in electrical form, but a total of 509EJ of primary energy. If solar PV systems would have to replace all other non electrical activities, then the « transformity » will operate in exactly the other way around with respect to quality and suitability for all of them that would requiere an energy carrier (i.e. merchant fleet, armies, aviation, mechanized agriculture, heavy machinery…), thus making the EROI going probably close to 1 :1». This is the criteria chosen for some studies to apply g=1 (e.g. (Ferroni and Hopkirk, 2016; Weißbach et al., 2013)). However, here we follow an intermediary approach and take g as the ratio between the TFEC and the TPES (excluding non-energy uses). For the year 2015, we obtain the ratio g=0.66 (however note that in MEDEAS this parameter is endogenous). This number matches well with other studies which assess the substitution of the global energy system to a RES electricity based system, such as (García-Olivares et al., 2012) which find that around 70% of the current TPEC would allow to fulfill the same uses in a 100% electrified society. Similarly, Jacobson and Delucchi (2011) think that ~11.5TW of mean annual electric power would be produced to replace the ~17TW of the present system.

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- **EROI over lifetime of dispatchable RES**: Values from the lower range of the literature review are consciously selected given that, as it has been showed, there has been a systematic overestimation of the EROI of these technologies in the literature. Different reasons explain that, such as the non inclusion of all materials involved in the LCA, the overestimation of Cp and efficiencies, picking of best-cases, etc. (Arvesen and Hertwich, 2012; Boccard, 2009; de Castro, 2009; de Castro et al., 2014; De Castro and Capellán-Pérez, 2018; Prieto and Hall, 2013). Thus, in these conditions taking median/average values from meta-analysis is problematic.

Table 31 ; EROI over lifetime for each of the RES technologies for electricity generation considered in MEDEAS. We take g(year=2015)=0.66) from MEDEAS. See section 0 for the recycling rates considered for estimating the EROI of dispatchable RES. Values of EROIpou can be estimated as EROIst-1. * EROIst including additional grids and storage is scenario dependent is not reported here.

Technology	EROIst over lifetime (static definition)	Reference
	Dispatchable RES	
Hydroelectricity	50	Annex 3 from (MEDEAS, 2016a)
Geothermal	7	Low range in Annex 3 from (MEDEAS, 2016a) and correction with real Cp from (IRENA db, 2017).
Solids bioenergy	1.5	(de Castro et al., 2014)
Oceanic	3.25	Own estimation (see text)
	*Variable RES**	
Wind onshore	10.2	This work
Wind offshore	6.5	This work
Solar PV	5.2	This work
CSP	3.5	(De Castro and Capellán-Pérez, 2018)
	Electricity storage (ESOI)	
EV batteries	6.1	This work

Oceanic technologies such as tidal and wave are in an early phase of commercialization level and available data of the performance and LCA of real plants are very limited (MEDEAS, 2016a). For this reason, we have roughly estimated the EROI of these technologies taking wind offshore as a

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reference given the relative similarities betwen both technologies. The review of the literature reveals that ocanic plants are usually characterized by a Cp between similar levels than wind offshore to 50% lower (IRENA, 2014a, 2014b). As for the other electricity generation technologies, the expected Cp (projects) tends to be higher than the Cp from real plants (e.g. for the wave power plant of Mutriku in Spain, a Cp expected of 0.23 (Torre-Enciso et al., 2009) and a real Cp <0.1). Moreover, oceanic technologies are more material intensive in the construction phase (roughly >1000Tn/MW[24]), and necessitate higher O&M requirements due to higher exposure to salt water (submerged or in permanent contact). Thus estimating that the CED of these technologies might be around 1/3 higher than the CED of wind offshore (likely conservative), and accounting for a Cp 50% lower, the EROI of oceanic technologies can be estimated to be around half of the wind offshore EROI.

Taking the case of the plant of Mutriku, the power installed is 0.3MW and only the « reinforced concreted » weights over 6,000Tn, i.e. 20,000Tn/MW, which is a material intensity 2 orders of magnitude higher than the wind offshore. Hence, taking the energy intensity of concrete of 4.5 kg/MW from (Hammond and Jones, 2011), an expected Cp of 0.23 and a lifetime of 25 years, the EROI just accounting for croncrete would be 2 :1. Hence, considering more realistic values (Cp=0.1) and the full material requirements of the complete infraestructure would likely drive the EROI to below 1 :1.

[24] http://www.tidalenergy.eu/sea_gen_turbine.html

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2.4.5. EROI as criteria for allocation of RES technologies for electricity generation

In MEDEAS, RES technologies have priority over NRE in the electricity mix (also in the heat mix). The allocation between different RES technologies for the generation of electricity is driven by their relative EROI, i.e. the higher EROI a RES technology has in relation to the total EROI of RES electricity generation, the more capacity will be installed. This way, we take a "net energy approach" that we consider more relevant for policy-advice than the more common allocation based on the monetary costs of each technology power plants due to the following reasons:[25]

- From a technical point of view, the EROI metric allows to internalize factors that affect the whole energy system that are not captured by the monetary costs of individual power plants. This is the case of overgrids and inter-regional grids requirements as well as storage of variable RES for the generation of electricity.
- From a societal/metabolic point of view, the relevant dimension is the energy available to the society (not the energy produced by power plants). In fact, the energy transition to new energy resources and new energy conversion and storage devices will affect the fraction of energy reinvestment, which may have significant economic impacts (Carbajales-Dale et al., 2014; Dale et al., 2012a; Hall et al., 2009). In fact, a favourable EROI over the long-term has been identified as an historical driver of evolution and increasing complexity (Hall, 2017b; Hall and Klitgaard, 2012; King, 2016).
- Computing the dynamic EROI of each technology allows to prevent potential issues related with a "too fast" implementation of alternative technologies, i.e. the so-called "energy trap" (Kessides and Wade, 2011; Zenzey, 2013). Other net energy analyses in the literature have taken a static EROI approach (e.g. (Dale et al., 2012b; Sgouridis et al., 2016)) considering constant parameters such as Cp and g that in reality evolve with the penetration of RES in the electricity system. By computing both the static and dynamic EROI in MEDEAS we capture thus both perspectives: the total energetic cost over the lifetime (which drives the allocation of technologies, i.e. allowing to self-regulate the system) as well as the instantaneous «energy loss » at any time.
- Modelling from a net energy perspective allows to explore the implications for the whole system of the evolution of the EROI of the energy system. While the EROI levels are « high

[25] See also (Hall, 2017a).

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», the energy losses are negligible. However, if the EROI of the energy system decreases, the pressure to extract higher levels of primary energy to supply the same level of final energy will increase. Surpassing a threshold, and if the system does not include « inteligent/correcting controls » (which could well be the case of the global socio-economic system), this process might produce a collapse of the system (Brandt, 2017). This way, the model allows to endogenously estimate the relevant EROI threshold (see section 0).

This way, the obtained electricity mix will be "optimal" from a biophysical point of view. To our knowledge, very few models take this approach (e.g. GEMBA (Dale et al., 2012b); NETSET (Sgouridis et al., 2016)), being the dominant approach of models used for policy-advice based on price-based allocations methods (e.g. IEA, IPCC, national governments, etc.). However, it should be keep in mind that the EROI does not capture all the benefits and disadvantages of a given technology. For example, in the case of rooftop PV, despite its lower efficiency in relation to ground-based plants, it does not require land.

Description of the allocation rule implemented in MEDEAS

As a starting point, each RES technology for generating electricity is deployed at the exogenous growth set in each scenario. The allocation rule implemented in MEDEAS compares, for each RES technology its EROI over lifetime (including the overgrids and storage for RES variables) with the total EROI over lifetime from all RES technologies (i.e. applying the static approach of EROI). The evolution of the EROI over time of all the electricity generation from RES is defined by the following expression:

$$EROI_{tot}^{elec}(t) = \frac{\sum_i Output\ electricity\ over\ lifetime_i(t)}{(\sum_i Total\ CED_i\ over\ lifetime_i(t)) \cdot g(t)}$$

With i: RES technology for generating electricity while it has not reached its maximum potential.

The above expression is corrected taking into account that when a RES technology is deployed at its maximum potential, the contribution to the $EROI^{elec}_{tot}$ of this technology is not considered. The allocation of technologies is thus performed as a function of the $EROI^{elec}_{tot}$ of the technologies that have the potential to be deployed. Since higher EROI technologies tend to reach their potential before (e.g. hydro, wind), this way we prevent that the allocation method unreasonably reduces the growth of new planned capacity of the available technologies in relation to the exogenous assumptions.

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The allocation rule in MEDEAS is defined assuming to fulfil the conditions represented in Table 32. This way, when the ratio between the EROI of each technology and the $EROI^{elec}_{tot}$ as estimated in the previous equation is 1:1, the growth in new planned capacity of this technology corresponds with the exogenous assumption defined by the scenario (variable "adapt growth RES elec"). We recall that the modelling considers that the growth in new planned capacity is affected by the proximity to fulfilling the maximum potential (see section 0).

Table 32: Assumptions to build the allocation rule of renewable technologies for producing electricity in MEDEAS.

ratio EROI per techn vs $EROI^{elec}_{tot}$	**Growth new planned capacity per techn (x-times exogenous value)**
0.1	0
1	1
10	2

A logarithmic expression was chosen in order to more rapidly remove from the mix those technologies which are characterized by a worse EROI ratio in relation to the $EROI^{elec}_{tot}$ (see Figure 58). It is important to check the consistency between the exogenous input parameters of the scenarios and the allocation rule to avoid unrealistic values of technology capacity growth.

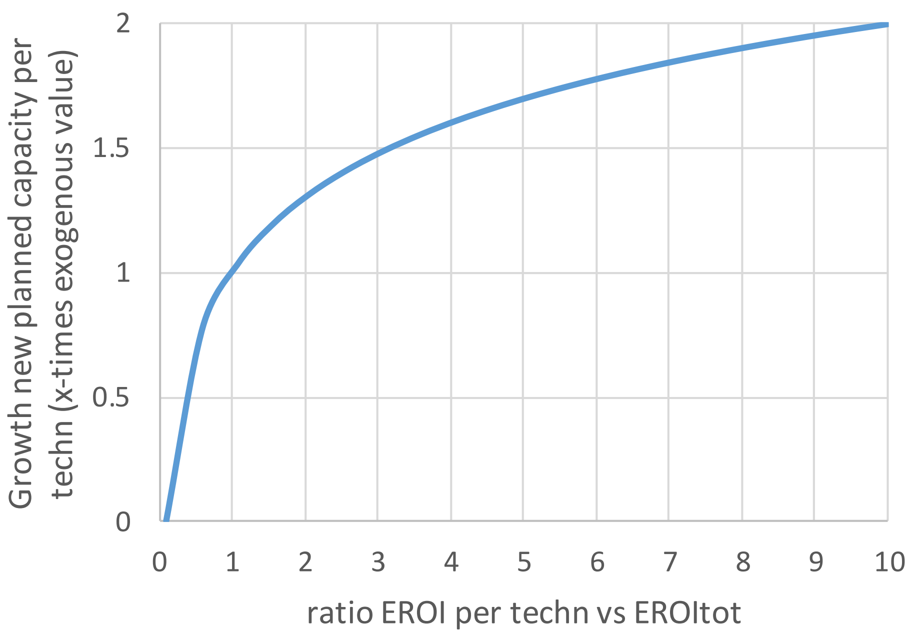

Figure 58 : Growth in new planned capacities per technology as a function of the ratio of its EROI and the EROIelectot.

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2.4.6. EROI of the system

In MEDEAS, the EROI of the system is defined as the ratio between the final energy delivered to society and the energy required for the production of energy vectors (see Figure 59).

$$EROI_{system}^{st} = \frac{(1)}{(2)}$$

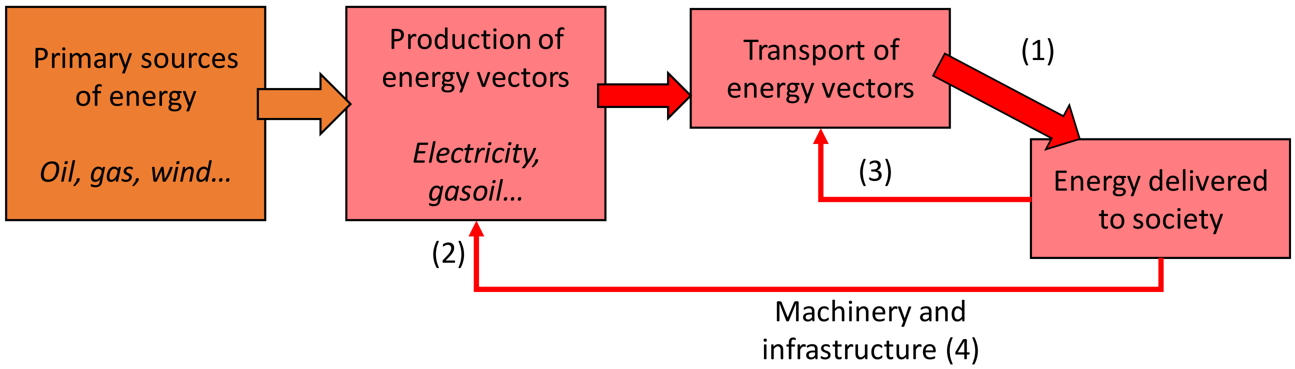

Figure 59: Representation of the energetic metabolism of our society. Red arrows refer to energy flows that are usable by human societies. The orange arrow is a flux of materials with potential energy which can be transformed. An exosomatic intermediary is always required so the useful exosomatic energy is transformed and used by the society (infrastructure represented by (4)). Red colors refer to anthroposphere, orange to the biosphere which includes it.

The above equation represents the EROI of the system from a "standard EROI" approach (see also (Trainer, 2017)). Next equations represent the EROI of the system from a "point of use" approach and "extended" approach, respectively:

$$EROI_{system}^{pou} = \frac{(1)}{(2)+(3)}$$

$$EROI_{system}^{ext} = \frac{(1)}{(2)+(3)+\frac{(4)}{EROI_{system}^{ext}}}$$

MEDEAS dynamically accounts for the EROI (standard approach) of the system as follows:

$$EROI(t)_{system}^{st} = \frac{TFEC(t)}{TFEC(t) * Own\ energy - use(t = 2013) + TFEI(t)_{RES\ elec} + TFEI(t)_{storage\ elec}}$$

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TFEC: total final energy consumption (excluding energy materials for non-energy uses).

$TFEI_{RES\ elec}$: total final energy investments for renewable technologies of electricity generation

$TFEI_{storage\ elec}$: total final energy investments for storage of electricity

As a proxy of the energy required for the production of energy vectors from non-renewable resources we take the currently reported "own energy-use" by the (IEA, 2018), assuming that its share in relation to the TFEC will remain constant in the future. This simplification implies that we assume that the EROI of the system will only be affected by the evolution of the final energy investment for renewable technologies of electricity generation and for the storage of electricity. Hence, in first approximation, it is assumed that the energy invested for building plants using fossil fuels and uranium is neglectable. Depending if the TFEI are defined from the "static EROI" (over the lifetime) approach or "dynamic", the EROI of the system will also be over the lifetime of technologies or dynamic, respectively.

The EROI of the system is a conservative estimate due to 2 main reasons:

- In the current version of MEDEAS, just the energy investments for renewable technologies of electricity generation and for storage of electricity have been modelled. An extension to include the EROI of the rest of renewables (heat and biofuels) as well as eventual decline in the EROI of the non-renewable resources would likely result in a decline of the metric

The most conservative approach of estimating EROI is selected ("standard" approach). At the cost underestimating the required energy investments, we avoid the uncertainties and potential double accountings due to the complexities of the "point-of-use and "extended" estimations.

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2.4.7. Feedback of the EROI to the economic and energy system

Given the lower EROIst values of RES (see section 0) in comparison with the NRE ones (Hall et al., 2014), it is likely that the integration of this feedback has the potential to substantially affect the dynamics of the model. In fact, if properly integrated, a declining EROI should be able to trigger a collapse of the system below a certain threshold (<10:1 Hall et al., (Hall et al., 2009; Prieto and Hall, 2013), <5:1 (Brandt, 2017)).

The EROI is commonly defined as the ratio of the amount of usable energy delivered from a particular energy resource to the amount of exergy used to obtain that energy resource.

The EROI varies with time or with the accumulated production of energy resources, as a result of technological improvement (the EROEI tends to increase) and the physical limits of the resource (tends to decrease over time) (Dale et al., 2011). In MEDEAS model, a dynamic estimation of the EROEI of some energy sources and an overall estimate of all the energy used is made. This EROEI is a consequence of the energy mix and the evolution of the EROEI of each energy source. The energy transition that will occur in the coming years, and which is the subject of this project, will imply a significant change in the energy mix and consequently in the EROEI.

For the operability of the concept, a clarification of the boundaries used for the EROI calculations is required and different definitions exist (see (Lambert et al., 2012) for further details):

- EROIst (standard) is the ratio between the energy produced and the required energy for the construction and O&M of a plant as well as the associated energy system,
- EROIpou (point of use) includes the energy losses derived from the EROIst, i.e. refers to the net energy delivered to the final users. In other words, it includes the energy required for the construction and O&M of additional plants (as well as the associated energy system) in order to compensate for the energy losses dedicated to the construction and O&M of the "initial" (i.e. computed in the EROIst) plants (as well as the associated energy system).
- EROIext (extended): EROIpout that includes the energy to use a unit of energy. In other words, the extension to include the non-energy system inputs to feed the energy system (e.g. energy required to build machines which are used to build the power plants).

Ideally, the concept of EROIext should be used, however, its practical estimation is very complex and is beyond the scope of MEDEAS. To date, few studies have attempted to evaluate it (e.g. (Ferroni

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and Hopkirk, 2016; Prieto and Hall, 2013)), estimating the economic costs associated with the construction of the energy system, and using average energy intensities to transform to energy inputs. This methodology is questioned by other authors, which prefer to assign a "zero" energy cost to those categories. Another alternative would be to only feedback the variation in EROI from the RES technologies applying the EROIpou definition of (Capellán-Pérez et al., 2017a), but this way we would miss most of the energy system.

The variation of EROI should affect the energy intensities of the economic sectors that generate, transform or transport energy, since the energy used to supply energy will be modified. However, in MEDEAS the economic sectors that generate, transform or transport energy cannot be disaggregated (WIOD structure, see section 0). Therefore, this effect on the intensities of these sectors cannot be modeled directly.

Thus, the adopted solution to model the change of the EROI has been to consider it an additional effect on the total energy required and consumed by the system in relation to a reference year. The decrease of the EROI, upon being fed-back, will have the effect in the model of increasing the demand of total energy. Similarly, the increase in EROI will have the effect of reducing the demand of total energy. We judge that the potential double accounting due to the combination of LCA of technologies with national accounts would more than compensated by using the EROIst metric instead of EROIpou or EROIext.

<u>Estimation of the EROI feedback factor</u>

Defining ENNE the energy consumed required by the part of the system which does not produce, transform or distribute energy, EA the energy required by the whole energy system to supply ENNE, thus the total energy (ET) would be ENNE + EA. Thus, the EROI can ge defined as :

$$EROI = \frac{ET}{EA} = \frac{ENNE + EA}{EA}$$

Operating :

$$ENNE = EROI \cdot EA - EA = EA \cdot (EROI - 1)$$

$$EA = \frac{ENNE}{EROI - 1}$$

From the point of view of the energy demand (D), and combining with the previous equation :

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$$D(t) = ET(t) = ENNE(t) + EA(t)$$

$$D(t) = ENNE(t) + \frac{ENNE(t)}{EROI(t) - 1}$$

$$D(t) = ENNE(t) \cdot \left(1 + \frac{1}{EROI(t) - 1}\right)$$

$$D(t) = ENNE(t) \cdot \frac{EROI(t)}{EROI(t) - 1}$$

The total demand of energy for any time in relation to the base year would then be:

$$D(t) = ENNE(t) \cdot \frac{EROI(t_0)}{EROI(t_0) - 1}$$

While the actual total demand of energy accounting for the dynamic EROI would be :

$$D(t+1) = ENNE(t+1) \cdot \frac{EROI(t)}{EROI(t) - 1}$$

Setting both previous expressions for D(t+1) and dividing we obtain the EROI feedback factor (EROI FC) :

$$EROI\ FC(t) = \left(\frac{EROI(t)}{EROI(t) - 1}\right) \cdot \left(\frac{EROI(t_0) - 1}{EROI(t_0)}\right)$$

t_0=2015

With this coefficient, the modified demand (D^m) to include the effect of the EROEI change, from the original demand (D), is obtained as:

$$D^m(t+1) = D(t+1) \cdot EROI\ FC(t+1)$$

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2.5. GHG emissions and climate submodule

2.5.1. Endogenous calculation of GHG emissions

The model computes the CO_2 and CH_4 emissions associated with the extraction and burning of fossil fuels (see Table 33). While CO_2 emissions are produced during the combustion of fossil fuels, CH_4 emissions are originated by the losses of methane during extraction, processing, transmission and distribution, notably of natural gas. Biofuels are far from being neutral carbon emitters due to Indirect Land Use Changes (ILUC); hence, in accordance with (European Commission, 2010; Fargione et al., 2008; Haberl et al., 2012; Searchinger et al., 2008), we assign a similar emission level than natural gas. Emission factors are considered constant over time.

Table 33: CO_2 and CH_4 emissions factor for non-renewable resources used in the model. Peat is assigned the same factor as for shale oil (IPCC, 2006). (1toe = 42GJ, i.e. 1tCO2/toe = 23,8gCO2/MJ). *In the absence of data, it was assumed the same emission coefficient of CH_4 than the respective conventional fuel from (Howarth, 2015) for CTL, GTL and unconventional oil.

Resource		Reference	Emission coefficient	
			CO_2 [gCO_2/MJ]	CH_4 [gCH_4/MJ]
Coal		(BP, 2013), (Howarth, 2015)	94.6	0.094
CTL		Average between low and high estimate from (Brandt and Farrell, 2007)	165.2	0.094*
Natural gas	Conventional	(BP, 2013), (Howarth, 2015)	56.1	0.78 ± 0.45
	Unconventional	(Howarth et al., 2011)	56.1	2.48 ± 1.28
GTL		Average between low and high estimate from (Brandt and Farrell, 2007)	103.3	0.094*
Oil	Conventional	(BP, 2013), (Howarth, 2015)	73.3	0.094
	Unconventional	Average between low and high estimate from (Brandt and Farrell, 2007)	91.4 (tar sand/extra heavy oil) 146.1 (shale oil)	0.094*

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In the case of considering a depletion curve of total resource for oil/gas (i.e. conventional + unconventional), it is assumed that unconventional oil/gas follows an exogenous linear path which is set by the expected share in 2050 (inferred by the original publication or estimated by the user of the model).

On the other hand, shale oil emissions are 146.1 gCO_2/MJ vs. 91.4 for the average of total unconventional oil. Since we have all unconventional oils in an aggregated manner, a function corrects the emissions related to total unconventional oil assuming that shale oil would follow the share in relation to total unconventional oil as estimated by (Mohr and Evans, 2010) (Low Case) for 2050 and 2100 (linear interpolation). Thus, the emission factor for unconventional oil considering shale oil higher emissions would be:

$$Emission\ factor_{unconventional\ oil} = 91.4 + (146.1 - 91.4) \cdot share_{shale\ oil}$$

See below Figure 60.

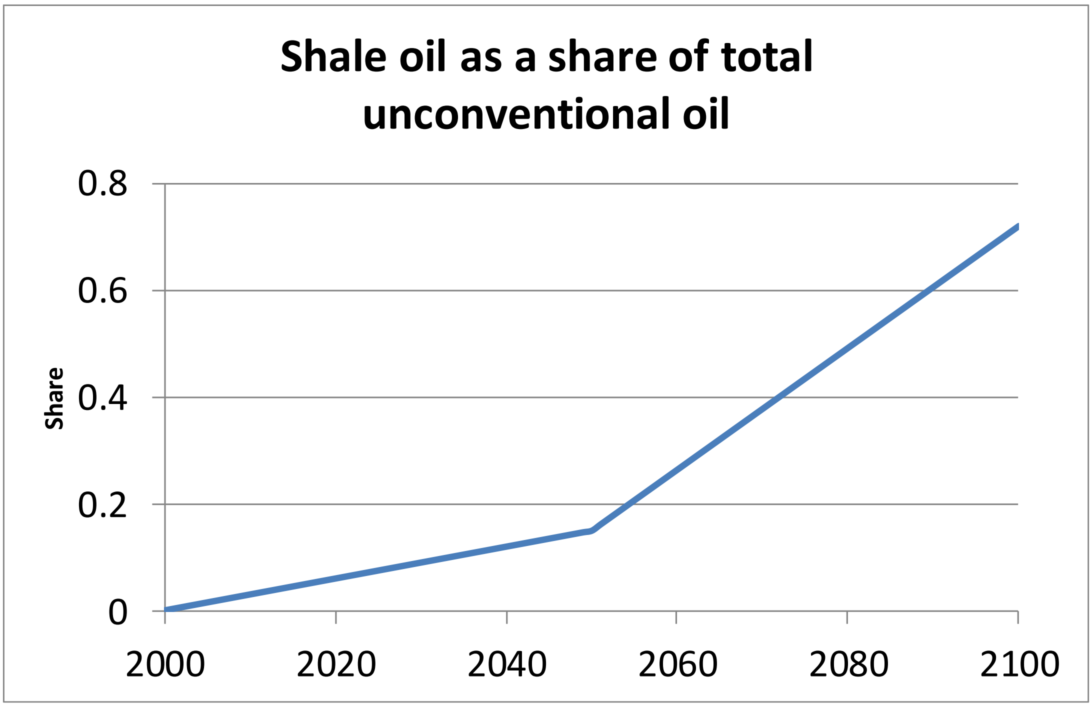

Figure 60: Shale oil as a share of total unconventional oil as estimated by (Mohr and Evans, 2010) (low case).

For projecting future emissions of the rest of GHG included in the model (CH_4, N_2O, PFCs, SF_6 and HFCs), the user can exogenously select a RCP pathway.

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2.5.2. Carbon cycle and climate model

Previous MEDEAS model versions incorporated a simplified representation of the climate based on the climate submodel of DICE-1994 (Nordhaus, 1994; W. D. Nordhaus, 1992) with updated parameters from the DICE-2013R (Nordhaus and Sztorc, 2013). However, the climate module based on DICE is a climatic model of just a few equations which fails to capture some important dynamics and dimensions of climate change (Fiddaman, 2002, 1997). In this sense, it was decided to be replaced by an adaptation of a more complete model. To avoid the complexities and time delays of building a model from scratch, different climate models were reviewed in order to be adapted to the MEDEAS framework. Six models were reviewed: C-ROADS (Fiddaman et al., 2016; Sterman et al., 2012b), DICE-1992 (William D. Nordhaus, 1992), DICE-2013R (Nordhaus and Sztorc, 2013), ESCIMO (Randers et al., 2016), FREE (Fiddaman, 2002, 1997) and MAGICC (Meinshausen et al., 2011b, 2011a). These candidates were checked to fulfill two main conditions:

- Being a simple representation of the climate system able to run on a laptot computer without compromising the handiness of MEDEAS-W (i.e. avoiding the complexity and long simulation times of Global Circulation Models (Meinshausen et al., 2011b)),
- Compatible licence with MEDEAS open-software framework.

After review of advantages and disavantages of the aforementioned models, C-ROADS was chosen to be adapted to the MEDEAS framework, having the additional advantage of having being developed and tested in system dynamics. This model is based on the biogeophysical and integrated assessment literature and includes representations of the carbon cycle, other GHGs, radiative forcing and global mean surface temperature. The core carbon cycle and climate sector of the model is based on Dr. Tom Fiddaman's MIT dissertation (Fiddaman, 1997). The model structure draws heavily from (Goudriaan and Ketner, 1984) Goudriaan and Ketner (1984) and (Oeschger et al., 1975). The model version adapted corresponds is v78b (Fiddaman et al., 2017).

It is also importante to keep in mind that the followed modeling philosophyin the development of C-ROADS is to ensure that the structure and assumptions represent accepted, peer-reviewed science. Thus, although a variety of climate-carbon cycle feedbacks are included, many of these feedbacks are set to zero in the base case because they are, at present, poorly constrained by data. Similarly, it is conservatively assumed no acceleration in ice discharge from Greenland or Antarctica ice sheets beyond what has been observed to date in the historical record. Consequently, C-ROADS is likely to underestimate future warming, sea level rise, and other impacts.

The adaptation procedure included the following steps :

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- Set the initializing time to 1995 instead of 1850,
- For the sake of simplicity, just the core dimensions of climate change required for the operation of MEDEAS-World were included. Other dimensions such as ocean acidification, sea-level rise have been not included in this version. The carbon sequestration options were documented in D.4.1.

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2.5.2.1. Structure of the climate module in MEDEAS-W

Figure 61 shows the main elements of the climate module modelled in MEDEAS-W: the anthropogenic CO2 emissions endogenously generated by the model enter the carbon cycle representation, which estimates the level of CO2 concentration in the atmosphere, the other GHG cycles which together contribute to the anthropogenic climate change. The cycle of each GHG is modelled separatelly, including the interaction between cycles such as between the CH4 and the N20, to obtain the contribution to increased radiative forcing levels from each GHG. Finally, outputs in terms of total radiative forcing and temperature change are computed. In total, 4 new views have been included to update the climate module in the model.

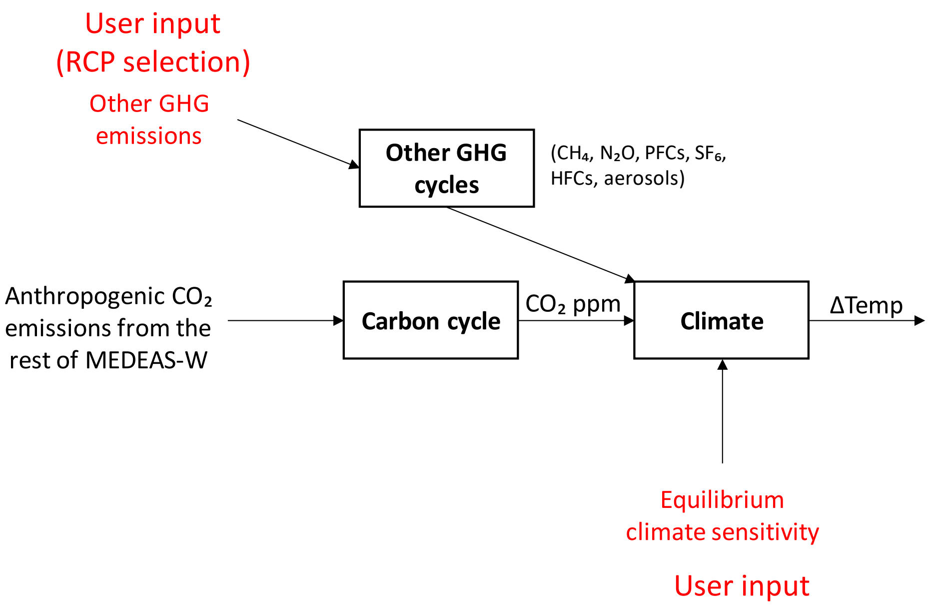

Figure 61 : Structure of the climate module in MEDEAS-World.

Figure 62 shows a simplified representation of the carbon cycle, which represents the dynamics between the carbon in the biosphere (humus and biomass) and the ocean.

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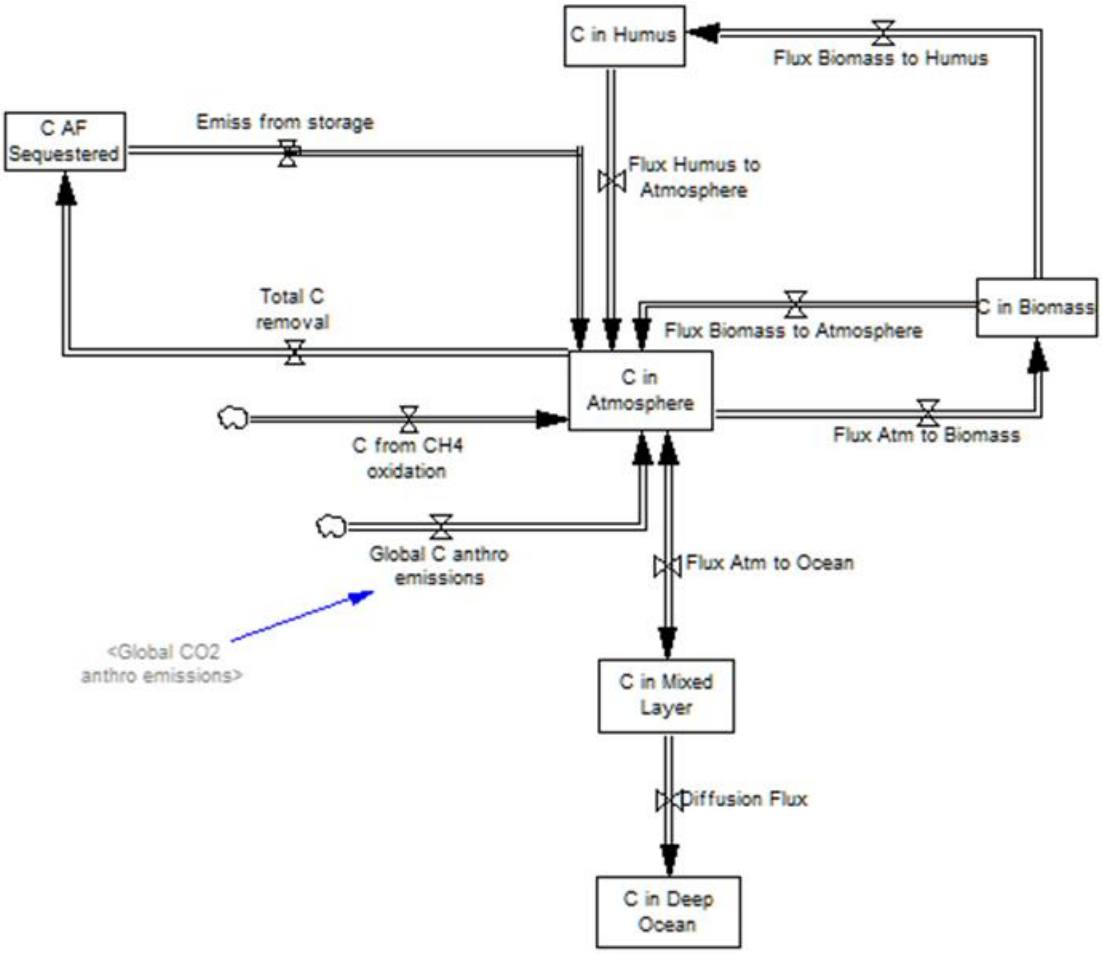

Figure 62 : Carbon cycle representation in MEDEAS-W.

The rest of GHG emissions which are not generated endogenously in MEDEAS-W need to be specified by the user through an external input and have been built consistent with the 4 RCP scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5, for more info see (van Vuuren et al., 2011)). This way, the cycles of the following GHG are explicitly modelled in MEDEAS: CH_4, N_2O, PFCs, SF_6 and HFCs.

Finally, the contribution of all GHG to global warming is aggregated through their respective radiative forcing coefficients, which ultimately enter the climate sector to compute the temperature increase associated with the emissions levels. The user is able also to modify assumptions in terms ofthe climate cycle as the equilibrium climate sensitivity, which is set to the standard value of 2.9 ºC by default. This part of the climate module has not significantly changed from the previous MEDEAS-W model version.

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For more information, see the documentation of C-ROADS (Fiddaman et al., 2016; Sterman et al., 2012b).

In this model version we implement the afforestation as the only CO_2 sequestration policy. As reference we use the work from (Nilsson and Schopfhauser, 1995) that analyzed the changes in the carbon cycle that could be achieved with a large global afforestation program covering 345 MHa. Thus, a maximum carbon capture of 1.5 GtC/year 50 years after the start of the program would be attained. Other technologies such as CCS are not considered in this study due to their uncertain development and benefits (Fischedick et al., 2008; Scott et al., 2013).

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2.5.3. Climate change impacts

The scale of human activities worldwide has grown so great that they are increasingly affecting the regular functioning of the biosphere and critically threatening its equilibrium: during the last few decades, human actions have become the main driver of global environmental change. The scale of the anthropogenic disruption of the biosphere can be illustrated by the current level of some indicators, such as the global ecological footprint (assessed at over 150% of the global biocapacity ratio (GFN, 2015)) or the 9 identified Planetary Boundaries (PBs) (Steffen et al., 2015). Among the latter, it is estimated that two (genetic diversity and biogeochemical flows) have already surpassed their PBs and other two (climate change and land-use system change) have been identified as currently lying in the uncertainty zone. Moreover, Global Environmental Assessments (GEAs) and similar analyses conclude that, if current trends are not amended, next decades will see an intensification of human alteration of the biosphere and the situation of the control variables of the PBs will worsen (e.g. (IPCC, 2014b; Meadows et al., 2004; Millenium Ecosystem Assessment, 2005; Randers, 2012)). Thus, if no corrective actions are taken in the next few decades, the disruptive potential of future global environmental change will likely escalate to levels that will prevent large parts of the biosphere from being inhabited by humans, thus threatening human societies as we know them nowadays (Hansen et al., 2016b, 2016a, 2013; Lelieveld et al., 2015).

Some authors have suggested that disasters can have a positive economic impact, falling the trap of what is known as the "broken window fallacy".[26] In fact, the literature review of environmental catastrophes shows that such events strongly impact the GDP level right after the catastrophe, and that even decades later after such events the GDP level is lower than the level which would have been reached without catastrophe (Hsiang and Jina, 2014; Kousky, 2014).

Policy-recommendations to propose sustainable alternatives to the current trends are usually derived from the application of energy-economy-environment models, or Environmental Integrated Assessment Models (IAMs). However, there is a large discrepancy between natural scientists' understanding of ecological feedbacks and the representations of environmental damage (if any)

[26] As described by (Kousky, 2014): "This is a reference to Frédéric Bastiat who, around 1850, wrote about a shop owner whose window was broken. Some onlookers convinced everyone that it was actually better for the economy because now the window-fixer would be employed and he would pay others, and so on, creating ripple effects in the economy. Our intuition suggests that the simple destruction of capital should not be a net benefit, and the error in the fallacy is the neglect of the fact that had the shop owner not needed to repair a window, he would have used the funds elsewhere—the broken window did not create new economic activity, but just diverted funds from one use to another. Similarly, owners of homes destroyed by tornadoes or hurricanes would have spent money elsewhere that they instead have to use for rebuilding."

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found in IAMs (Cumming et al., 2005; Lenton and Ciscar, 2013; Pollitt et al., 2010; Stern, 2013; Weitzman, 2012). To date, these models do either not include any impact from environmental damages, or just a partial incorporation that translate into practically negligible impacts in the baseline scenarios (i.e. scenarios without additional policies) which project increases of global GDP of several times the current level by 2100. We recall that GEAs follow the conventional economics approach where GDP per capita growth and welfare are tightly connected. As a result of not considering the costs of non-action, recommendations issued from modeling exercises usually lead to misguided political advice (e.g. delayed action, sustainable policies reported as requiring net *costs* instead of *benefits*) (Capellán-Pérez, 2016b).

These shortcomings have especially been pointed out by some authors for climate change, which is the most researched PB. In particular, the usefulness of the applied damage functions, which relate temperature increase with GDP loss, has been questioned given their underestimation of impacts in relation to the forecasts by physical scientists and the fact that they are not calibrated for temperature increases such as the likely ones to be reached at the end of this century in baseline scenarios (i.e. +3.7-4.8°C above the average for 1850–1900 for a median climate response). In fact, current estimations of impacts of climate change or environmental degradation are based upon monetized damages that omit many key factors. These deficiencies have led to questioning the usefulness of current IAMs and argue for a new generation of models (Dietz and Stern, 2015; Giraud et al., 2016; Pindyck, 2015, 2013; Stern, 2013).

However, representations of global environmental change threat to human societies in energy-economy-environment models consistent with the physical science literature have to date been scarce. In MEDEAS, the applied methodology builds on the aforementioned critics from a strong sustainability approach, and follows the subsequent assumptions (Capellán-Pérez and de Castro, 2017):

(1) Focus on the climate change PB as a proxy of global environmental degradation due to the current development level of the MEDEAS framework. However, some consistency is assured by the fact that recent findings suggest the existence of a two-level hierarchy in biosphere processes where climate change is one of the two identified core planetary boundaries through which the other boundaries operate (Steffen et al., 2015).
(2) Application of precautionary principle given the high uncertainties and risk of potential disruptive environmental/climate change in the next decades as proposed by (Pindyck, 2015).
(3) "Energy loss function" (ELF):

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- Environmental/climate change damages affect net energy availability to the society, i.e. affecting the drivers of growth instead of the level of GDP output (Dietz and Stern, 2015).
- Quantitative function with associated uncertainty.

(4) Use of CO_2e concentrations and total radiative forcing as drivers of climate change alteration instead of temperature increases since:
  - Global environmental change is not solely driven by temperature increase (e.g. ocean acidification is driven by CO_2 concentration increase); climate is defined by many factors such as humidity, winds, solar radiation, etc.
  - Thus, the PB of climate change is defined by these two variables (350 ppm and +1.0 W/m^2 relative to pre-industrial levels) (Steffen et al., 2015),
  - The large uncertainty on equilibrium climate sensitivity do not affect the policy-making process (focus on targets such as the carbon-budget (IPCC, 2014b)).

(5) No discounting of impacts (inter-generational equity).

The implementation of the damages from environmental/climate changes in MEDEAS is performed through the integration of an ELF that reduces the overall net energy delivered to the society, assuming that when climate change reaches a certain threshold not compatible with humanity as it is nowadays configured, the energy losses would reach 100% of the total energy supply (see Figure 63). Thus, these damages are modelled as losses (share of final energy) due to the unavoidable impacts from climate change after adaptation. Conceptually, these losses are modelled as defensive expenditures. The resulting GDP change depends on the interaction between this energy consumption, the evolution of final energy intensities and the economic structure and parameters.

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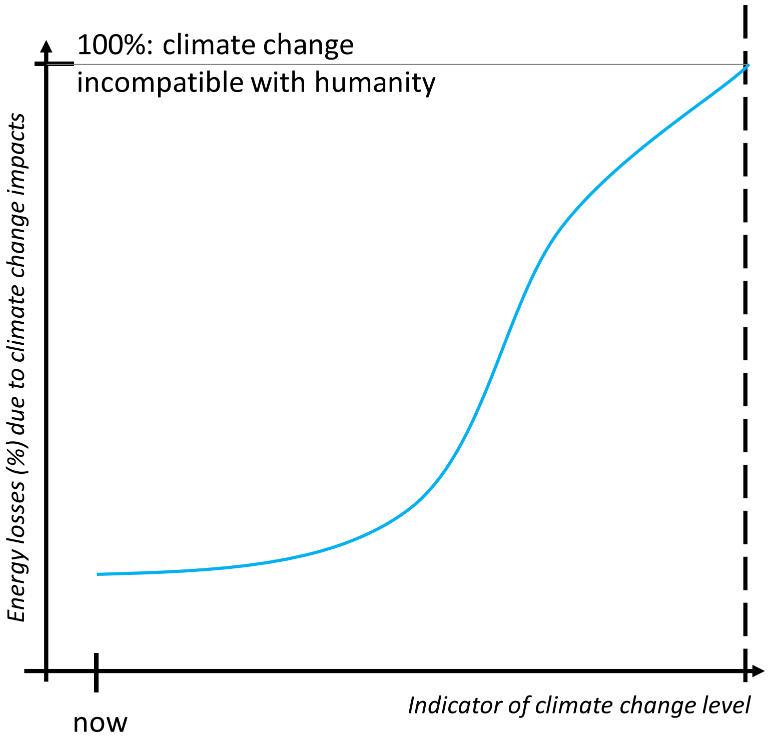

Figure 63: Qualitative representation of the energy loss function (ELF) applied in the MEDEAS framework.

In the standard version of MEDEAS an ELF with a logistic shape that uses CO_2 concentrations from the combustion of fossil fuels and land-use change as climate change indicator is implemented. This function assumes a very low contribution of damages nowadays and takes 1,000 ppm as the threshold of climate change incompatible with humanity:

$$E_{loss}(a;b) = 1 - \frac{1}{1+e^{\frac{ppm-a}{b}}}$$

The parameters a and b can be freely set by the user. In the standard version of MEDEAS the following parameters are implemented by default:

- a= 750: represents the ppm level when the energy losses due to CC impacts reach 50% of the total final consumption.
- b= 50: the lowest is this parameters, the fastest the 100% of damage is reached.

These parameters have been calibrated as follows: considering the possibility to reach a "dangerous" level of climate change by the mid-century under continuation of current trends, we assume a and b in order to hinder economic growth in a BAU scenario by the mid-century.

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The implementation of these energy losses due to climate change impacts is done by reducing the final energy consumption (FEC, thus after accounting for potential energy availability constraints) (see Figure 64):

$$FEC(t)_i^* = FEC(t)_i \cdot (1 - EL(t))$$

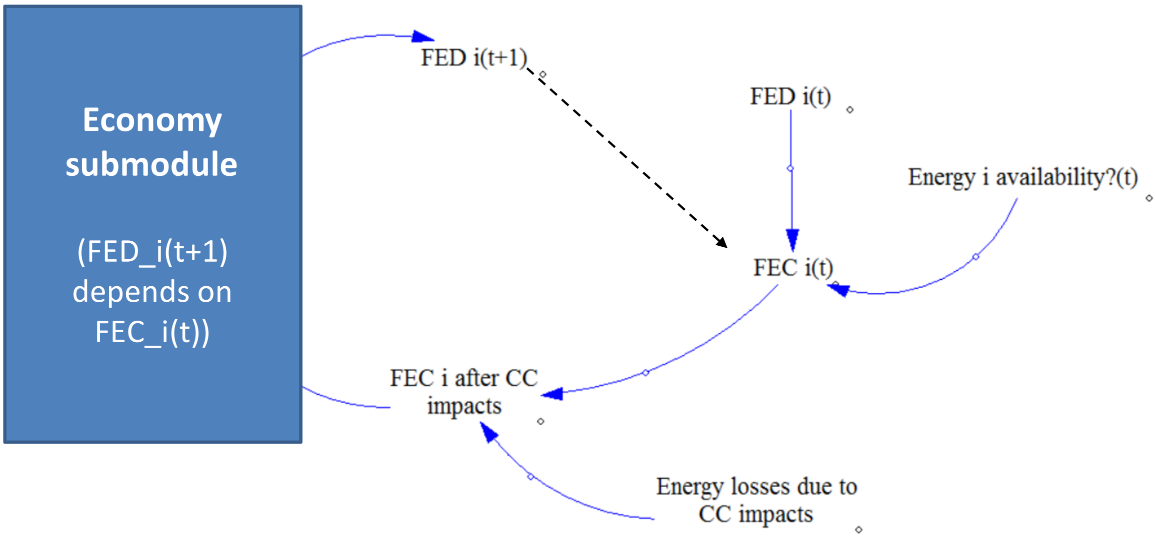

Figure 64: Implementation in MEDEAS framework of the energy losses due to climate change impacts.

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2.6. Land-use module

The land-use module in MEDEAS has two main objectives:

- Estimation of the land-use change GHG emissions: including positive anthropogenic emissions as well as potential ways of capturing carbon,
- Land availability as a potential restriction for RES deployment, with a focus on biomass, solar and hydro.

A simplified model was built in which population, GDP as well as diet patterns conform the non-energy land demand; low carbon policies promote the expansion of RES and climate change impacts tend to decrease the arable model (Figure 71) the module of land-use in the current version of MEDEAS has not been finally integrated in the full MEDEAS framework as initially programmed (see (GEEDS, 2016)), mainly given to the complexity of the design and integration within the rest of the structure of the model.

Thus, in the current version of MEDEAS an effort has been done to implicitly account for the land-use limitations for RES deployment (see for example the section 0 about the potential of bioenergy). On the other hand, the land-use change emissions are introduced exogenously following DICE standard assumption. Current land-use module computes the land requirements for the RES technologies: biofuels, solar, wind and hydro.

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2.7. Social and environmental impacts indicators

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. This section has received key inputs from the D2.2 Task e (MEDEAS, 2016b).

2.7.1. Context and MEDEAS approach

The meaning of "good life" and what is a desirable society has been discussed probably for millennia. In the last decades, several alternative approaches to defining and measuring quality of life were suggested. According to (Diener and Suh, 1997), these are (1) social indicators such as health, education, etc.; (2) subjective well-being measures (assessing people's evaluative reactions to their lives and societies, such as self-reported happiness); and (3) economic indices. These indicators come from three approaches to well-being that are based, respectively, on normative ideals (the more education we have, the better), subjective experiences, and the ability to produce or purchase goods and services (measuring income or levels of production).

The main aim of this module in MEDEAS framework is to translate the behaviour 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 (to a lesser extent) monetary variables. Thus the computation of indicators such as HDI is in principle further the scope of the project (the computing of subjective well-being measures such as "happiness indexes" is obviously discarded). Thus, 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 welfare. We consider that welfare is a multidimensional feature which cannot be reduced to a single variable (UN, 1990). In place, 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, able to provision ecosystem services (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, 2016b).

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2.7.2. List of indicators

An adequate energy supply has been identified as a key prerequisite for economic, cultural and social development in complex societies (Cottrell, 1955; Tainter, 1990; White, 1943). The review of the literature shows that there is a strong correlation between energy use and living standards at lower energy use levels, however after surpassing a threshold, higher consumption of energy does not distinctly translate into better living standards (Iñaki Arto et al., 2016). Different studies focus on primary, final, or electricity energy.

On September 25, 2015, the General Assembly of United Nations adopted resolution 70/1. "*Transforming our world: the 2030 Agenda for Sustainable Development*". This resolution proposes 17 Sustainable Development Goals and 169 targets. The universal access to affordable, reliable and sustainable energy is one of the key issues. Goal 7 states "Ensure access to affordable, reliable, sustainable and modern energy for all". This goal is developed with several targets, such as:

> 7.2. By 2030, increase substantially the share of renewable energy in the global energy mix
>
> 7.3. By 2030, double the global rate of improvement in energy efficiency

The MEDEAS World model can help to design the best policies to meet these targets. In addition, SDGs include other objectives and targets that are closely related to the variables used in the MEDEAS model, which will also help to assess their degree of compliance depending on the scenarios and policies adopted. Some of these objectives are for example:

- Goal 12. Ensure sustainable consumption and production patterns.
- Goal 13. Take urgent action to combat climate change and its impacts.

Despite MEDEAS only estimates 1 out of 3 of the components of the HDI (neither life expectancy at birth nor adult literacy and school enrolment are modelled), there is an alternative way to estimate the potential HDI that can be reached by a society given its final energy use. Given that the quality of life has a material dimension (minimum energy requirements), data for final energy footprint of 40 countries for the timeframe 1995-2009 has been used to estimate a regression between potential HDI levels and energy use per person (see Figure 65). Despite its shortcomings (e.g. (Fleurbaey and Blanchet, 2013; Ranis et al., 2006; Sagar and Najam, 1998) the HDI is yet the most accepted indicator to assess the development of a country.

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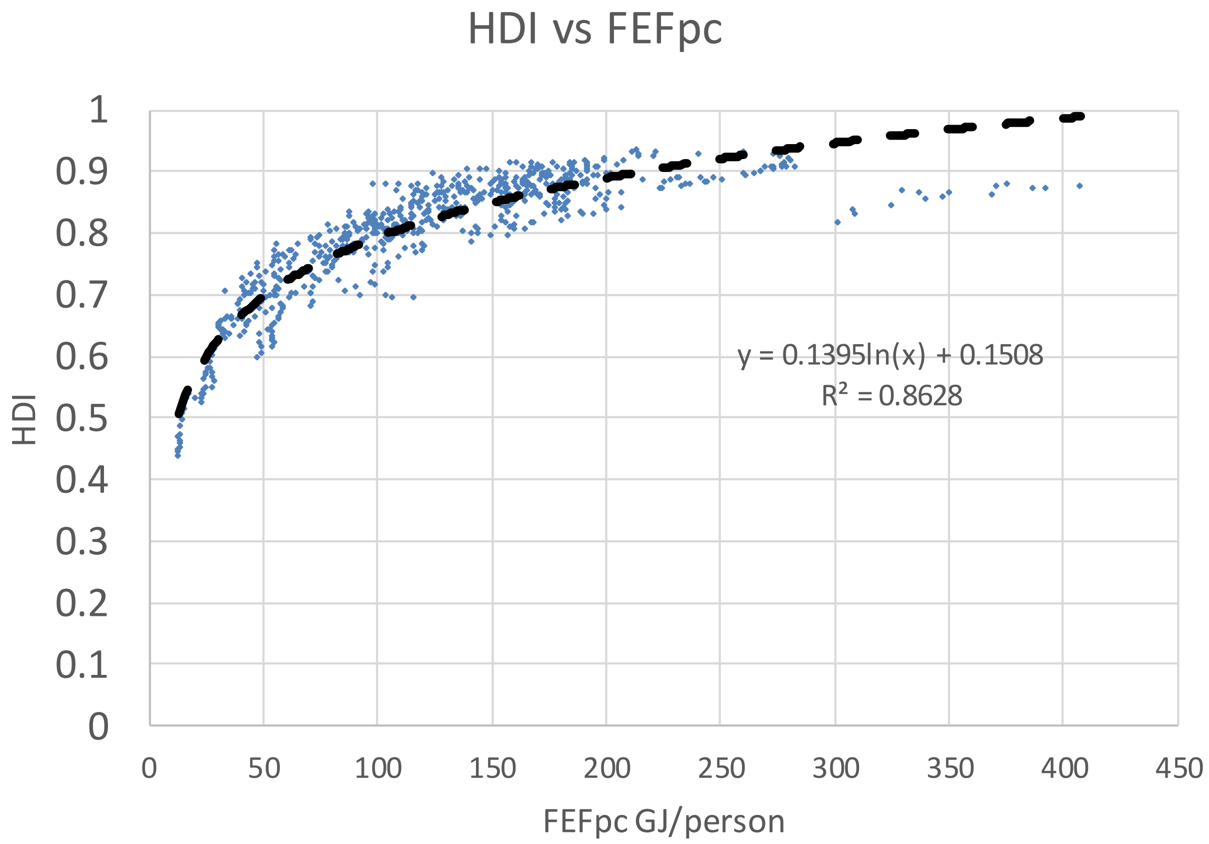

Figure 65: HDI vs Final Energy Footprint per capita (FEFpc) for 40 countries (1995-2009). Source: own work from data from (Iñaki Arto et al., 2016). Regressions published in the paper refer to primary energy, however from the point of view of the quality of life and in the context of scenarios of penetration of RES (the same final energy can be provided with much lower primary energy), the relevant magnitude is the final energy.

MEDEAS objective is to propose feasible alternatives for the energy transition towards a low-carbon energy system. In this context, metrics of RES share and their annual penetration growth in the total and final and primary energy consumption are reported.

Annual GDP per capita represents the per capita monetary measure of the market value of all final goods and services produced in a year. GDP represents a "purely economic" approach to measure social welfare, based on utility maximization. We stress that GDP per capita is not and was never designed as a measure of social or economic welfare, despite being the most common indicator of progress for policy-makers and Governments. In fact, above a certain level, reductions in GDP may be welfare enhancing (Costanza et al., 2014; Kubiszewski et al., 2013; Van den Bergh, 2007; van den Bergh, 2009).

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We also estimate the EROI of the electricity supplied by RES. In the context of a required transition to 100% RES-based systems, it is necessary that these technologies supply a certain level of energy surplus for the system to be sustainable (Hall et al., 2009). However, as seen in section 0, the EROI of some of the key RES systems are far from the historical values of fossil fuels, on which our society currently relies. Thus, to assess the feasibility of the scenarios a net energy approach is fundamental (Carbajales-Dale et al., 2014).

We also focus on the potential level of climate change through variables such as GHG emissions per capita and temperature increase levels over pre-industrial levels. Despite MEDEAS explicitly incorporates a feedback to the energy and economic system of the climate change impacts, it is still important to track the evolution of climate change to assess the scale of potential impacts.

Hence, in MEDEAS framework we identify as social indicators the following variables:

- Total Final and by final fuel Consumption per capita
- Total Primary and by fuel Consumption per capita
- Electricity consumption per capita
- Total water consumption 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. CO2 emission per unit of value added

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Future developments of MEDEAS-World/MEDEAS-EU might expand number of social and environmental impacts indicators, which could in some cases help to endogenize some currently exogenous variables of the model, as well as expand the assessment of other planetary boundaries beyond climate change:

- Equity indicator (monetary and energetic). In fact, equitable resource allocation has been found as a central element of stable and sustainable scenarios (Motesharrei et al., 2014)
- Net employment balance of the transition to RES (i.e. accounting also for the employment loss in NRE technologies)
- Land use by type per capita (Forest, arable, RES production, buffer for biodiversity, etc.), which allow also to compute environmental impacts indicators such as the Global Assessment of Human-induced Soil Degradation (GLASOD)
- Material consumption per capita
- Life expectancy (e.g. through impacts of climate change (Crimmins et al., 2016; WHO, 2014)
- EROI of the whole system (standard, point of use, extended)
- Net primary production (NPP) is the rate of organic matter synthesized by photosynthesis by producers minus the rate of energy rate used for respiration and other damages. NPP integrates aspects of five of the currently defined planetary boundaries (Steffen et al., 2015): land-use change, freshwater use, biodiversity loss, and global nitrogen and phosphorus cycles. It is also influenced directly by two others, climate change and chemical pollution.
- Ecological Footprint

Thus, further developments of the model might allow to estimate the following indicators from the Sustainable Development Goal Indicators (UN, 2015) within MEDEAS framework:

8.4.1 Resource productivity

11.3.1 Ratio of land consumption rate to population growth rate

15.1.1 Forest area as a percentage of total land area

15.3.1 Percentage of land that is degraded over total land area

2.7.3. Water use

The implementation in MEDEAS-World of this dimension allows calculating water use by type (blue, green and gray) by economic sector and for households. This dimension belongs to the "Social and

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Environmental Impacts Indicators" module of the MEDEAS framework. The aggregated values allow to calculate the total water use and social indicators such as the total water use per capita.

2.7.3.1. Context

Freshwater (water which is not salty) represents around 2.5% of the total volume of water on Earth. Out of this percentage, two thirds are locked in glaciers and ice caps. Just ~0.77% of all water (around 10,665,000 km3) is held in aquifers, soil pores, lakes, swamps, rivers, plant life and the atmosphere (Postel et al., 1996). Water resources are renewable (except for some groundwaters) but there are significant differences in availability around the world as well as wide variations in seasonal and annual precipitation (UNESCO, 2009).

Global freshwater distribution must be considered regarding its accessibility. About 75% of total annual runoff is accessible (i.e. accessible runoff (AR)) to slightly more than 80% of the world's population. They are served by renewable and accessible water. However, almost 20% of people need to obtain their supply from aquifers, interbasin transfers and desalinized seawater (UNESCO, 2009).

(AR, this is runoff that is realistically available for human use)

Agriculture uses by far most of the accessible runoff. This sector has a water demand of 2,880 km3 each year and about 65% of total demand is consumed. Industrial use of water is estimated to be around 975 km3 but in contrast to the agricultural sector, industry only consumes a small share of this water, around 9%. Most of it is released back to the environment, however, it is usually polluted (Postel et al., 1996).

In this way, it is notice that the consumption of water will influence significantly in the environment development and, in particular, it will affect potential climate change policies. Recent estimates suggest that climate change will account for about 20% of the increase in global water scarcity (UN, 2003).

Most IAMs do not usually focus on modelling water demand and supply because they have assumed that adaptation to climate change will not be affected by water scarcity. However, there are some exceptions like the Global Change Assessment Model (GCAM) which incorporates a water-balance

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global hydrologic model (GWAM) and quantifies the possible consequences of water availability on climate adaptation. This is important as the natural environment and our society are interconnected, any change on the climate and natural environment implies social adaptation, but also this adaptation will influence on the environment again (Hejazi et al., 2014).

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2.7.3.2. Data

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

So first, we needed to aggregate all countries in order to have water data for the world.

In this way, data in WIOD is divided in three different types of water (Genty et al., 2012):

- *Blue water*: refers to consumption of surface and ground water
- *Green water*: is the volume of rainwater consumed, mainly in crop production.
- *Gray water*: is the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards.

Figure 66 represents the global consumption of water by type for the 1995-2009 period:

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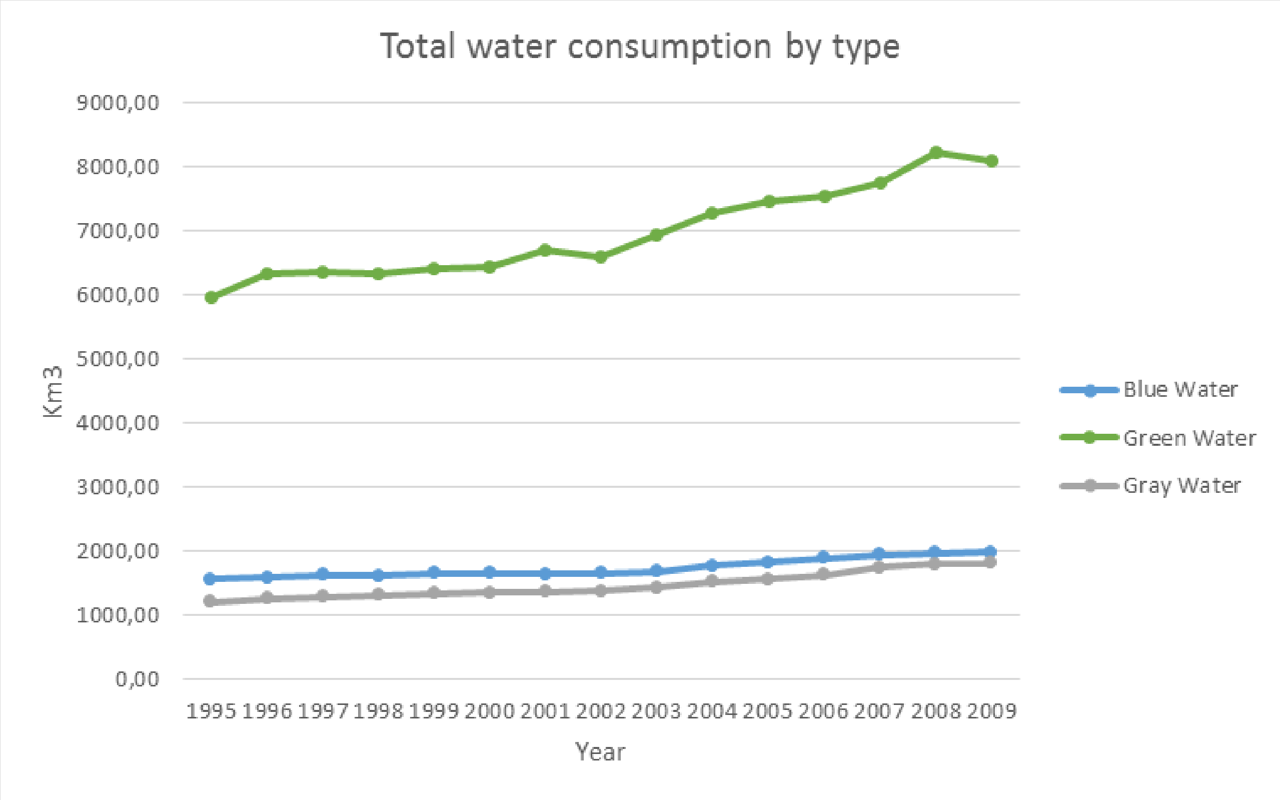

Figure 66: Global water consumption (1995-2009) by type from WIOD database.

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2.7.3.3. Methodology for estimating water use in MEDEAS

Use of water in MEDEAS comes from three sources: (1) economic sectors, (2) households and (3) the operation and maintenance of PV and CSP power plants. The two first sources are modelled in a similar way through the water intensities:

1. **Water intensity by sector**. First, we calculate the historical water intensity data dividing the historical water use by the output (both by sector). Next, the water intensity annual variations are calculated. These data are used to determine the water intensity by sector and type of water. Finally, this water intensity is multiplied by the total output in order to obtain the water use by sector. Water intensity levels by sector are assumed to remain constant at 2009 levels from that year for the simulations.
2. **Water intensity for households**. This second stock presents the same structure as the first but with the difference that the water intensity is calculated for households, so, we don't need a vector for the 35 sectors. The water intensity level of households is assumed to remain constant at 2009 levels from that year for the simulations.

Once the water use by type for sectors and households are calculated, we add them to obtain the total water use by type of water. At this point, we also add the total water used for the operation and maintenance of PV and CSP power plants. The type of water used for this type of maintenance is blue water, so it is added to the blue water consumed by sectors and households. Right after, we gather all types of water and calculate the total water use. We obtain the total water use per capita as well.

Figure 67 shows the Stock and flow diagram of the estimation of water use in MEDEAS

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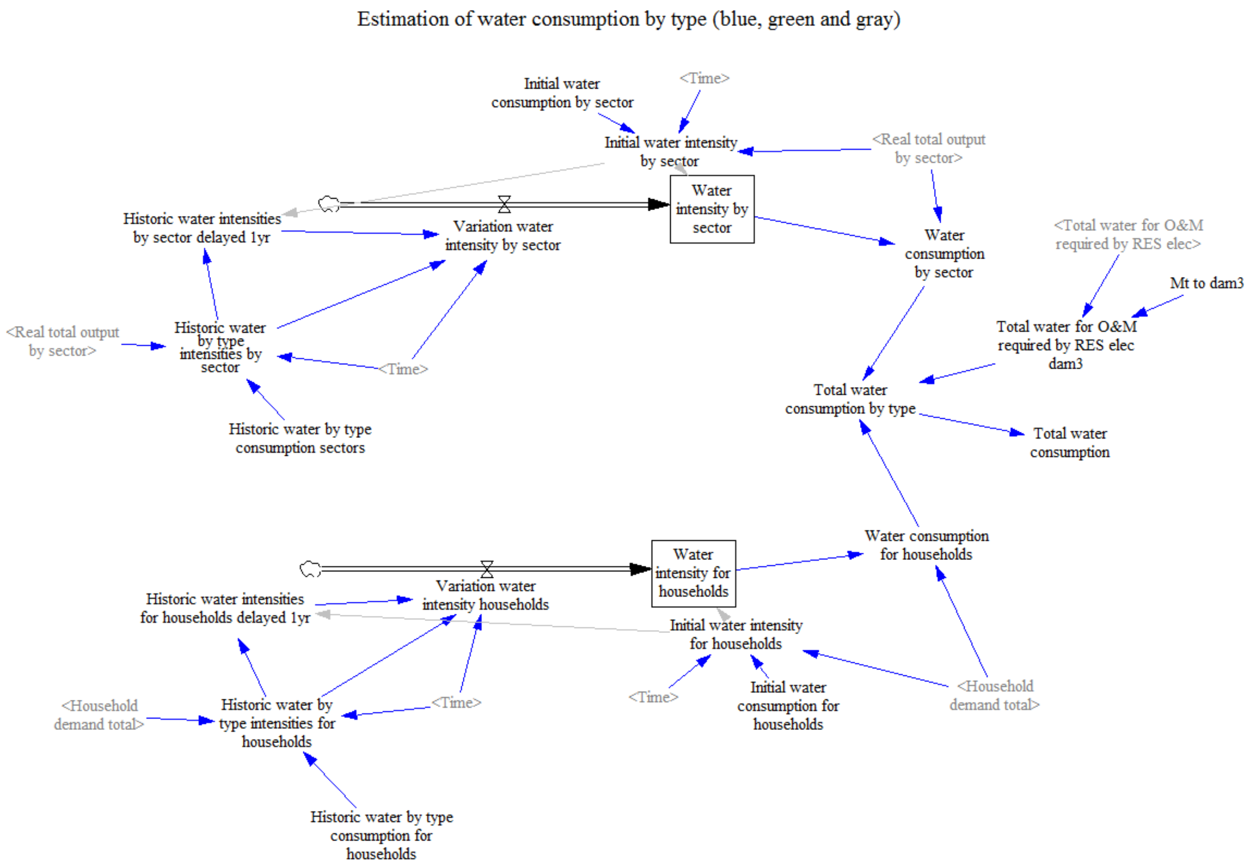

Figure 67: Stock and flow diagram of the estimation of water use in MEDEAS.

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2.7.3.4. Water potential

Most (99%) offstream water uses – irrigation, domestic, industry and energy – are met by withdrawals[27] from renewable sources, either surface water or groundwater. Less than 1% (currently estimated at 30 km3 a year) comes from non-renewable (fossil) aquifers. Some additional supplies can be made available through non-conventional means, such as desalination, often at substantial cost in infrastructure and operations. The global renewable water resources have been estimated at 43,659 km3 (UNESCO, 2009). Comparing the annual use of water with this potential MEDEAS computes the ratio of use of annual renewable water resources.

The accessible runoff, i.e. runoff that is realistically available for human use, is obviously smaller. (UN, 2003) reports that humans withdraw 54% of AR, i.e. the AR can be calculated as 3,829/54% = 7,091 km^3. Comparing the annual use of water with the AR MEDEAS computes the ratio of use of annual AR. Note that this estimate is higher than the one from (Postel et al., 1996), which estimated 12,500 km^3.

[27] Water withdrawal is the gross amount of water extracted from any source in the natural environment for human purposes (Box 7.2 (UNESCO, 2009)).

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3. Policy options available in MEDEAS

MEDEAS includes a diverse set of policy options (mainly technologic) in order to explore the measures which would allow for a transition to a low carbon economy (see Table 34). Some of them can be interpreted as either hypotheses or policy targets, depending on the storyline of the applied scenario (e.g. GDPpc; population). Other should be interpreted as "desired" policy targets (marked with "*" in the table), i.e. they are targets that may or may not be in the end be achieved depending on the evolution of the scenario, the importance of the biophysical constraints operating or the activated policy options. This approach is detailed in (MEDEAS, 2017) as "adaptative scenarios".

	Policy targets/hypotheses
Socioeconomic inputs	GDPpc* Population*
Replacement of existing technologies by alternative low carbon technologies	Electricity* (8 renewables, nuclear[28]) Heat* (3 renewables) Liquids* (3 biofuels) Transportation: electric and gas vehicles (14 types of vehicles)
Efficiency improvement	By sector (and households) and final fuel ((35+1)x5)
Minerals	Recycling rates (19 minerals)
Carbon sequestration	Afforestation

[28] Nuclear energy is included in MEDEAS framework although the developers acknowledge the existence of a lack of consistency between the visions of nuclear power commonly put forward by governments and industry and the experience associated with economic viability, nuclear accidents, waste handling, and so on. (Diaz-Maurin and Kovacic, 2015)

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Other GHG (not endogenously modelled)	Selection of RCP scenario

Table 34 : Main policy targets inluded in the MEDEAS framework. « * » indicates « desired » policy targets, i.e.

In relation to the alternative energy technologies considered in MEDEAS, two criteria have been applied for the choice of their integration of the modelling framework:

1. Focus on those technologies currently available, demonstrated and commercial (i.e. not prohibitively expensive) given the need for urgent action to stabilize climate and reverse current unsustainable trends. Moreover, it has been showed that new technologies and energy systems take about 50 years to diffuse through the economy (Fouquet, 2010). By doing so, we intend to send the message to policy-makers that it seems more reasonable, given the urgency of action to stabilize the climate, to stop financing the R&D of very expensive speculative technologies or different demand and management policies.

2. Assure that the net energy balance of the considered technologies is positive, i.e. that the technology will be a « reasonable » net energy contributor to the society. For a technology to be « reasonable », its $EROI_{st}$ must of course be > 1, but additional criteria should also be fulfilled to assure that the energy costs of the extended boundaries are also covered and the overcapacities required are not exorbitant. For example, an EROI of 2 for a given energy system translates into a doubling of overcapacity (Capellán-Pérez et al., 2017a). Although an energy system with EROI < 1-2 could still be used for some specific purposes, it would rather be an anecdotal technology given the burden that it would impose to the whole energy system (it would be an energy drain rather than source).

In the light of these criteria the following technologies were not included in MEDEAS framework:

- Carbon capture and storage (CCS) and negative emissions (section 3.1),
- Hydrogen (section 0),
- Nuclear fast breeders and nuclear fusion (section 0).

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3.1. Carbon capture and storage (CCS) and negative emissions

Carbon capture and storage (CCS) usually refers to the technological process of capturing emitted CO_2 from large point sources, such as fossil fuel power plants, transporting it to a storage site, and depositing it where it will not enter the atmosphere, usually an underground geological formation. Still, power plants combined with CCS are not a free-source of carbon since their GWP can be reduced just by 63–82% and other environmental impacts such as acidification and human toxicity are higher with than without CCS (Cuéllar-Franca and Azapagic, 2015). Despite extensive research and development in the last decades, no large fossil-fuel power plants are currently using CCS at commercial level, and publicly supported demonstration programmes are struggling to deliver actual projects, such as the European NER3000. There is in fact large uncertainty in relation to the future technical and commercial availability of large-scale CCS (Reiner, 2016; Scott et al., 2013).

The rapid application of carbon capture and storage is a much heralded means to tackle emissions from both existing and future sources. The combination of advanced bioenergy and CCS (BECCS) has been assessed in the last IPCC report as the most critical technology in the context of the timing of emission reductions. This is due to the fact that, while GHGs continue to grow globally and we approach the carbon-budget, the possibility to make the transition to low-carbon technologies without removing emissions from the atmosphere fades. As a result, models targeting stabilization scenarios below 2ºC (or 2.6 W/m2, i.e. RCP2.6) include substantial amounts of BECCS to be deployed along the century (Anderson and Peters, 2016; Fuss et al., 2014; IPCC, 2014c; Smith et al., 2016; Vaughan and Gough, 2016).

In relation to the net energy balance and given the lack of estimates in the literature, we have roughly estimated the EROI of energy systems for electricity production burning coal and bioenergy with and without CCS. We have selected coal since it is the fossil fuel with higher EROI and larger estimated resources, and bioenergy since, as aforementioned, most IAMs strongly rely on BECCS to deliver stabilization scenarios. Firstly, it should be highlighted that in the literature about the processes of capture, transport and storage of CO2 from fossil fuel plants (coal and gas mainly) is strongly biased towards techno-optimism. For example, the Cp usually considered in these theoretical studies is 0.9 while data of real power centrals shows Cp values of 0.5-0.6 for coal and 0.6 for natural gas (IEA, 2018; Shearer et al., 2016). Besides the correction of Cp, the following factors have been taken into account based on literature review:

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- CCS energy penalty, i.e. the operation of CCS incurs in supplementary energy losses to the power plant. The review of LCA studies shows a range of 16-44% for fossil fuels, with a rough average of 30% (Corsten et al., 2013; Haszeldine, 2009; Schreiber et al., 2012; Viebahn et al., 2007). Cormos (2012) found that in the case of coal power plants, the consumption of coal increases +25% with CCS to generate the same electricity output.
- Oversizing of the plant to integrate the CCS mechanism (which also increases the energy requirements for plant dismantling). For example, Hammond and Spargo (2014) estimate that the oversizing of the power plant to integrate the CCS mechanism reduces the EROI of the power plant from 10.9 to 9.9:1. As reference, we take the middle range of the values reported in the meta-analysis from (Schreiber et al., 2012).
- Energy requirements for the construction and O&M of the electric network (own estimation considering 1% of losses due to construction and maintenance and 6% due to joule effect, see Table 35).

Table 35 shows the results taking into account the EROIst of each energy source (coal or bioenergy[29]), the additional energy requirements for the CCS process, the energy requirements for plant dismantling and the energy requirements for the operation of the electric network. The following equations shows how the efficiency of each energy system i can be estimated from the EROI (or efficiency) of each phase j accounting for the current quality factor of the electricity (g):

$$\chi^i = \prod_j \chi_j^i$$

$$X_j^i = 1 - \frac{1}{EROI_j^i}$$

$$EROI^i = \frac{\frac{1}{1-\chi^i}}{g}$$

[29] The process of making available biomass (e.g. in the form of pellets or chips) to the end user requires energy for forest management, harvesting, wood processing, transportation, pelleting, etc., which under current mechanic practices typically require the combustion of fossil fuels (chain saws, tractors, lorries, etc.). There is for example a trade-off for biomass EROI between pelletization, which consumes large share of energy processing, and improved efficiency of the combustion in the power plant/boiler (Furtula et al., 2017).

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For example, the estimation of the EROIst of coal+CCS energy system is obtained as follows (taking into account the factor of Cp correction and the energy requirements for the construction and O&M of the electric network):

$$\chi^{coal+CCS} = \frac{(\frac{1}{1-46}) \cdot (1 - 0.0057 \cdot 1.5) \cdot (1 - 0.0262 \cdot 1.5) \cdot (1 - 0.01 \cdot 1.5) \cdot (1 - 0.06)}{1.25}$$

$$EROI_{st}^{coal+CCS} = \frac{\frac{1}{1 - \chi^{coal+CCS}}}{g}$$

Table 35 reports the estimated $EROI_{st}$ and $EROI_{pou}$ of coal and bioenergy power plants with and without CCS.

Table 35: EROI estimation of coal and bioenergy power plants with and without CCS.

	Coal	**Coal+CCS**	**BioE**	**BioE+CCS**
EROIst of energy source	46 (Hall et al., 2014)		2-3 (de Castro et al., 2014; Furtula et al., 2017)	
Energy penalty of CCS operation	0	+25% (Cormos, 2012) and literature review (see text)	0	As for coal+CCS
Additional energy requirements for building the CCS infraestructure	0	0.57% (middle of the range from (Schreiber et al., 2012))	0	As for coal+CCS
Energy requirements for plant dismantling	0.2% (Schreiber et al., 2012)	2.62% (middle of the range from (Schreiber et al., 2012))	As for coal	As for coal+CCS

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Energy requirements for the construction and O&M of the electric network	1% construction and maintenance 6% joule effect (own estimations assuming Cp=0.5 and a lifetime of 30 years)			
Cp correction	$\frac{Cp^{theoric}}{Cp^{real}} = \frac{0.9}{0.6} = 1.5$			
g	0.7 (current value, see section 0)			
EROIst of the electricity generation system	14.7	4.6	2.7 – 3.7	1.9 – 2.1
EROIpou of the electricity generation system (defined as EROIst-1)	13.7	3.6	1.7 – 2.7	0.9 – 1.1

In the light of the results presented in Table 35, current coal power plants have an EROI clearly > 10, which allow them to positively contribute to the energy balance of the society. The introduction of the CCS devices implies a drastic reduction of its EROI to below 5:1 level. In particular, the EROIpou of 3.6:1 implies that just to compensate its inherent energy losses, an overcapacity of almost +40% would be required. In the case of BECCS, the results are even worse, given that we find an EROIpou < 1. In the light of these results, the technology BEECS would be an energy drain rather than an energy source. in other words, BECCS technology should be rather considered as a technology to store carbon at an energy cost.

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Additionally to the uncertainty in relation to the future technical availability of CCS, its expected high cost and the low energy balance of BECCS, the deployment of large amounts of bioenergy crops faces biophysical constraints due to the requirement of large areas, high fertilizer and water use, and that likely compete with other vital land uses such as agriculture of biodiversity conservation (Anderson and Peters, 2016; Fuss et al., 2014; Kartha and Dooley, 2016; Scott et al., 2013; Smith, 2016) (see also section 0 on land competition).[30] In fact, a recent expert elicitation focusing on the potential of BECCS concluded that assumptions regarding the extent of bioenergy deployment, and development of adequate societal support and governance structures for BECCS are unrealistic (Vaughan and Gough, 2016). Direct air capture has less area and water needs than BECCS and no fertilizer equipment, but it has high energy use, has not been demonstrated at scale, and cost estimates exceed those of BECCS (Hansen et al., 2016b; Smith et al., 2016).

For example, in relation to land occupation, a recent review found that <2ºC stabilization scenarios in IAMs require a range of 380-700 MHa by 2100 for BECCS (considering high-productivity dedicated energy crops), which represents 7–25% of current global agricultural land, and 25–46% of arable plus permanent crop area, a range of land demand which is the magnitude order than land identified as abandoned or marginal (Smith et al., 2016). These calculations refer to 3.3 Gt Ceq/yr of negative emissions, i.e. just ~25% of the total GHG emissions in 2010 (IPCC, 2014c).

Follows a back-of-envelope calculation considering more realistic/average parameters. For the case of biopower from a short-rotation poplar with clones on degraded lands in Siria and with the use of fertilizants, (Dillen et al., 2013)Dillen et al. found an average gross energy power of 1,1 We/m2 (i.e. > 10x larger than the typical ranges of net power density found in the literature). Applying this density and taking into account the carbon content of dry biomass (47.5% (Schlesinger, 1991)), 6,9TnCO2/Ha·yr would be emitted by the burning of the biomass. Since CCS capture at most 90% of emissions, this system would require 1 Ha to absorb 6Tn of CO2 (without taking into account of the indirect emissions during the process of making available the biomass). Thus, these calculations indicate that to absorb 10% of the current emissions over 650 Mha of fast growing trees should be dedicated to this end.

Thus, it is very likely that the use of bioenergy for negative emissions impacts the amount of land available for food, biodiversity and other human uses if scaled substantially.

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[30] The logistics of collating and transporting vast quantities of bioenergy globally —equivalent to up to half of the total global primary energy consumption— is also seldom addressed.

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Additionally, IAMs and LCAs usually assume bioenergy carbon neutrality, i.e. that the CO2 released from their combustion matches the CO2 uptake during feedstock growth. That convention is premised on globally complete carbon accounting in which biogenic emissions are not counted in energy sectors when carbon stock changes are counted in land-use sectors. However, when accounting for biogenic emissions in soils, real examples show that the extraction of biomass disbalance the soil carbon cycle, provoking unintended additional emissions (or additional supplies such as fertilizers which also imply additional emissions during their life-cycle). For example DeCicco et al., (2016) found for USA that «carbon uptake on cropland was enough to offset only 37% of the biofuel-related biogenic CO2 emssions… [far] from the 100% assumption made by LCA and other GHG accounting methods that asume biofuel carbon neutrality ».

Hence, the dependence of the majority of policy-influential models such as the integrated assessment models participating in the IPCC processes on these speculative technologies affected by such uncertainties, large biophysical requirements and extraordinary costs which may be never available at the timing and scale required, is problematic. Some authors have suggested that the pervasive inclusion of these speculative technologies is a consequence to fine-tune the analyses to conform to dominant political and economic sensibilities rather than to sound scientific modelling (Anderson, 2015; Spash, 2016). Moreover, the expectation that this technology may be available in the future provides a justification for building new fossil fuel power centrals that may be adapted in the future, exacerbating the problem of lock-in infrastructures. Given the risks at play, we judge that a precuationary principle approach is more sensitive for policy-advice. Thus, for these reasons, in MEDEAS we do not consider that CCS technology will be available in the future at the (early) timing and (extensive) scale required.

In contrast, we decided to focus on the potential of carbon capture in soils through land management practices and afforestation which are already available, low cost demonstrated technologies (Hansen et al., 2016b; Houghton et al., 2015; IPCC, 2014c).

Recommended Management Practices (RPM) such as crop rotations, low and no-tillage practices, cover crops, holistic management of pastures, agroforestry, use of manure and biosolids and precision irrigation have a great potential to enhance the soil organic carbon (Jarecki and Lal, 2003; Smith et al., 2008). According to FAO (2017), for example, no-till practices have an estimated potential of carbon capture sequestration that ranges from 0 to 150 kgC ha-1/year in warm and dry climates, and to 100 1 000 kgC ha-1/year in humid and cool climates. Although more research in this field is needed, and the actual values of these potential are questioned by same researchers (Baker et al., 2007; Powlson et al., 2011; Sommer and Bossio, 2014), RMP's are technologies interesting by

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themselves since their adoption increases soil quality and agronomic yield, therefore, they do not necessarily compete with food production and might be profitable for farmers, instead of requiring extra economic investments as BECCS do. In particular, increasing the carbon stock in the soil plays a role in four important ecosystem services: resistance to soil erosion, soil water retention, soil fertility for plants and soil biodiversity; being also a key policy for climate adaptation in many regions of the globe.

In relation to the potential of afforestation and reforestation, Kartha and Dooley (2016) found a potential of 370-480 GtCO2 of negative emissions based in ecosystem restoration and reforestation (0GtC02 for BECCS). However, these options also face land limitations: annual negative emissions of 1.1–3.3 Gt Ceq yr^{-1} would require 320–970 Mha, representing 6–20% of total agricultural land, and 21–64% of arable plus permanent crop area, a range of land demand which corresponds with the magnitude order of land identified as abandoned or marginal (Smith et al., 2016). These negative emissions refer to just to 8-25% of the total GHG emissions in 2010 (IPCC, 2014c).

However, it should be kept in mind that the first step towards a land system which would store carbon would be to reverse the current trends, since currently ~10% of global emissions are from land-use changes. This growing trend endures the last centuries, and its reversal may well imply radical socio-economic changes (Kartha and Dooley, 2016).

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3.2. Hydrogen/« Renewable hydrogen economy»

Hydrogen commercialization began in Europe and the US in 1930 for industrial uses. Currently, every year over half a billion cubic metres of hydrogen are produced (mostly from natural gas in industrial processes but mostly as raw material for various other chemicals and not as a fuel (Abbasi and Abbasi, 2011)), i.e. an energy capacity equal to over 10 % of oil consumed. Its applications are expanding towards electrical production associated to a fuel cell with a wide potential range of uses, particularly in transport. Among its advantages: clean fuel if hydrogene generated from RES, high energy capacity (in mass account) in comparison to other storage options (although still 1 kilo of hydrogen equals 3.5 l of oil but 1liter of hydrogen at atmospheric conditions equals to 13KJ –termal-, 5,6MJ at 700bar versus 35,8 MJ of diesel); potential improvement in energy safety if generated by local RES; contributes to mitigate the intermittency of the main RES and has the potential to be used in a wide spectrum of applications. Nevertheless, hydrogen has three serious limitations, i.e. it is a secondary fuel, thus energy must be used to obtain it; it needs to be stored at high pressure (especially in vehicles), since it is the most volatile gas ; and has a relative low efficiency (Bermejo, 2014, chap. 14; Ehteshami and Chan, 2014).

Excepting for solar and biomass, the rest of RES technologies require an electrolyzer to generate H_2, which is a process with an efficiency of around 60-70% (Abbasi and Abbasi, 2011; Levene et al., 2007), while fuel cells operate with efficiencies ranging 40-60% (Bermejo, 2014, chap. 14). This indicates that for most technologies the efficiency of the whole transformation RES electricity-hydrogene-electricity is around 1/3,[31] which is really poor. In terms of net energy analysis, it has been estimated that energy stored on energy invested (ESOI) of RES electricity-hydrogene-electricity is close or even below to 1. In this context, it would be energetically better to curtail than to store as hydrogene.

When the energy source is direct solar, it can be converted to hydrogen via both electrolytic and direct conversion routes. Intensive efforts are also being made to generate hydrogen from anaerobic digestion of biomass and biowastes, but, as of now, success hasn't been achieved (Abbasi and Abbasi, 2011).

[31] (Bernal-Agustín and Dufo-López, 2008) also report an efficiency of the whole chain RES electricity-hydrogene-electricity of around 30%.

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In terms of deployment timing, the IPCC reports that “during the second-half of the century, many integrated studies also include substantial shares of electricity and/or hydrogen to fuel electric and fuel-cell light-duty vehicles” (IPCC, 2014c), confirming the current immature state of this technology.

From the point of view of net energy analysis, few estimates of the ESOI of the whole chain exist in the literature, although the high costs of the technology indirectly indicate a low energy return on energy stored. Hacatoglu et al., (2012), for example, find that the EROI of the transformation of electricity from wind and solar to hydrogen would be 1.8 and 0.7 respectively, i.e. an ESOI of the whole chain electricity-hydrogene-electricity clearly < 1 for both RES technologies assuming a fuel cell efficiency of 50%. These results are confirmed by Mori et al., (2014) who also find ESOI levels <<1.

Summarizing, the “renewable hydrogen economy” is estimated to be a marginal option in the MEDEAS timeframe due to its current unfavourable net energy output (ESOI<1), which makes that other alternative technologies for energy storage such as PHS and electric batteries seem better options. For example, in MEDEAS the ESOI of PHS ranges between 12.7 and 5 :1 (see section 0).

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3.3. Nuclear fast breeders and nuclear fusion

Breeder reactors refer to plutonium-fueled nuclear power plants that could produce more fuel than consumed. This technology started to be researched as early as during the World War II in the USA by scientists in the atomic bomb program. A recent report from the International Panel of Fissile Materials concluded for the current status of this technology that « such reactors are expensive to build, complex to operate, susceptible to prolonged shutdown as a result of even minor malfunctions, and dificult and time-consuming to repair ». These are the same words than an expert in the field reported in 1956 (Cochran et al., 2010). Thus, despite enormous breeder research funding beetween 1950-2007 (tens of billions of dollars), this technology has still to surmount technical difficulties and is thus far from reaching commercial level. These reactors have failed to be a safe and reliable source of energy; accidents and long shutdowns have characterized fast breeder reactors reseach. For example, during the Superphénix French project life time (the biggest ever made) the Cp was less than 7%). In fact, most experimental reactors in Rusia, USA or France have been suspended. Cochran et al., (2010) conclude: « After 6 decades and tens of billions of dollars, the promise of breeders… remains… unfulfilled and [funding] is cut back [dramatically] in most countries ». Thus, we assume that fast breeders will not be available in the timeframe of MEDEAS.

Nuclear fusion is not considered since the ITER and DEMO projects estimate that the first commercial fusion power would not be available before 2040 (http://www.iter.org), which would prevent this technology to substantially contribute to the mix in the timeline of MEDEAS.

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4. Limitations and further developments of MEDEAS-World model

As any model, MEDEAS-World presents a number of limitations. Some of these may be handled in further versions of the global model, as well as in the forthcoming European model version. Limitations and further developments are organized in two main blocks, the first one referring to improvements in the structure of the model (section 0), and the second related to the policy options to be implemented within the modelling framework (section 4.2).

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4.1. Structure of the model

We identify the most significant potential developments by modules and in relation to their interactions:

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, which would subsequently affect public investment,
- Model inventories as a residual of production not met by demand (demand function).

Energy and infrastructures module

- Expand the modelling of energy infrastructures to all energy generation and distribution technologies,
- Improve the modelling of demand and supply of heat. Despite energy for heating currently represents over 40% of total final energy demand, a greater share than the entire power sector, global data related to heat are of bad quality and this type of energy does not feature high on the agenda in energy debates. Also, interactions between heat and electricity (e.g. generation of electricity from heat sources, storage for thermal loads is less costly than electricity storage, etc.)
- Computation of the EROIst (and allocation mechanism) to all energy sources and technologies,
- Estimation of EROIst, EROIpou and EROIext of the whole system.

Interaction of Energy and Economy

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- Integration of primary energy intensities,
- 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.

Materials

- Consider better estimates and data for the availability of minerals than the conventional metrics of reserves and resources given their uncertainties.
- 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.

Land-use module

- Fully develop and integrate the land-use module framework which has been already advanced within the rest of the model (see Figure 68). The integration of such a module would allow to consistently integrate the different uses of land (food, biocrops, biodiversity conservation, afforestation, etc.) and assist in the assessment of sustainable potentials for biocrops and other land-intensive RES technologies. The modelling of agriculture and food production would also be required.

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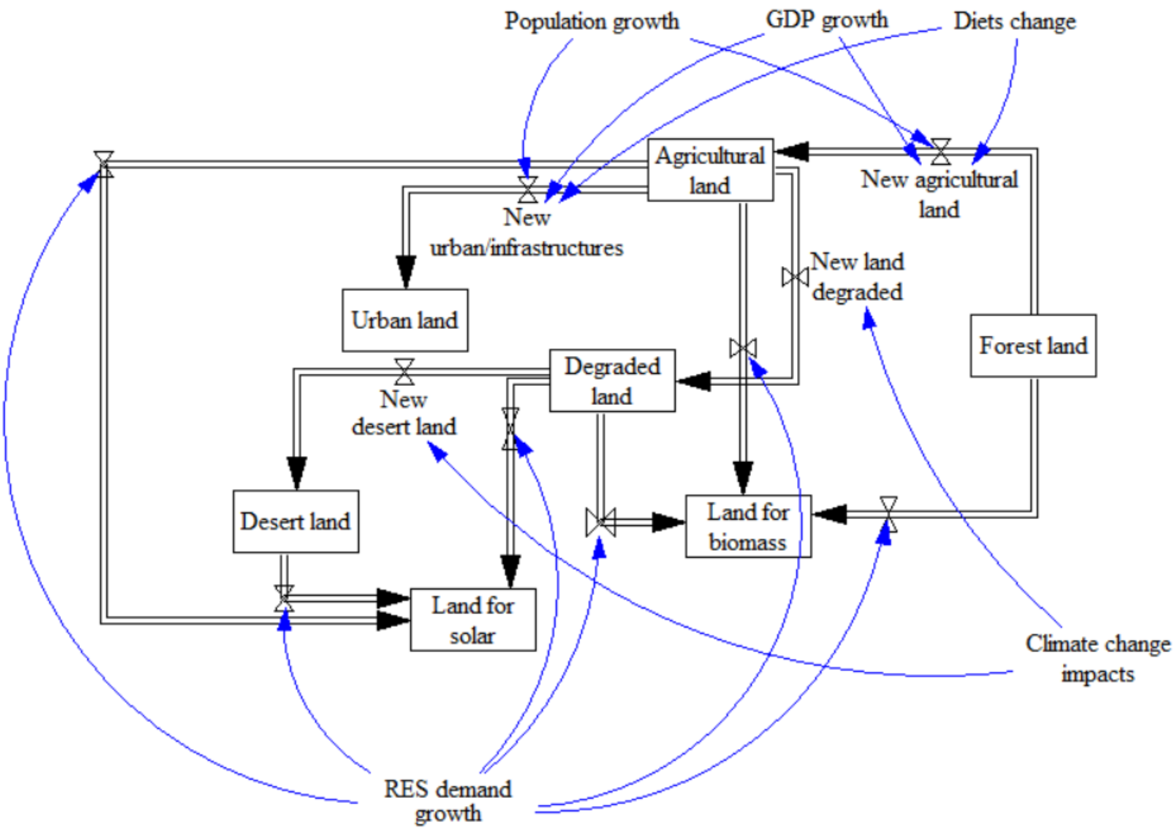

Figure 68: Modelling approach of the land-use module in MEDEAS framework. However this structure has not been finally included in the current version of the model.

Climate 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, capital damage, etc. (Dietz and Stern, 2015; Taylor et al., 2016)),
- Consistent integration of potential irreversible, large-scale events such as tipping points (Cai et al., 2016; González-Eguino et al., 2017; González-Eguino and Neumann, 2016).

Social and environmental impacts indicators

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- 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 labor 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 structural linkages to be developed in further work are represented in Figure 69 by dashed arrows.

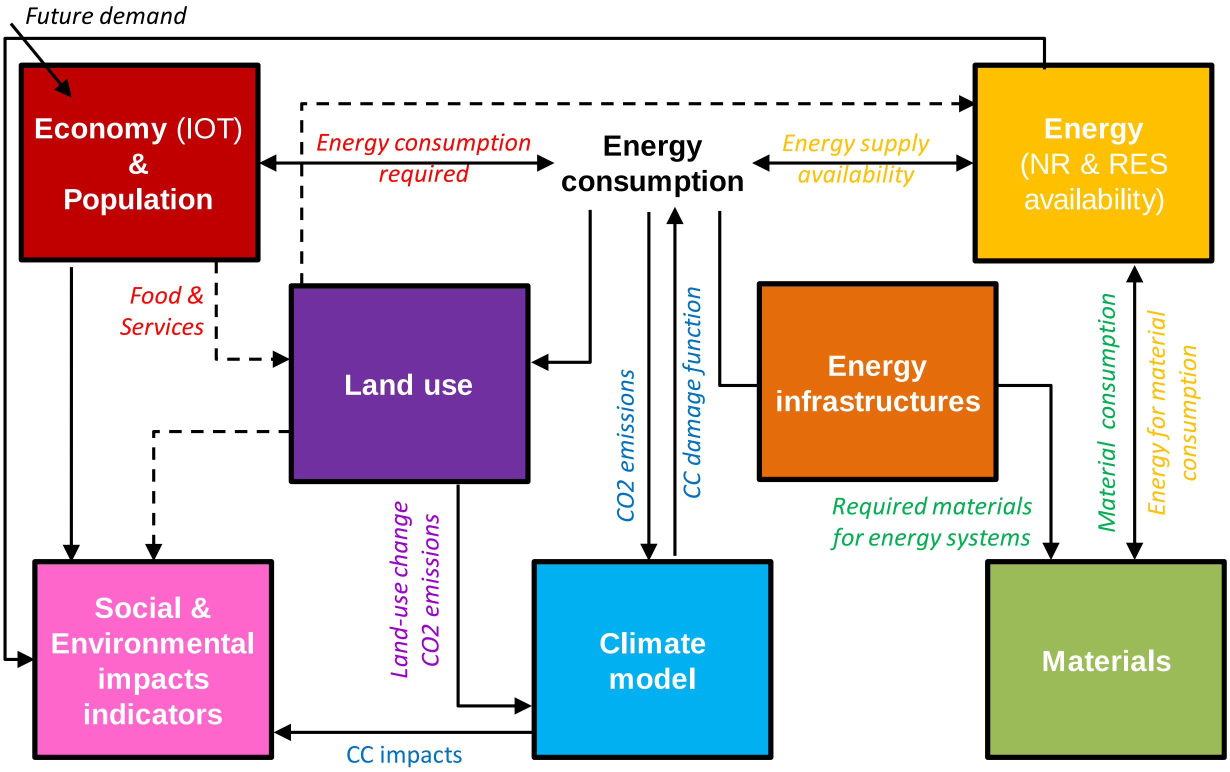

Figure 69: Overview of MEDEAS-World by modules. Straight lines represent relationships currently modelled, while dashed lines represent future potential developments.

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 implementation of aspects of the other dimensions: biosphere integrity, 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;

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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 focused 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 (Bardi, 2017).

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4.2. Policy options

The current MEDEAS-W includes 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 de Ven et al., 2017; 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, 2016b),
- Reduction in working hours per person (MEDEAS, 2016b),
- Demand management policies (mobility, etc.),
- Agroecologic 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).
- Possibility to keep fossil fuel resources in the ground (McGlade and Ekins, 2015).

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5. Conclusions

Models are useful tools to guide policy-making and they should not be employed as tools to predict the future. This report extensively documents the approach to build MEDEAS-World, a new global-aggregated energy-economy-environment model. It has been designed applying System Dynamics, which facilitates the integration of knowledge from different perspectives as well as the feedbacks from different subsystems. MEDEAS-World is structured into 7 submodules: Economy, Energy, Energy Infrastructures, Materials, Land Use, Social and Environmental Impacts Indicators and Climate Change. These submodules have been programmed in approximately 100 simulation windows and using more than 4,000 variables. The modules of economy and energy are the most extensive and reach the highest degree of disaggregation. The model includes several novelties in relation to the current state-of-the-art of the field:

- Integration of Input-Output Matrices in the Economy submodel within a System Dynamics structure,
- Comprehensive analysis of the techno-sustainable potential of RES for electricity and heat,
- Supply-demand closures model implementation. The energy shortage determines the feedback between the energy and the economic submodule.
- Comprehensive estimation of the EROI of those RES technologies for the generation of electricity with greater techno-sustainable potential.
- Estimations of the potential mineral scarcity,
- Estimation of the EROI of the system and integration of its feedback within the system.
- The impacts of climate change are feedback into energy consumption.
- Implementation of environmental and socio-economic indicators.

Regarding the literature in macro-economic modelling in IAMs, MEDEAS economy module makes several contributions. Firstly, it contributes to widen the simulation and non-optimisation models literature. Secondly, regarding the previous consideration, it is a feedback-rich model based on system dynamics. It is worth to mention the energy-economy feedback, which allows modelling GDP endogenously and subject to biophysical constraints. Thirdly, sectoral structure of economy matters, regarding the different energy requirements by industries. Finally, it takes into consideration inequality throughout the primary income distribution, leading to different outcomes according to scenarios.

MEDEAS incorporates three limits to growth that are rather rarely considered (even separately) in the scientific literature: declining EROI levels, energy availability and consistent climate change

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impacts. Experimental results show that these factors have the potential to qualitatively alter the commonly obtained results by those models not incorporating these factors.

As any modelling framework, MEDEAS is subject to a number of limitations which will be addressed in further developments. On the one hand, the structure of the model should be improved in order to include more dynamics in the Economy module (e.g. endogenize the coefficients of the A matrix) and to improve the interlinkages between the Economy and the Energy modules (e.g. better modelling the allocation of scarcities); represent the potential constraints which mineral constraints may suppose in the future; fully develop and integrate a land-use module; improve the representation of climate damages on the system; or expand the social dimensions represented in the modelling framework. For these and other reasons detailed in the report, the interpretation of the results must be done with caution. Despite these limitations, the current version provides a solid enough basis to serve as a framework for the European scale model. A nested approach is required in order to assure consistency in the results obtained in the European model, given that the European energy, social and environmental situation is (and will continue to be) strongly conditioned by the international context.

We recall that global IAM models are not tools intended to predict the future, but rather to qualitatively guide the best options for the energy transition towards a low carbon economy and more sustainable society. Thus, MEDEAS-W is a tool to explore strategies, not specific policies, since the latter are applied at a different (reduced) political scale.

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Annex2: MEDEAS_eu model description

Document info sheet

Lead Beneficiary: University of Valladolid

WP: 4, Model building and models implementation

Task: 4.2, MEDEAS European model

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MEDEAS
MODELING THE RENEWABLE ENERGY TRANSITION IN EUROPE

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.

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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

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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

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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

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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

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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 assestment 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.

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- 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.

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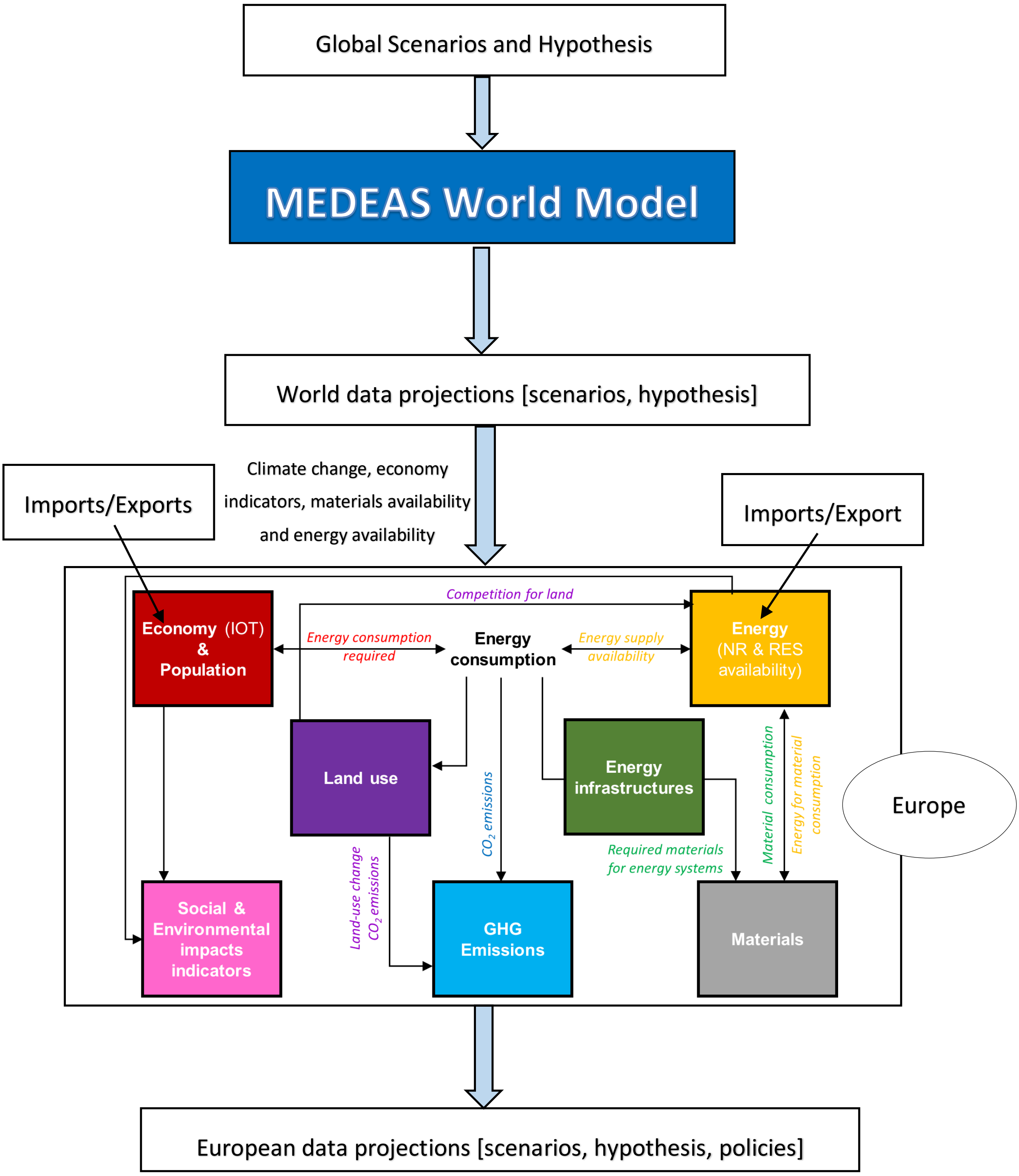

Figure 70. Flow chart representing the working mode of the European model.

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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.

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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.

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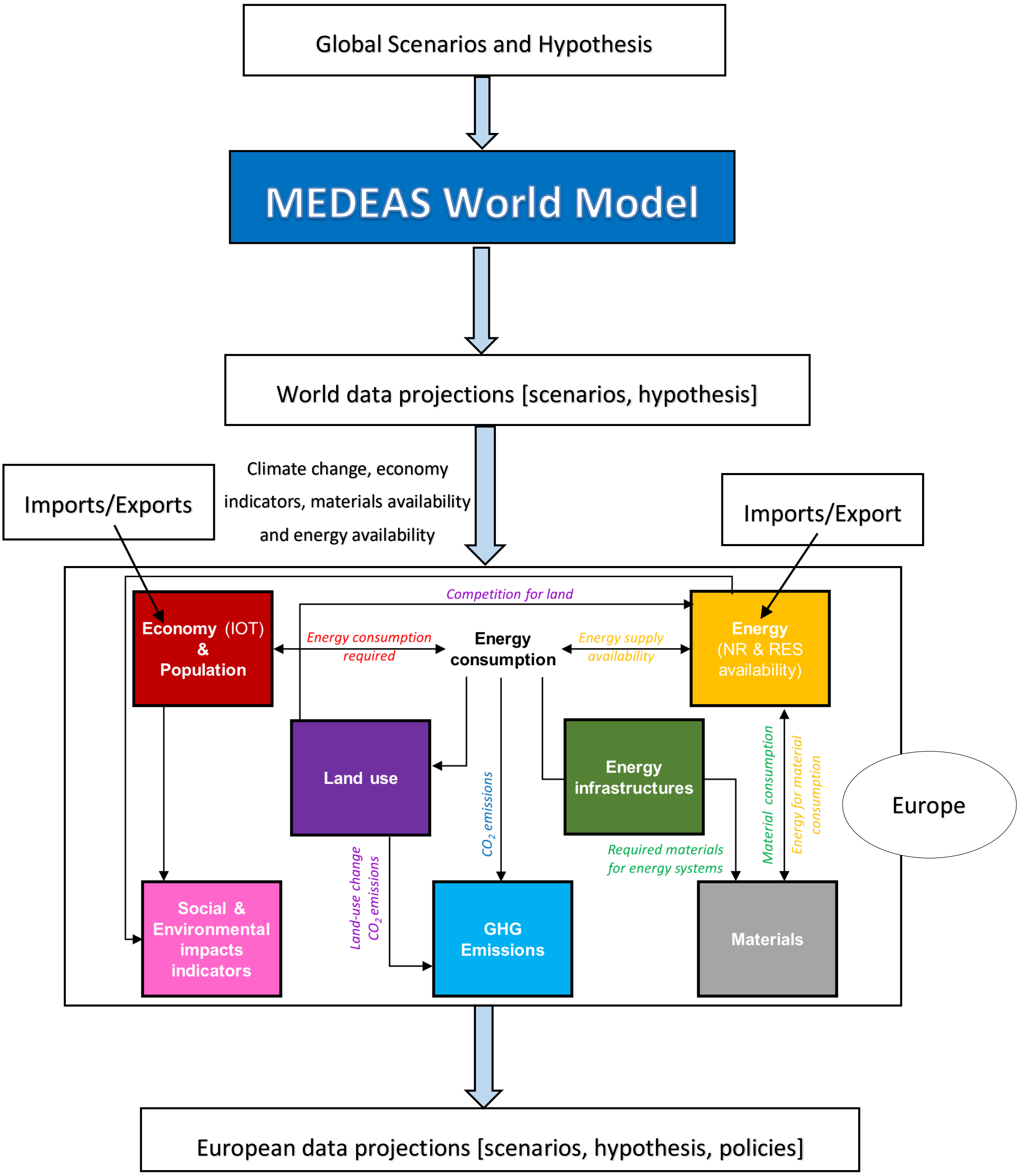

Figure 71. Flow chart representing the working mode of the European model.

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.

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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.

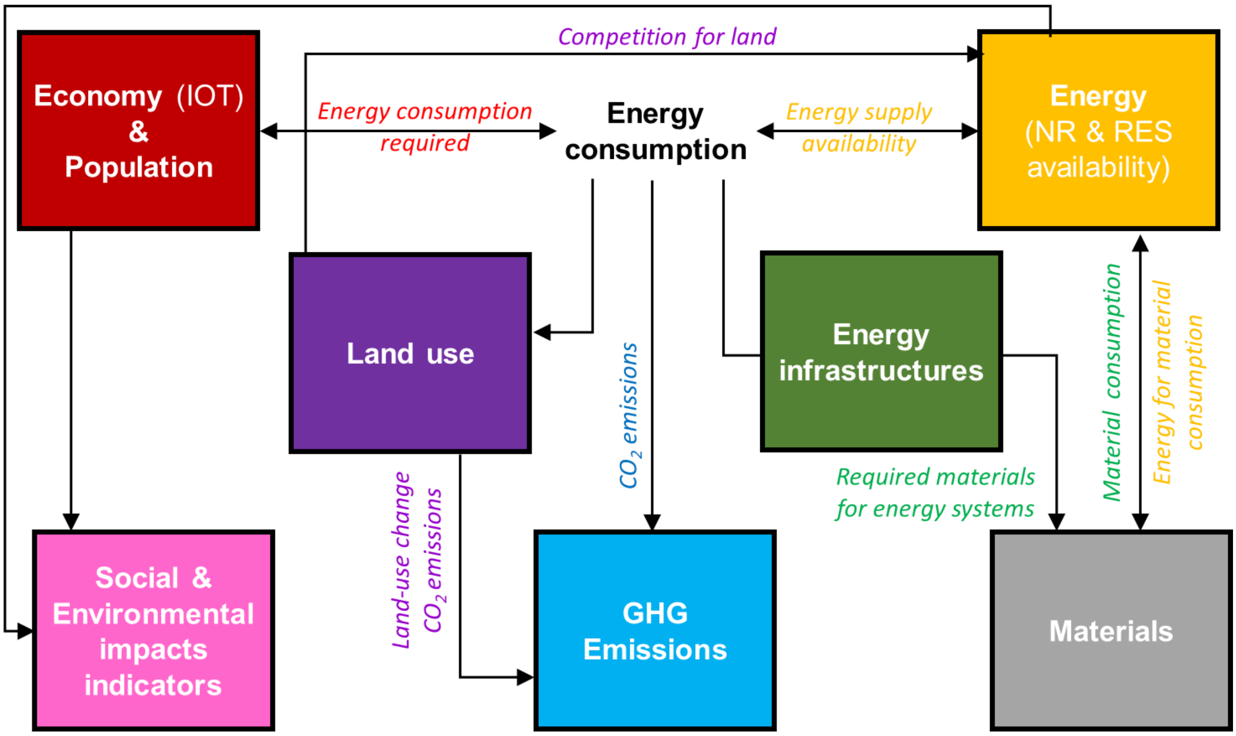

Figure 72. Schematic module interactions within MEDEAS-Europe.

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.

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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

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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).

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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 36. 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.

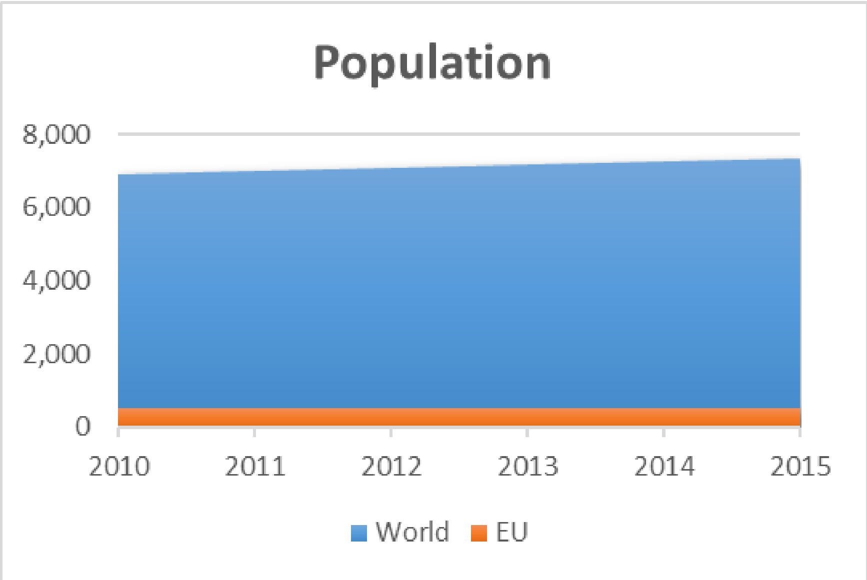

Figure 73. Evolution of the population for the World and the EU-28.

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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 37. 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%

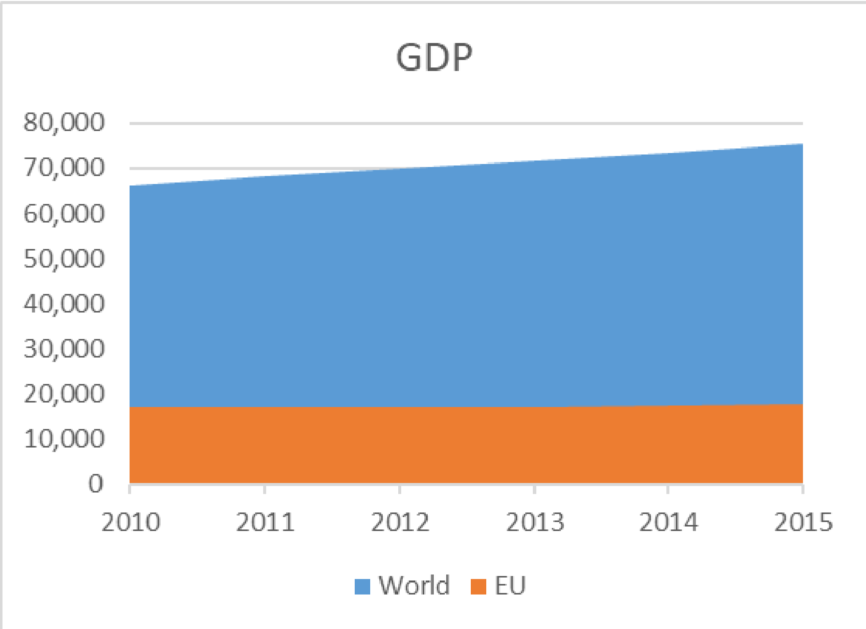

Figure 74. Evolution of the GDP for the World and the EU-28.

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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 38. 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.

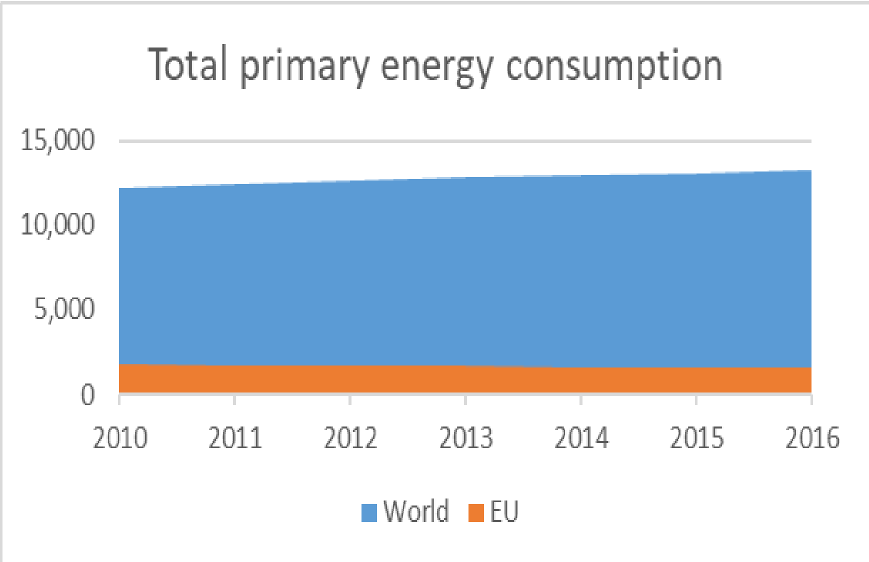

Figure 75. Evolution of the Total Primary Energy consumption in the World and the EU-28.

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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 39. 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).

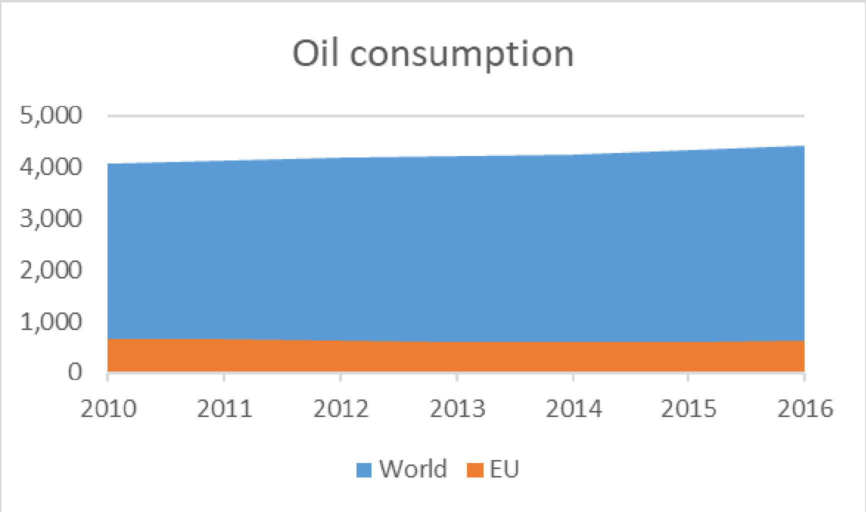

Figure 76. Evolution of the oil consumption in the World and the EU-28.

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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 40. 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.

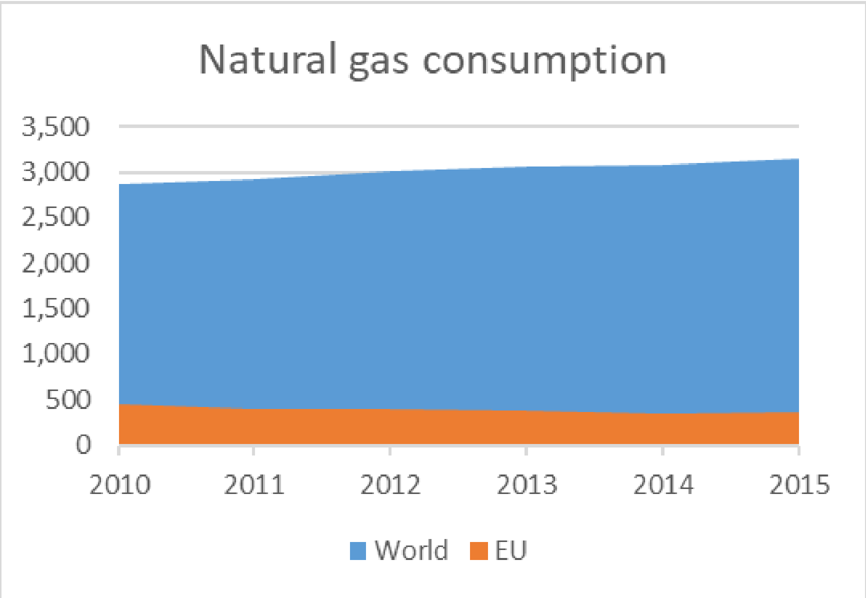

Figure 77. Evolution of Natural gas consumption in the World and the EU-28.

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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 41. World and European Union coal consumption data. Source: BP.

	2010	2011	2012	2013	2014	2015	2016	Percentag e
World Coal consumptio n (Mtoe)	3,635.6 4	3,807.1 9	3,817.2 9	3,886.9 7	3,889.4 2	3,784.6 5	3,732.0 0	100%
EU Coal consumptio n (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.

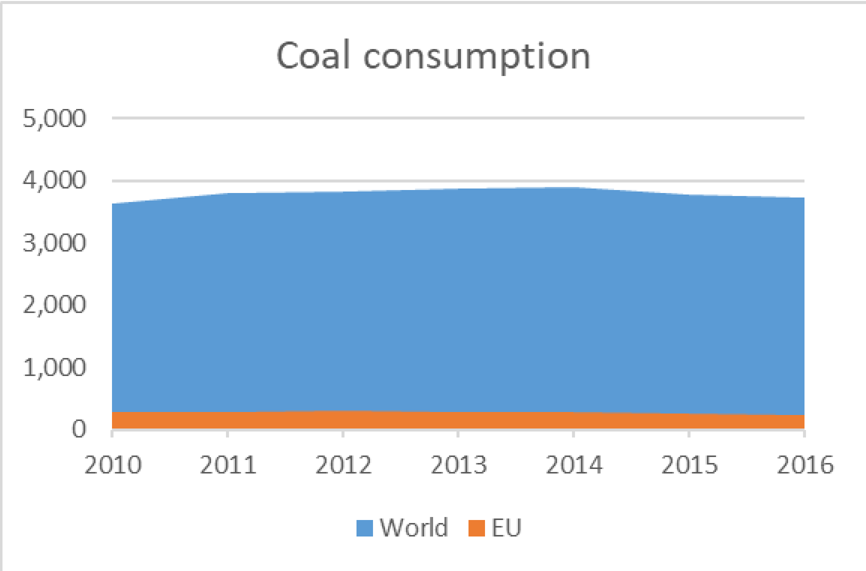

Figure 78. Evolution of Coal consumption in the World and the EU-28.

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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 42. 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.

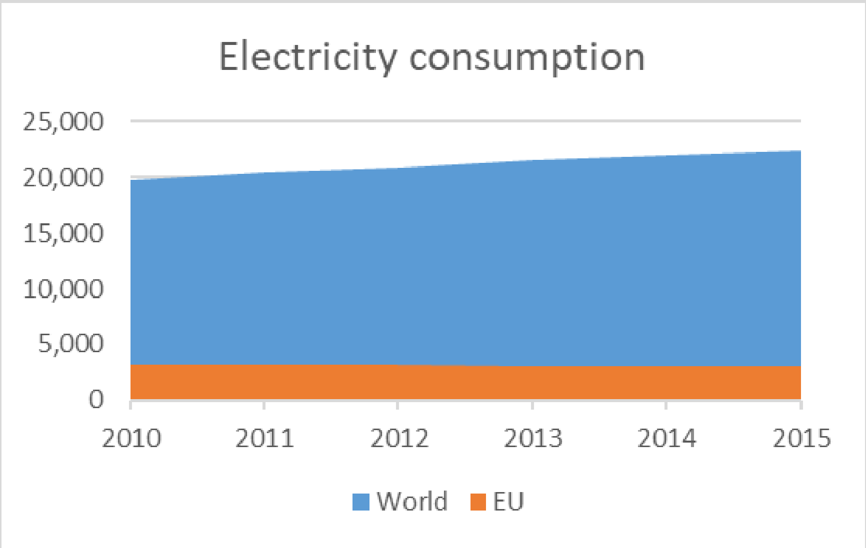

Figure 79. Evolution of the Electricity consumption in the World and the EU-28.

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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 43. 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.

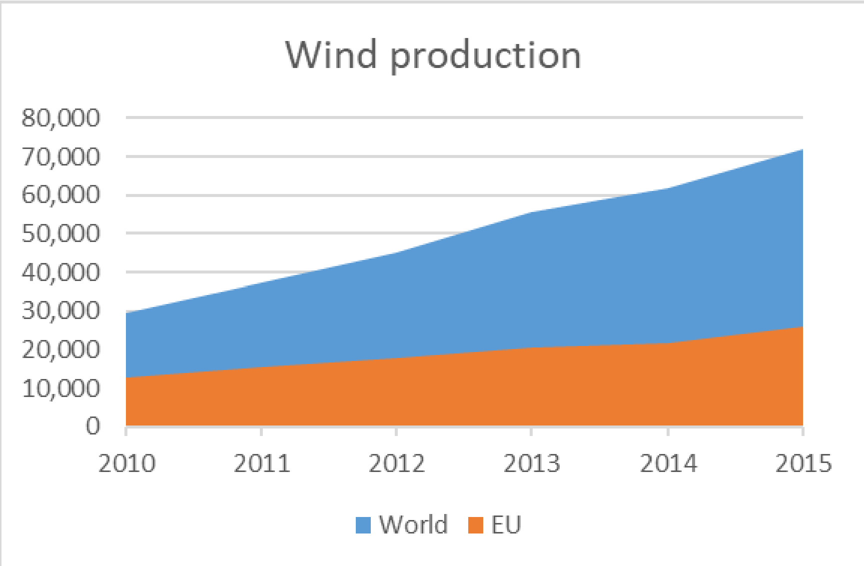

Figure 80. Evolution of Wind energy production in the World and the EU-28.

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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 44. 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.

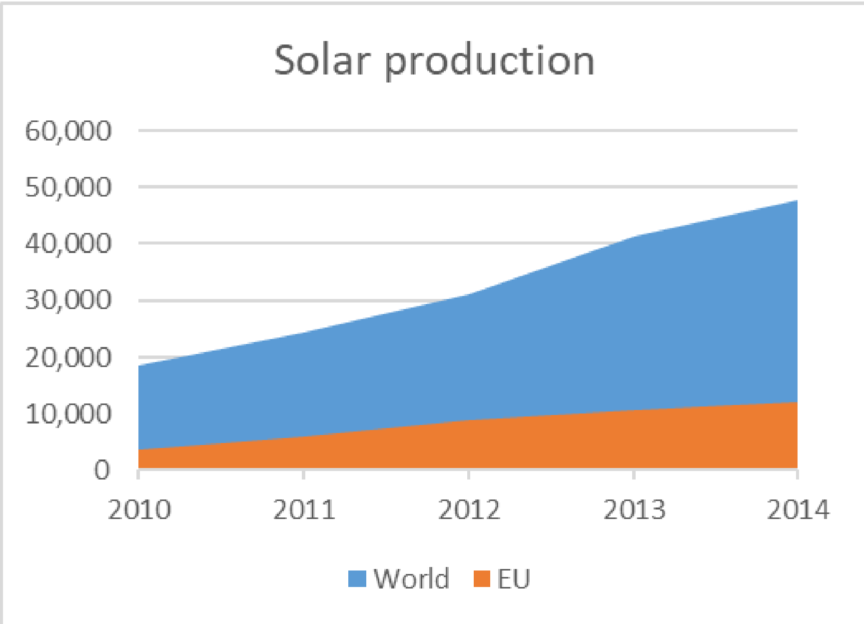

Figure 81. Evolution of Solar energy production in the World and the EU-28.

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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 45. 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).

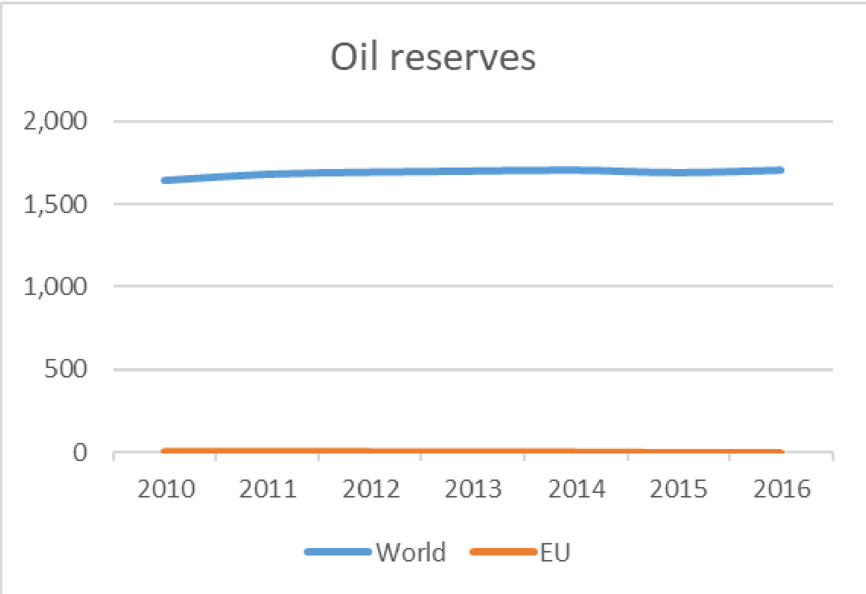

Figure 82. Evolution of Oil reserves in the World and the EU-28.

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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 46. 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.

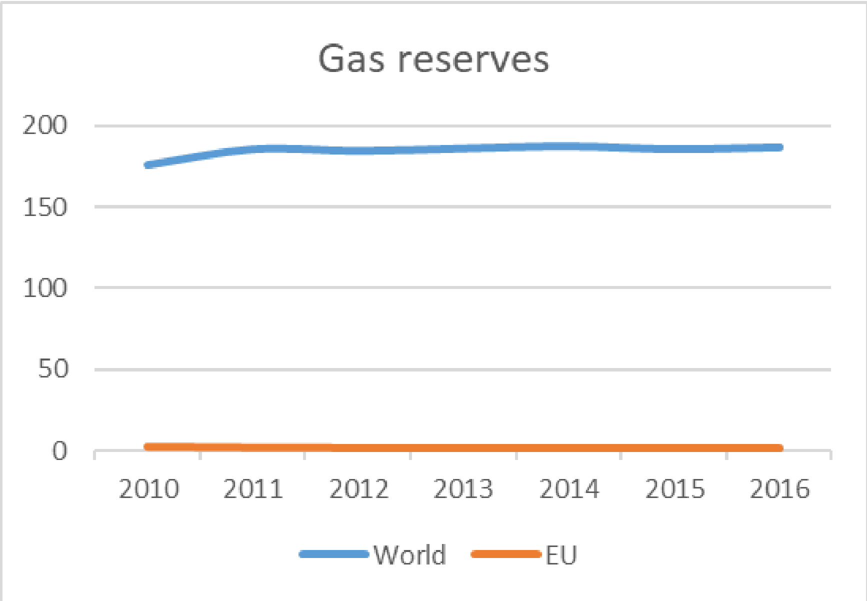

Figure 83. Evolution of Gas reserves in the World and the EU-28.

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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 47. 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).

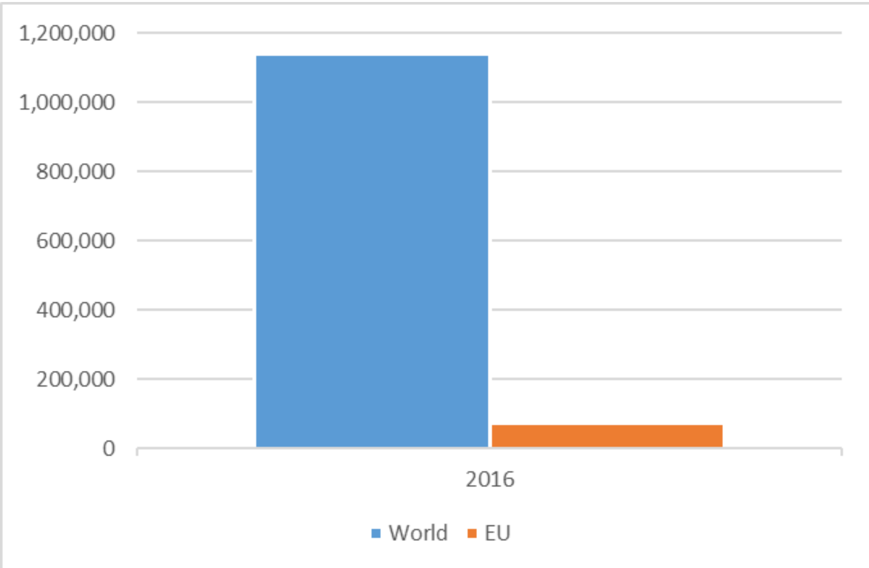

Figure 84. Coal reserves in 2016 for the World and the EU-28.

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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 48. 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.

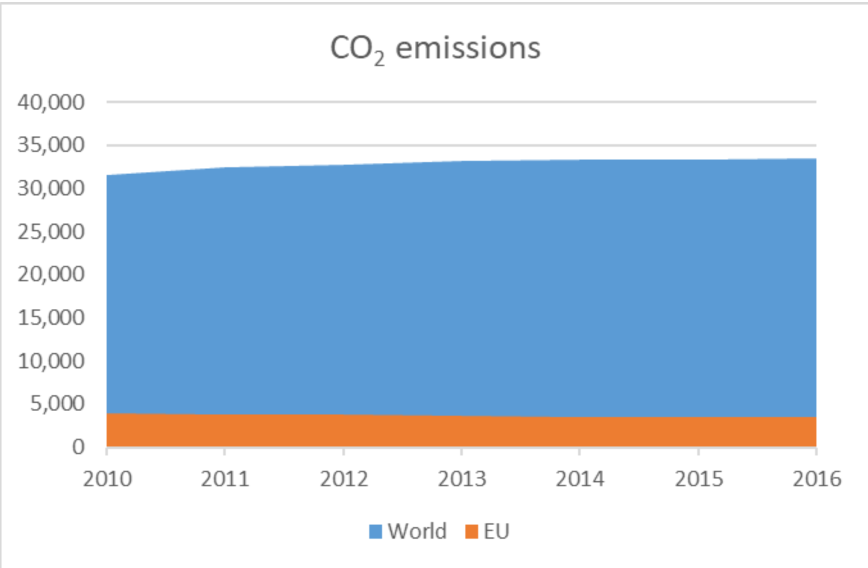

Figure 85. Evolution of CO_2 emissions in the World and the EU-28.

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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 49. 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.

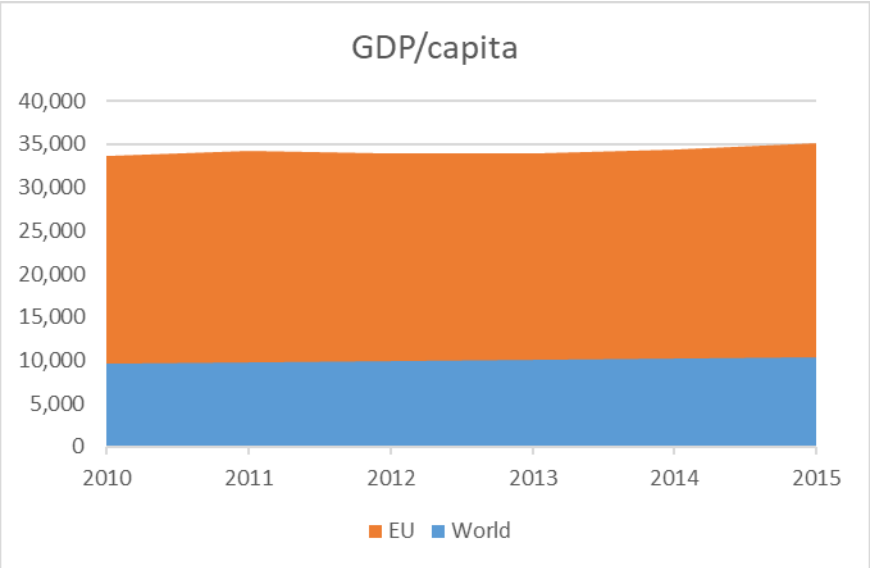

Figure 86. Evolution of GDP per capita in the World and the EU-28.

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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 50. 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.

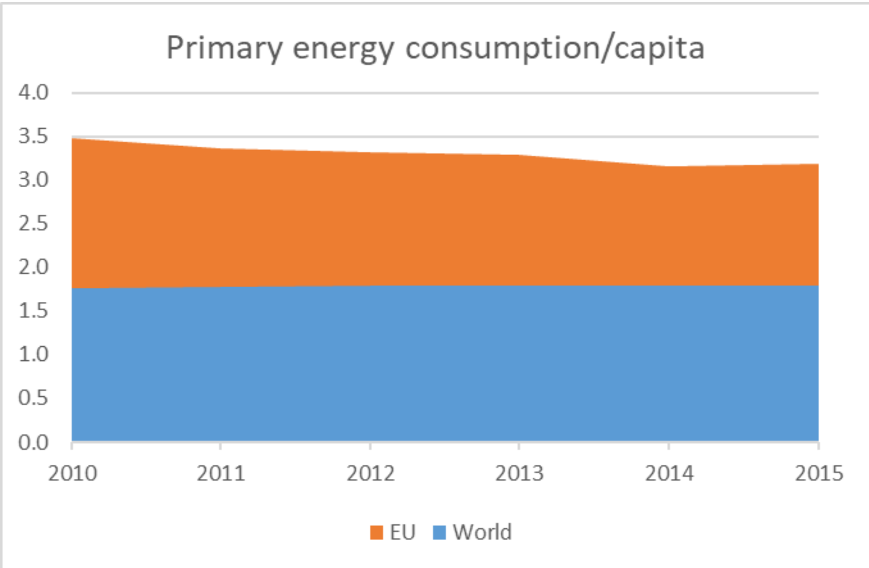

Figure 87. Evolution of Primary Energy consumption per capita in the World and the EU-28.

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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 51. 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.

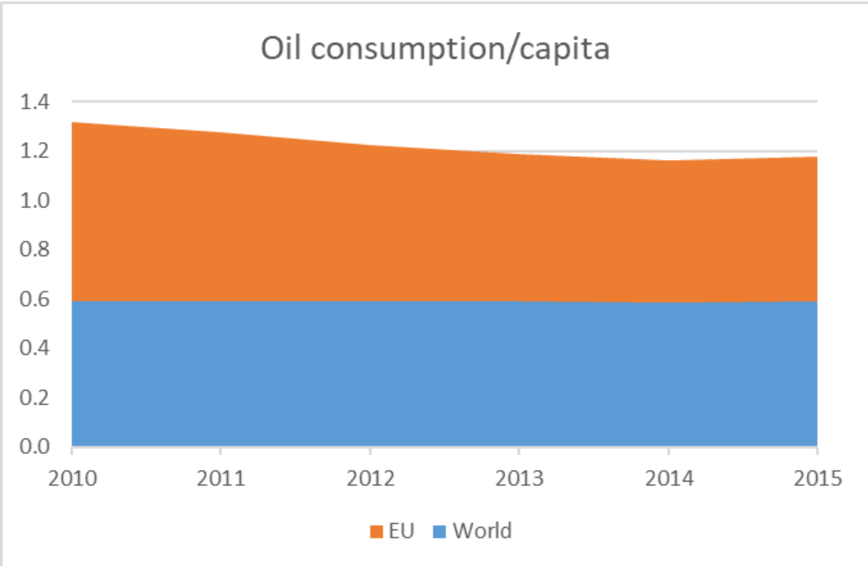

Figure 88. Evolution of Oil consumption per capita in the World and the EU-28.

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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 52. 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.

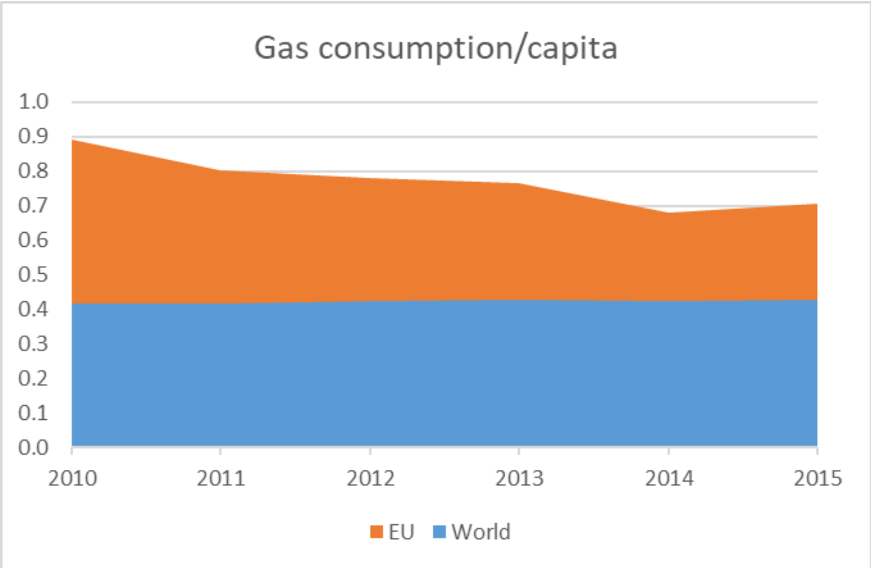

Figure 89. Evolution of the Gas consumption per capita in the World and the EU-28.

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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 53. 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.

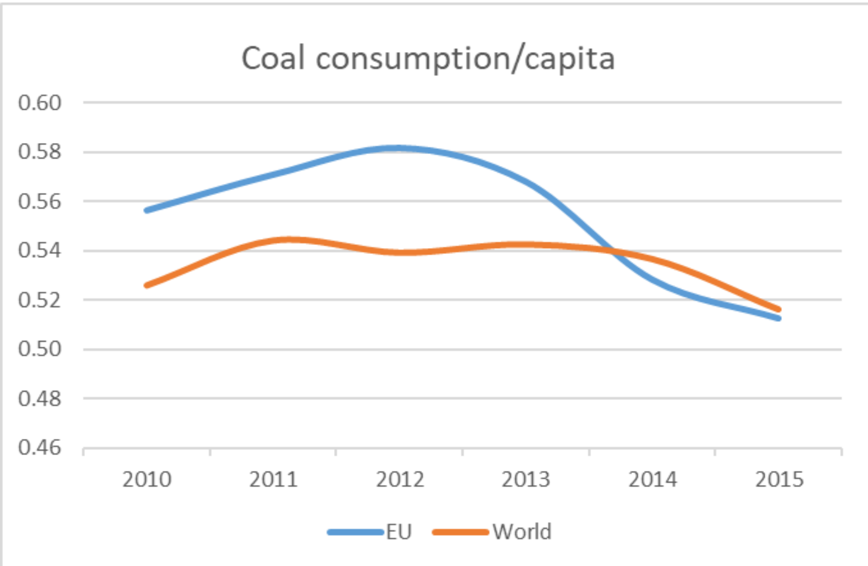

Figure 90. Evolution of the Coal consumption per capita in the World and the EU-28.

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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 54. 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.

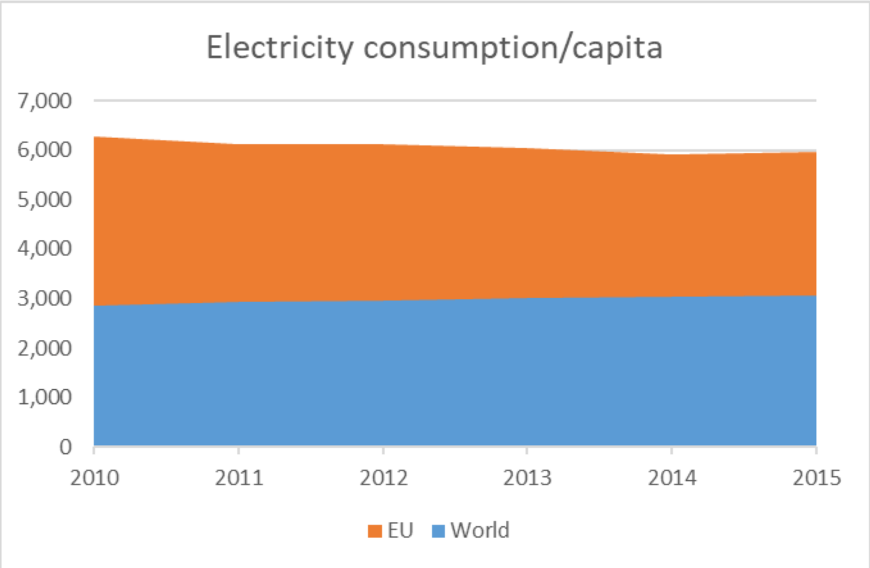

Figure 91. Evolution of Electricity consumption per capita in the World and the EU-28.

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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 55. 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.

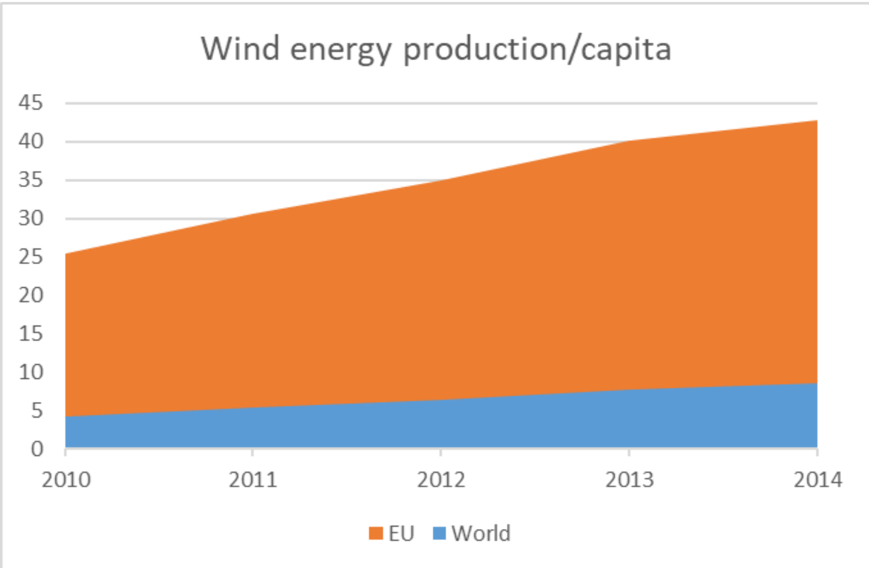

Figure 92. Evolution of the Wind power generation per capita in the World and the EU-28.

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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 56. 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.

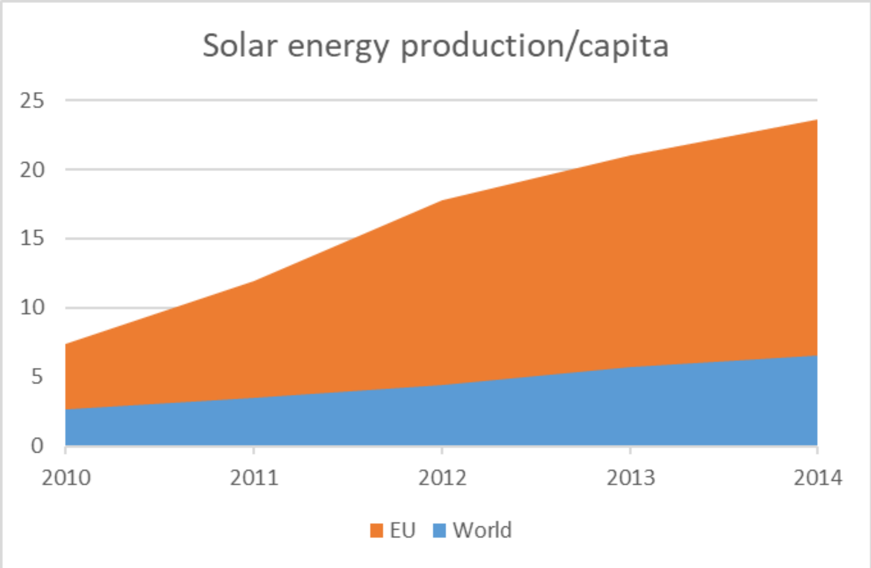

Figure 93. Evolution of Solar power generation per capita in the World and the EU-28.

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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 57. 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.

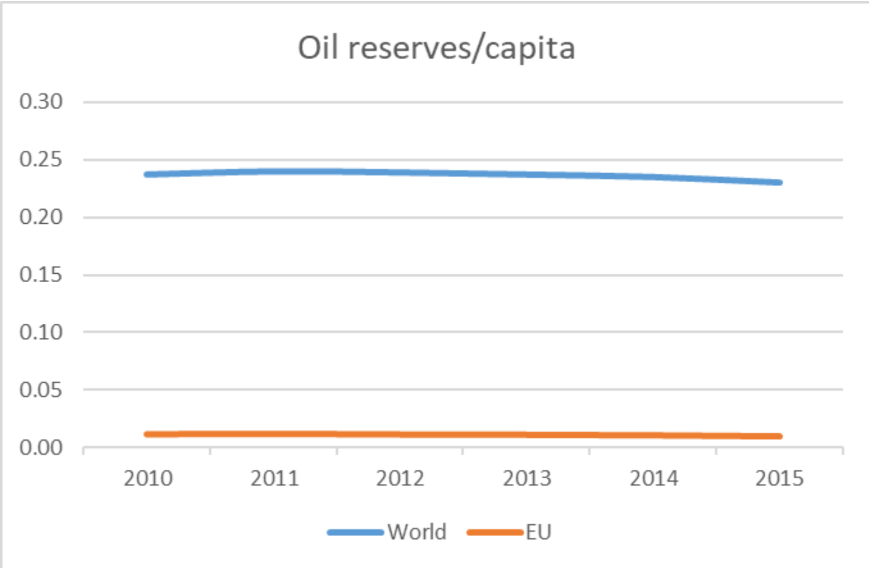

Figure 94. Evolution of the Oil reserves per capita in the World and the EU-28.

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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 58. 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.

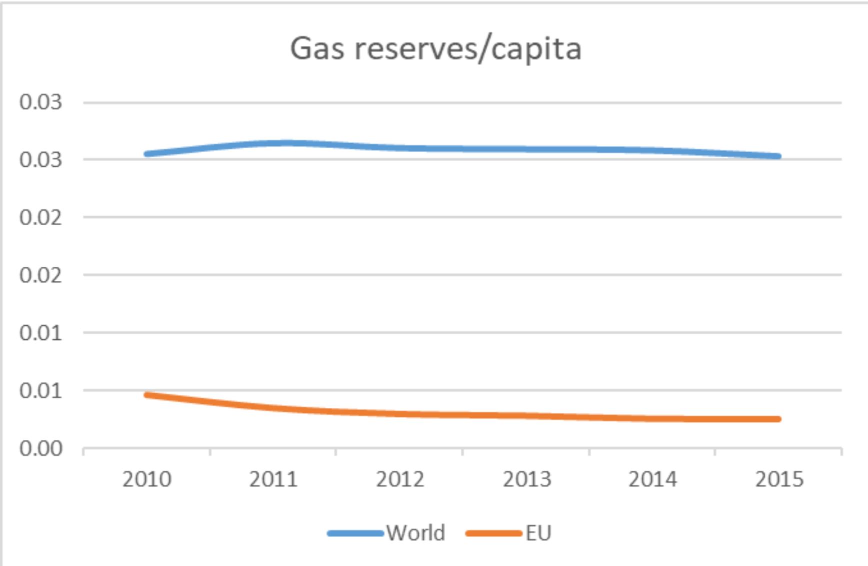

Figure 95. Evolution of Gas reserves per capita in the World and the EU-28.

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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 59. 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.

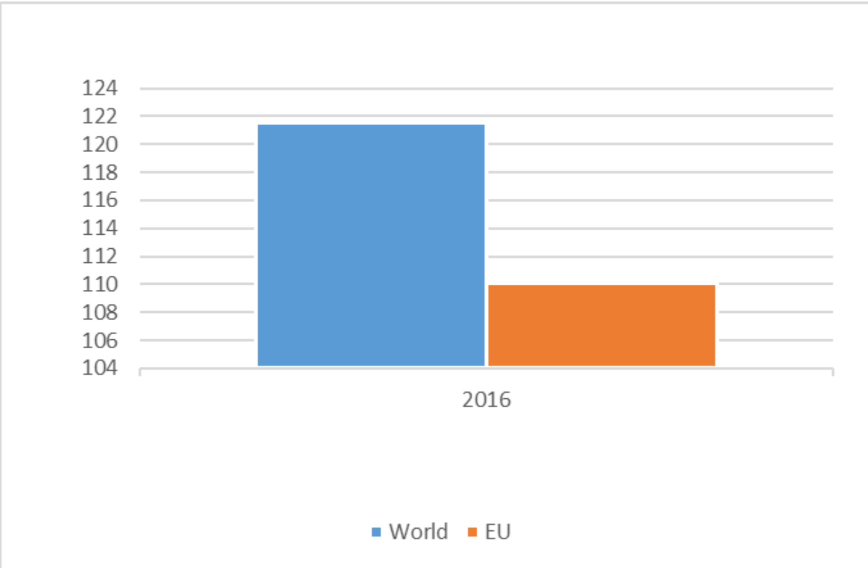

Figure 96. Coal reserves per capita in 2016 for the World and the EU-28.

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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 60. 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.

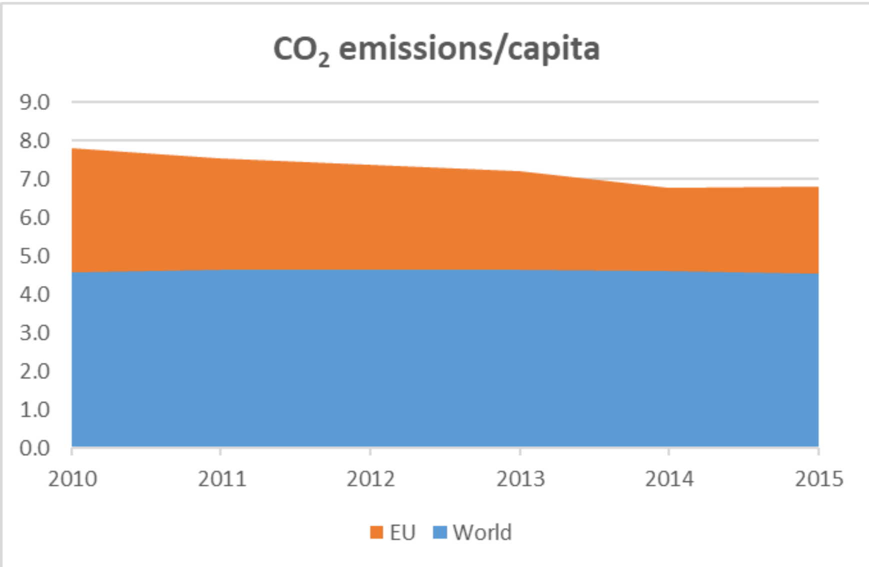

Figure 97. Evolution of the CO_2 emissions per capita in the World and the EU-28.

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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"

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

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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 equilibrium

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–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.

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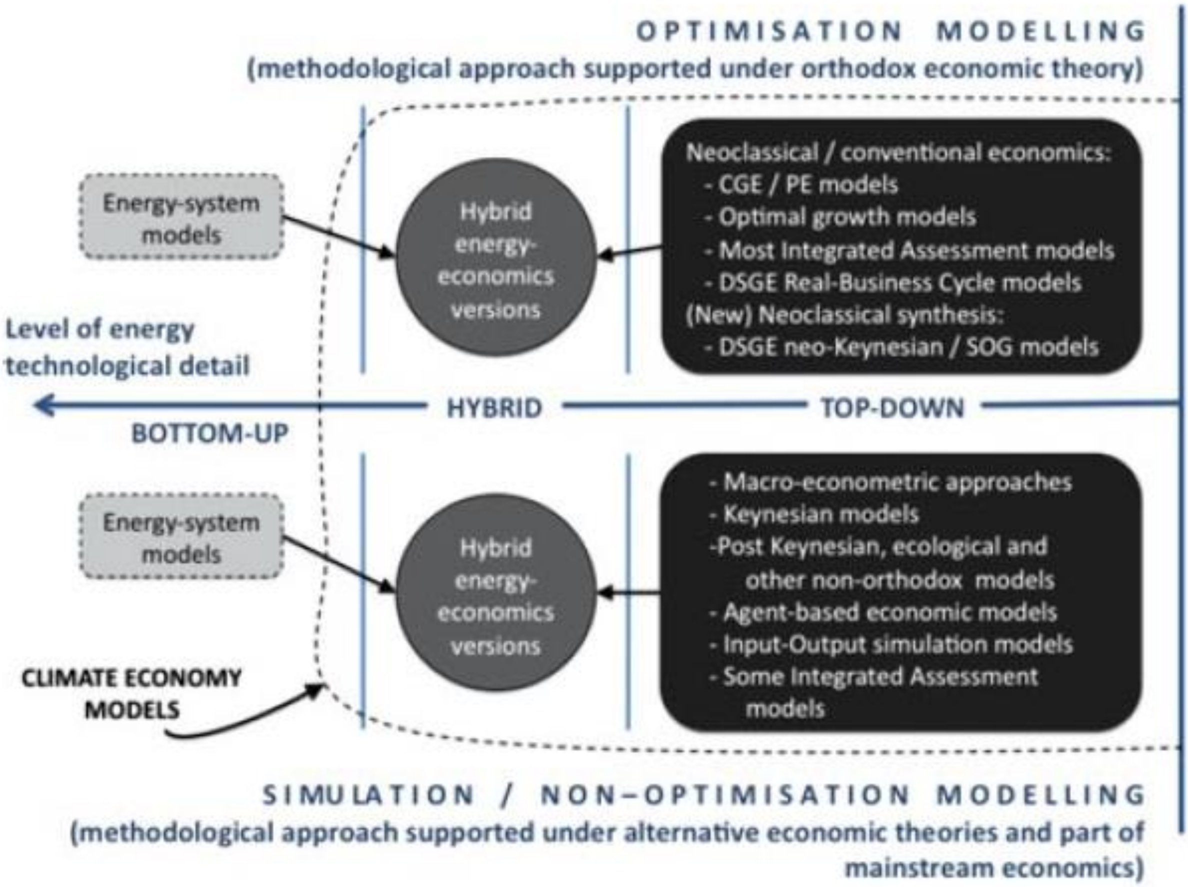

Figure 98. Macro-economic modelling in IAMs.

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 unemployment and under-utilisation of

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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).

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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.

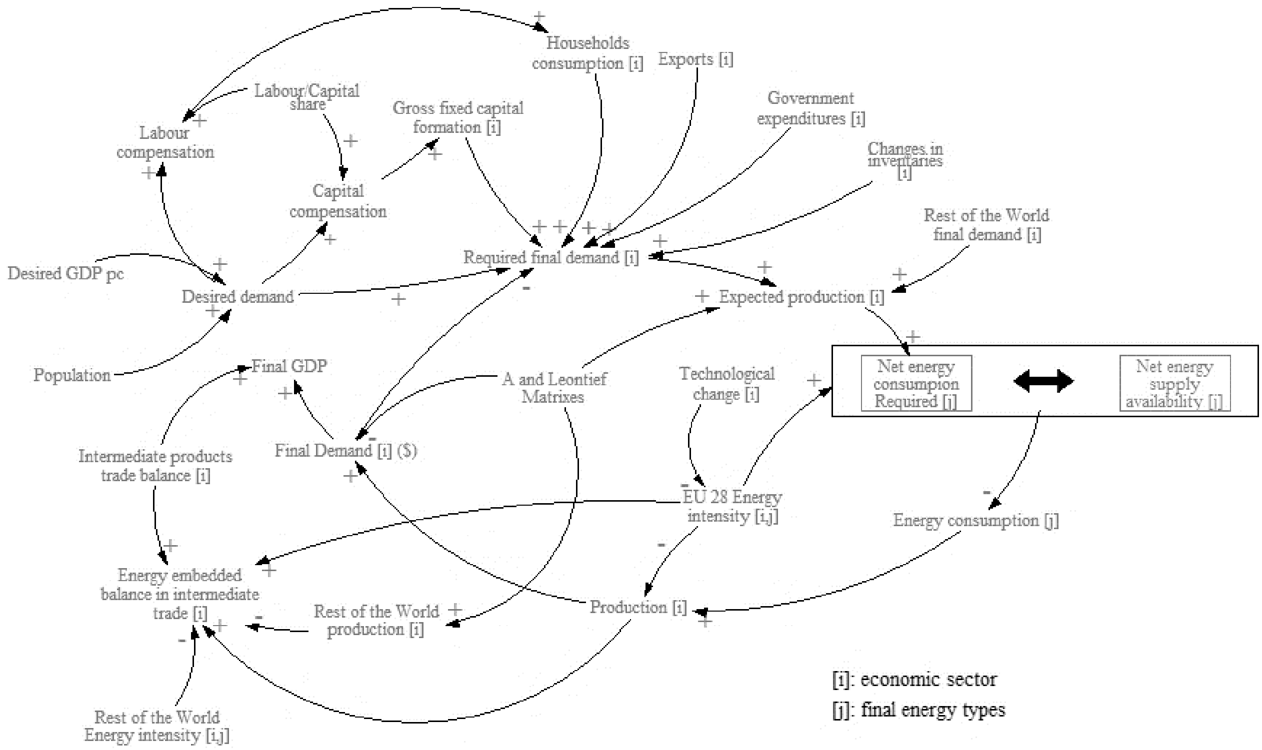

Figure 99. Overview of MEDEAS-Europe economy module.

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.). Moreover, there are

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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.

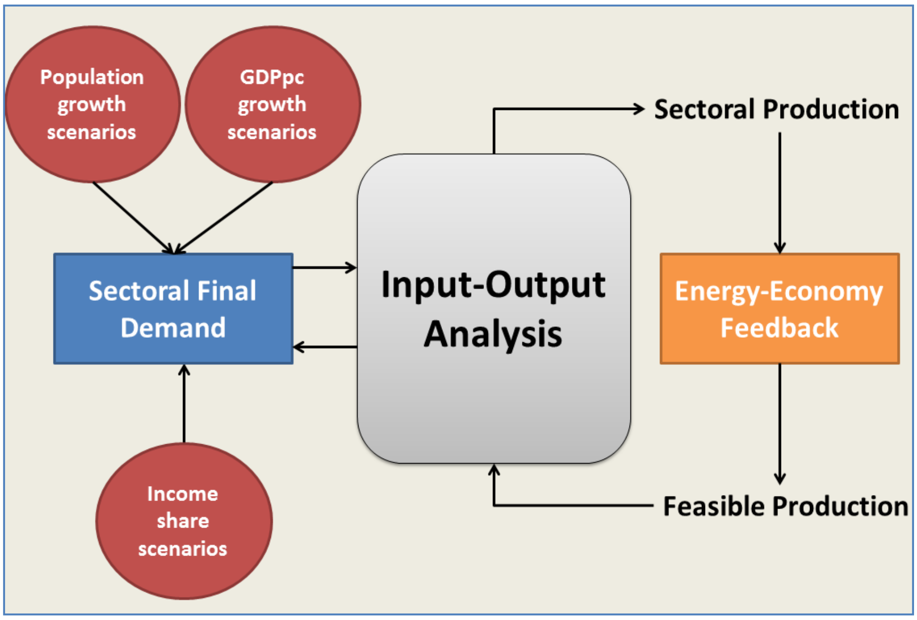

Figure 100. Schematic overview of MEDEAS-Europe economy module.

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.

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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 respectively)

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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):

$$lnHH_{it} = \beta_0 + \beta_{1i}Sec_i + \beta_2 lnLab_t \qquad i \in 1\ldots35 \qquad (2)$$

$$lnGFCF_{it} = \beta_0 + \beta_{1i}Sec_i + \beta_2 lnCap_t \qquad i \in 1\ldots35 \qquad (3)$$

$$lnEXP_{it} = \beta_0 + \beta_1 Sec_i + \beta_2 reer_t + \beta_3 lnworld\_gdp_t \qquad i \in 1\ldots35 \qquad (4)$$

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 different scenarios. Finally,

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$world\_gdp$ 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.

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Table 61. 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):

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

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

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Table 62. 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.

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Table 63. 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.

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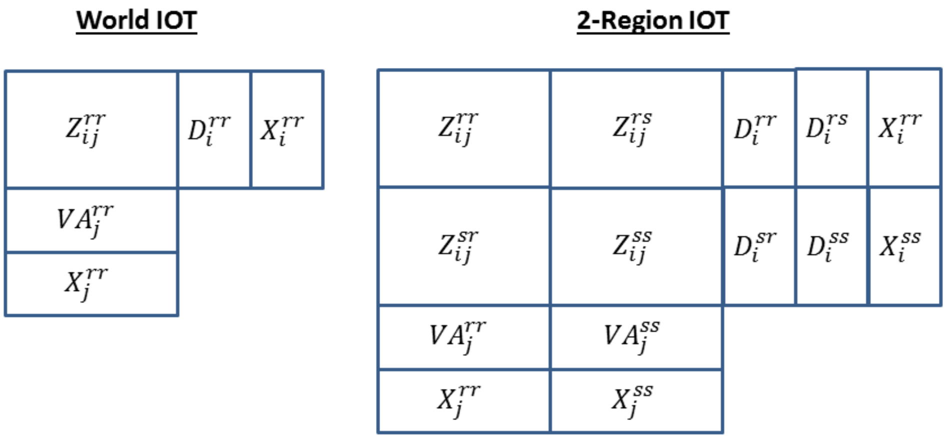
2.2.3.2. Input-output analysis

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.



$Z_{ij}^{rr/ss}$: 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 101. 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 transform it in

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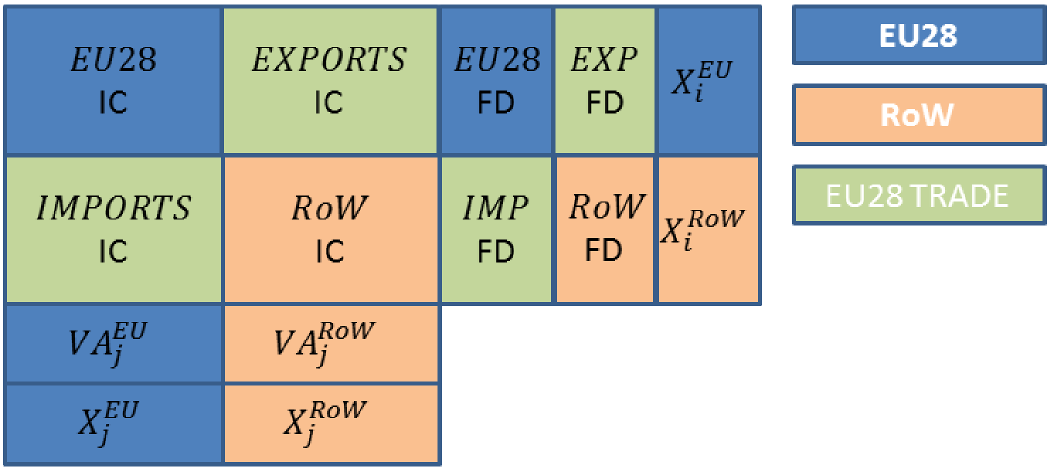
EU28 and deduct it in the new RoW region. Once this process is fulfilled, we have a 2RIOT consisting of EU28 and RoW, with different sub-matrixes taking into account the bilateral economic flows between the two regions (Figure 33).



$EU28_{IC}/RoW_{IC}$: 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 102. 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).

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

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

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

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$$Z_{ij}^{rr} + Z_{ij}^{rs} + D_i^{rr} + D_i^{rs} = Z_{ij}^{rr} + Z_{ij}^{sr} + VA_j^{rr} \quad (9)$$

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 ($GDP = \sum VA$[32]). 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 64. 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}	$EXP_{IC} + EU28_{FD} + EXP_{FD} - IMP_{IC}$

[32] 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).

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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.

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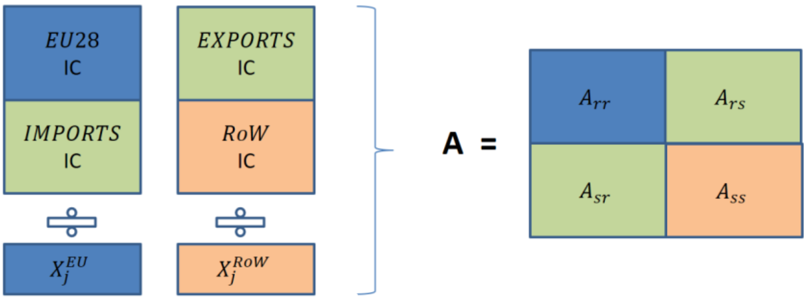

$\boldsymbol{A_{rr}}$: Intermediate inputs produced in EU28 required for EU28 production.

$\boldsymbol{A_{rs}}$: 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 103. 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.

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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.

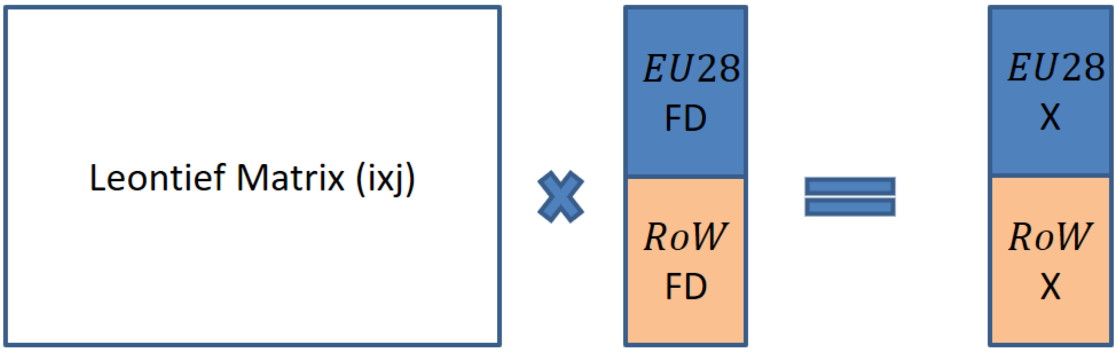

Figure 104. Obtaining EU28 production in the 2-region Input-Output Analysis.

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 105. 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 products,

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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 106. 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 107. 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

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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.

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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.

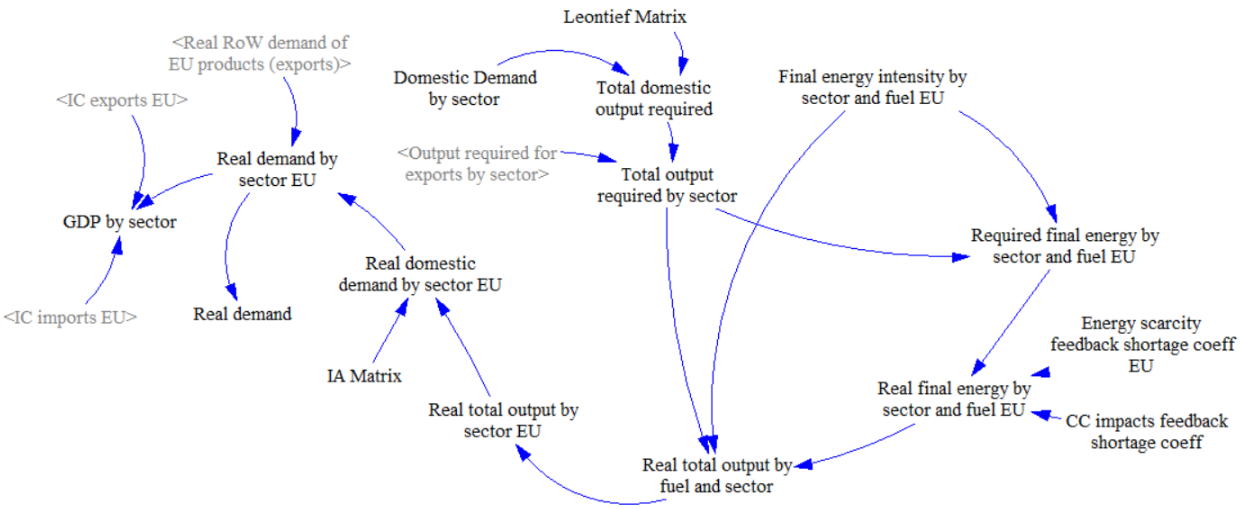

Figure 108. Simplified influences diagram for Input-Output Analysis in MEDEAS-Europe.

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.

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

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

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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:

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

$(I - A)$ 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.

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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).

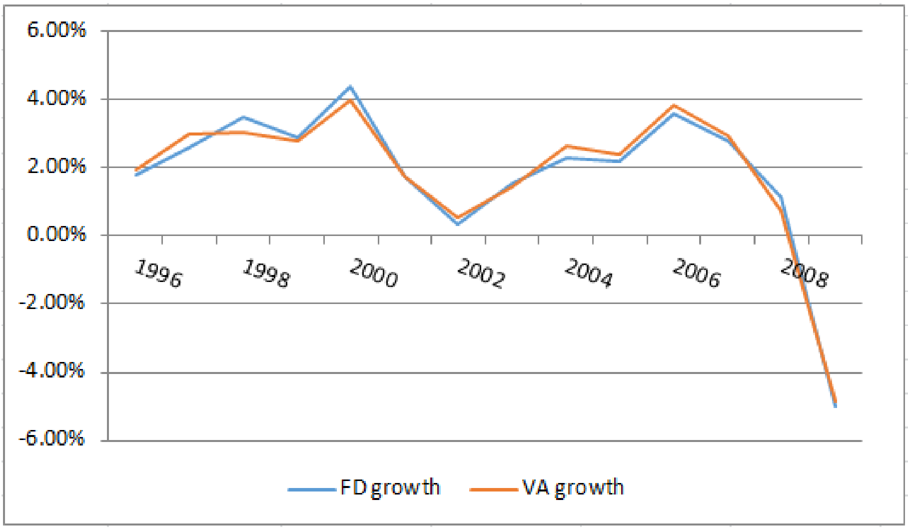

Figure 109. Final demand and value added growth in EU28 (1996-2009).

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).

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Table 65. 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.

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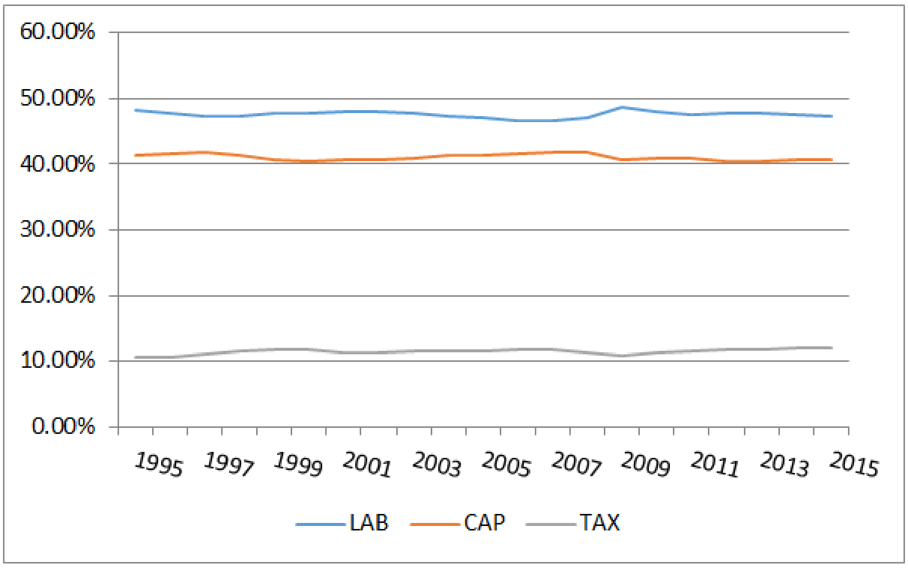

Figure 110. Functional income distribution EU 28 (1995-2015).

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.

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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).

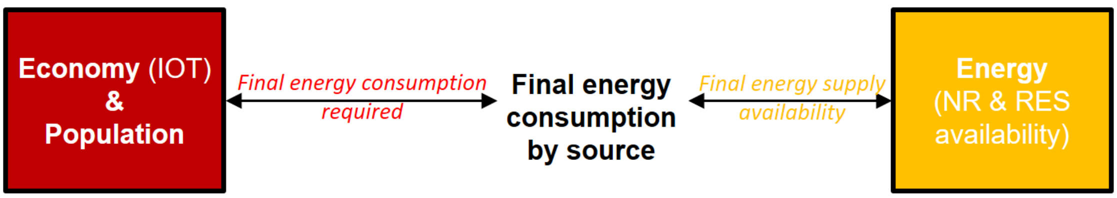

Figure 111. Energy-Economy feedback in MEDEAS.

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 model

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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):

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

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$$FD' = X(I - A) \tag{27}$$

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 $\hat{\mathrm{I}}_{ek}\ L_{rr}$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.

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Table 66. 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

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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 67. 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.

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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).

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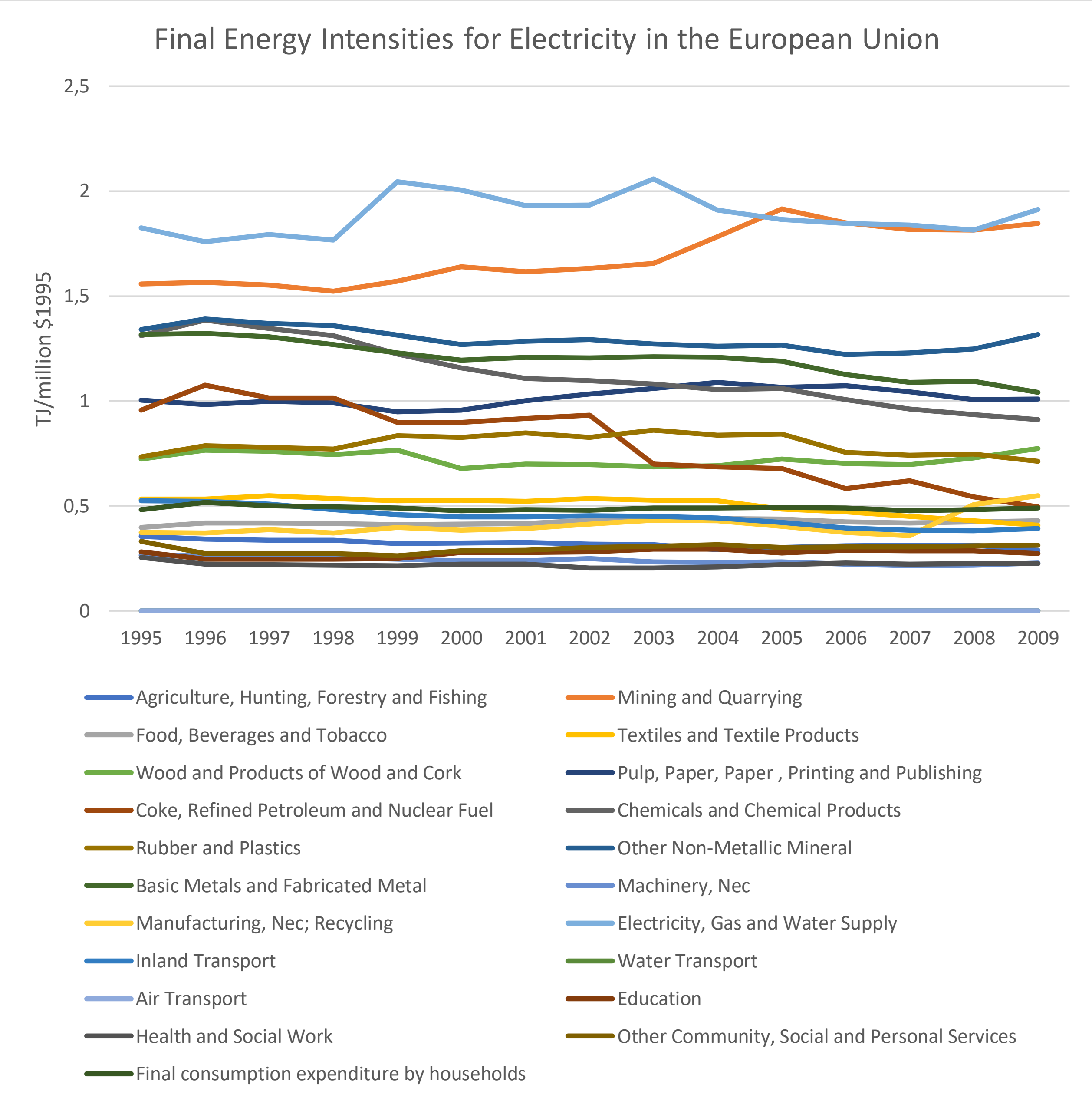

Figure 112. Historical evolution of electricity intensity by sector

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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**0**), and the modelling of transport (section2.3.5). Primary energy in the model refers to the direct equivalent method.[33]

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.

[33] 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).

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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).

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2.3.2. Energy supply in MEDEAS-EU

In MEDEAS-EU primary total energy demand is covered with different primary energy sources (see Table 10).

Table 68. 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

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Although in practical terms heat can be demanded at different temperature levels (IEA, 2014),34 for the sake of simplicity, in this model version all heat demand and supply is aggregated.

[34] 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).

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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 2044 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.

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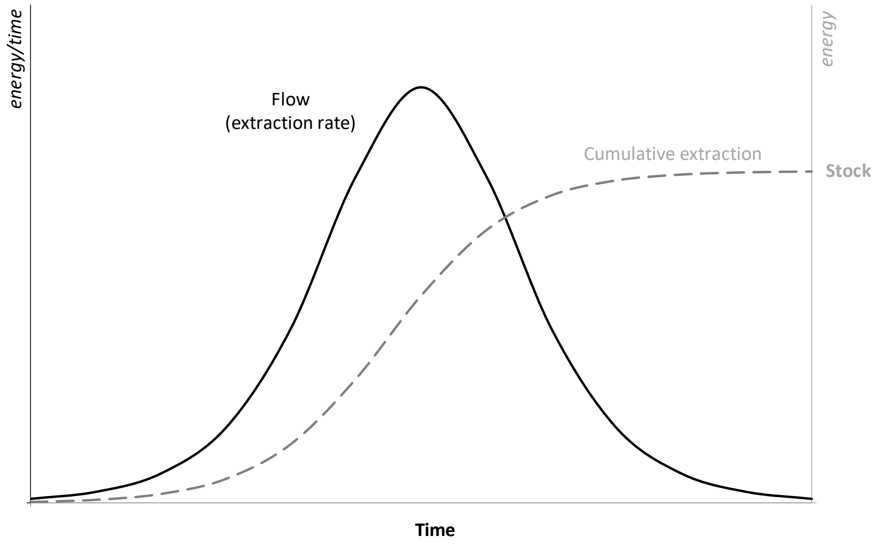

Figure 113. Simplified representation of the depletion of a non-renewable resource in the absence of non-geologic constraints. Stocks and flows of energy relative to time.

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).

$$RURR_t = URR - cumulative\_extraction_t \quad (28)$$

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

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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 2145a). 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 2145b).

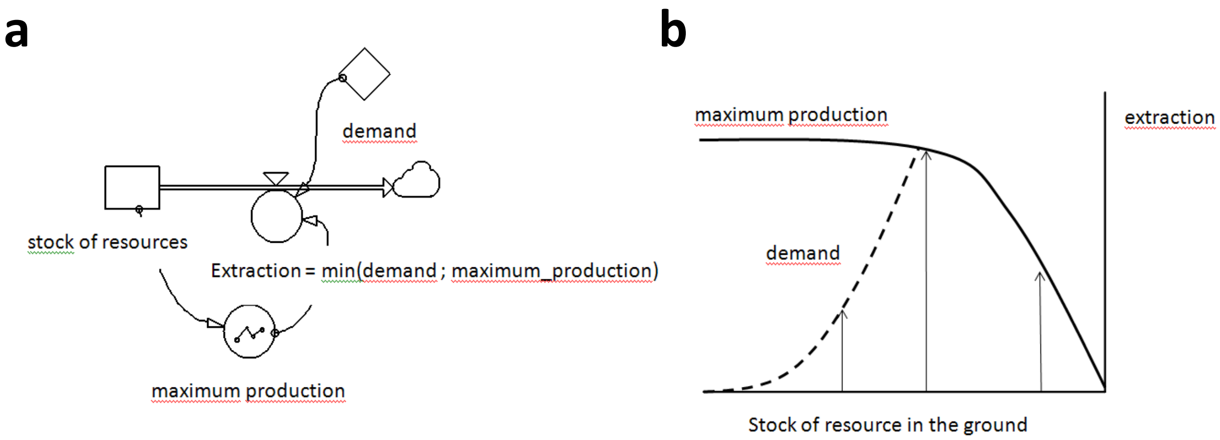

Figure 114. Integration of depletion curves in the model. (a) SD model. (b) A curve of maximum extraction (solid) compared with the demand (dashed).

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

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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).

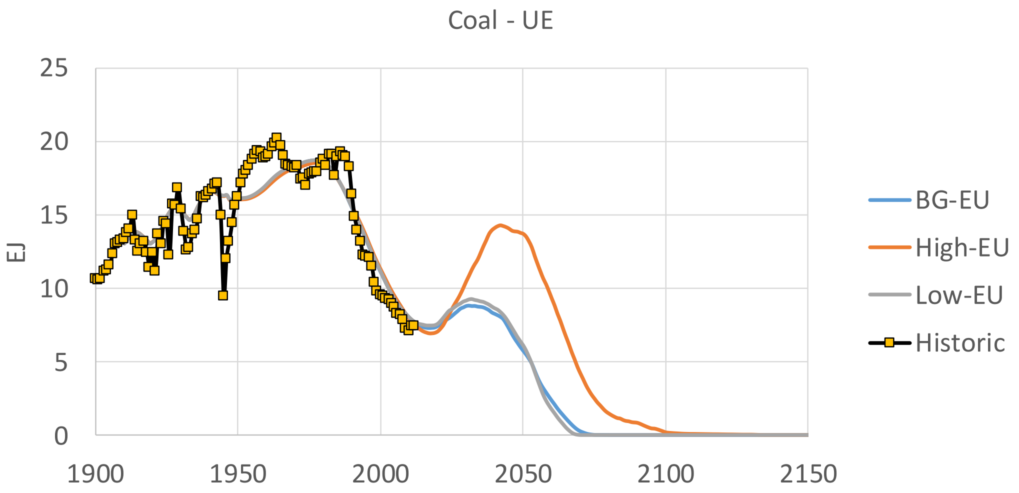

Figure 115. Coal historical extraction in UE-28 and 3 future availability cases (low, BG and high).

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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).

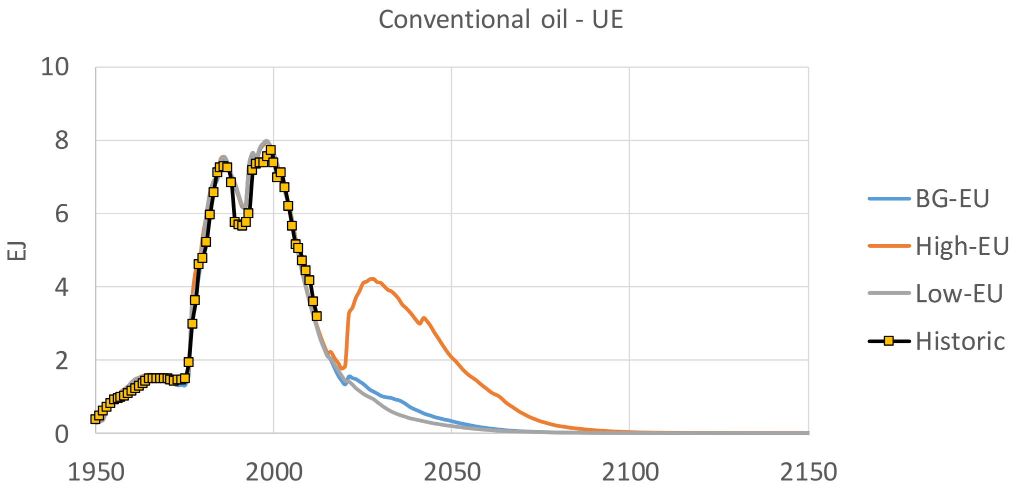

Figure 116. Conventional oil historical extraction in UE-28 and 3 future availability cases (low, BG and high).

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).

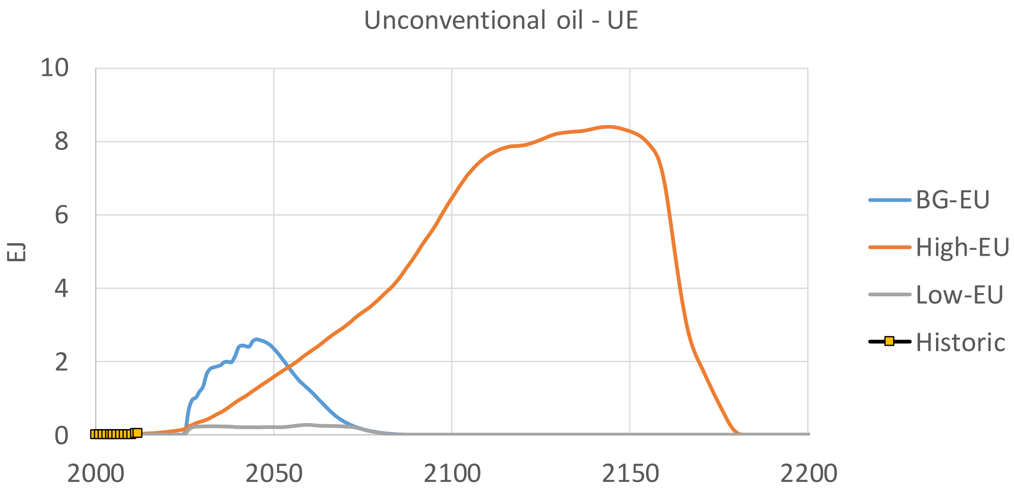

Figure 117. Unconventional oil historical extraction in UE-28 and 3 future availability cases (low, BG and high).

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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).

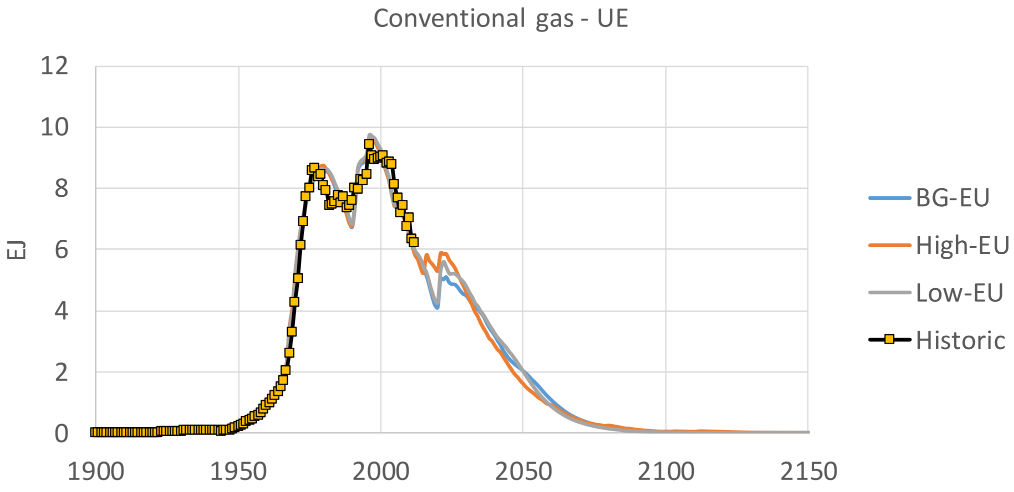

Figure 118. Conventional gas historical extraction in UE-28 and 3 future availability cases (low, BG and high).

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).

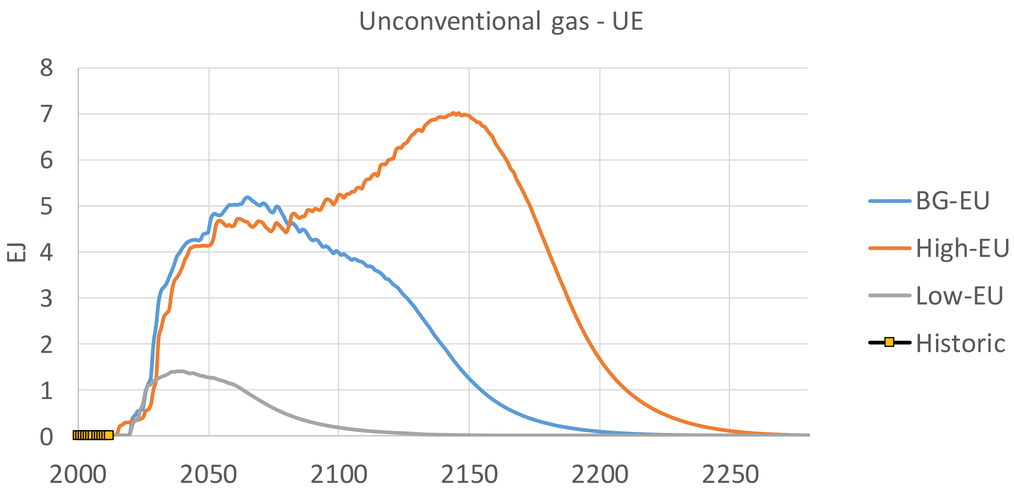

Figure 119. Unconventional oil historical extraction in UE-28 and 3 future availability cases (low, BG and high).

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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).

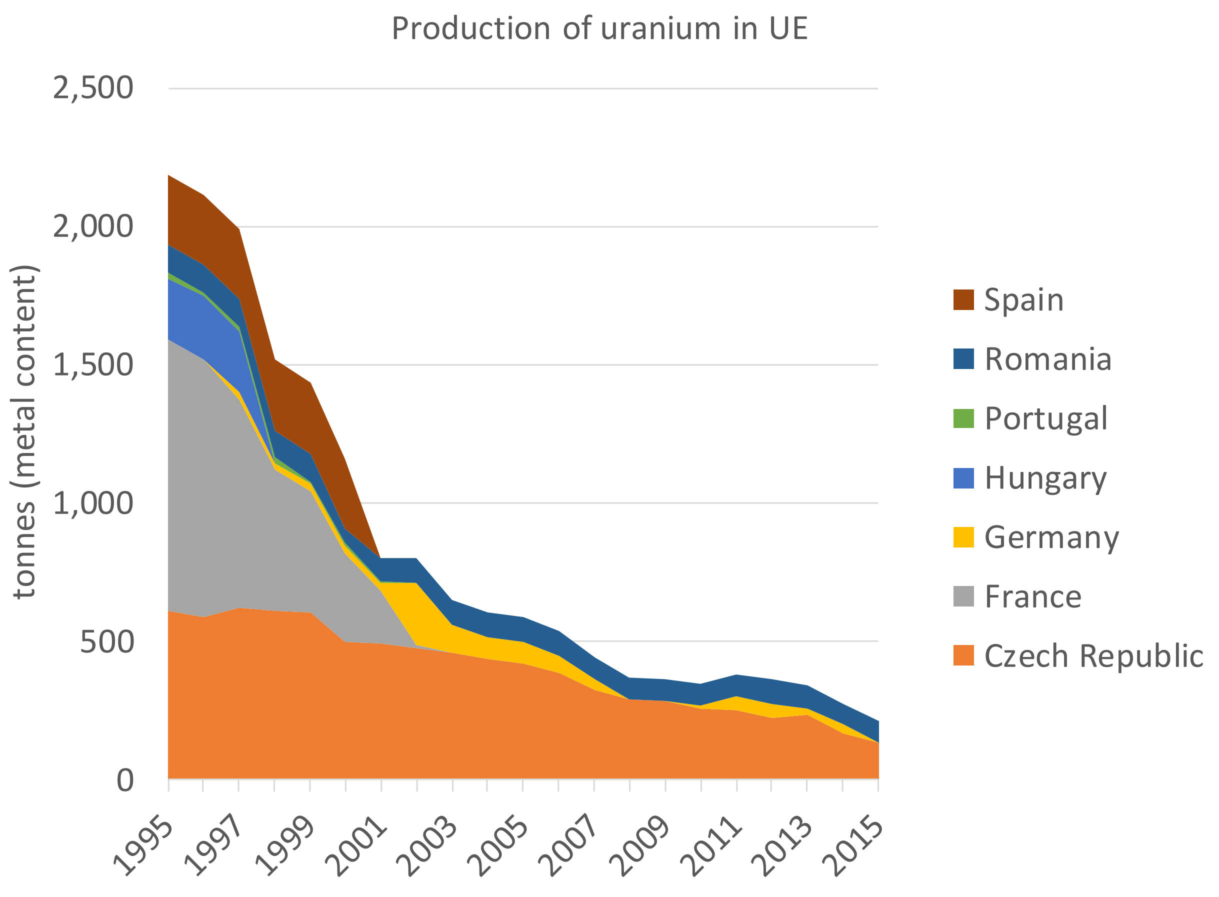

Figure 120. Historic production of uranium in UE (1995-2015).

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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 69. 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).

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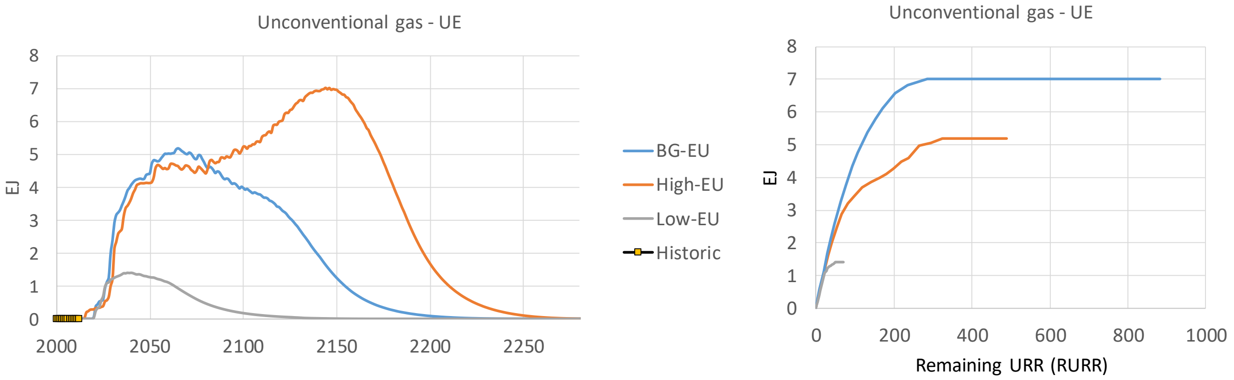

Figure 121. Domestic EU unconventional gas availability: (a) depletion curve as a function of time from the original reference; (b) curves of maximum extraction in function of the RURR as implemented in the model. The y-axis represents the maximum achievable extraction rate (EJ/year) in function of the 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.

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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).

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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.

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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)

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

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).

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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.

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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.

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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 share of rooftops

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for PV in relation to other uses (solar thermal, green roofs, daylighting, etc.)[35]. 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).

$$potential\ PV\ urban(t) = urban\ area \cdot \rho_e(t) \qquad (30)$$

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

$$\rho_e(t) = I \cdot f_1(t) \cdot f_2 \cdot f_3 \qquad (31)$$

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):

$$f_3 = 2.5\% \cdot share\ of\ rooftops\ available\ for\ PV \cdot \qquad (32)$$

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:

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

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- 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.

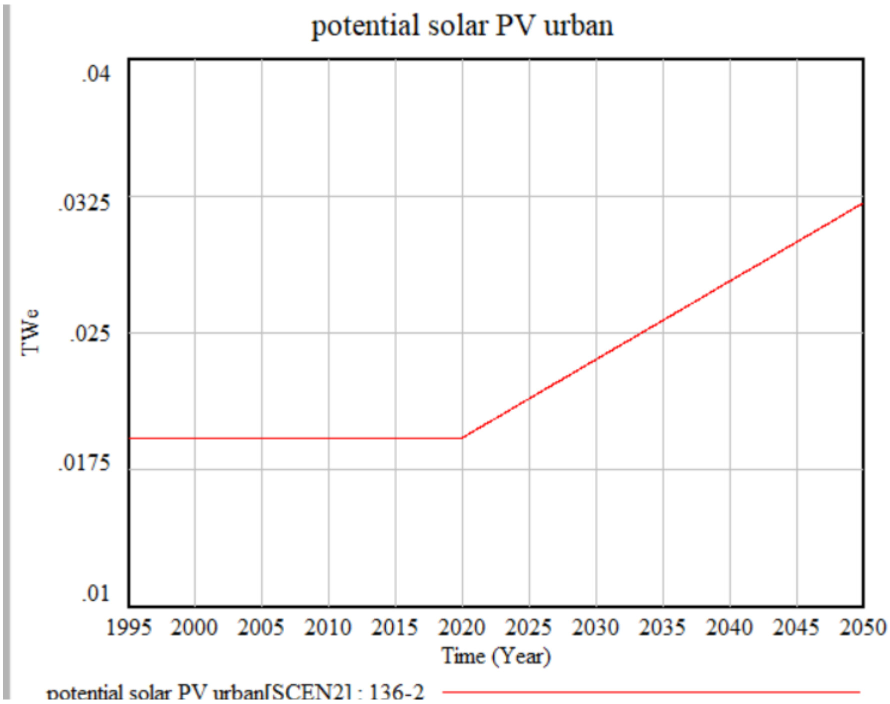

Figure 122. Potential of PV on urban land at European level

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).

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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).

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

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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):

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

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

$$\frac{dI_{gas\ inland\ t}}{dt} = CX_{HV} \cdot sr_{gas\ HV} \cdot \frac{d}{dt}\%HV_{gas} + CX_{LV} \cdot sr_{gas\ LV} \cdot \frac{d}{dt}\%LV_{gas} + $$

$$+CX_{bus} \cdot sr_{gas\ bus} \cdot \frac{d}{dt}\%bus_{gas} \quad (38)$$

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.

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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 70. 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	-	-

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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.

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Table 71. 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

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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.

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Table 72. 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

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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 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).

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Table 73. 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

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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):

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

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).

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

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.

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Table 74. 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.

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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.

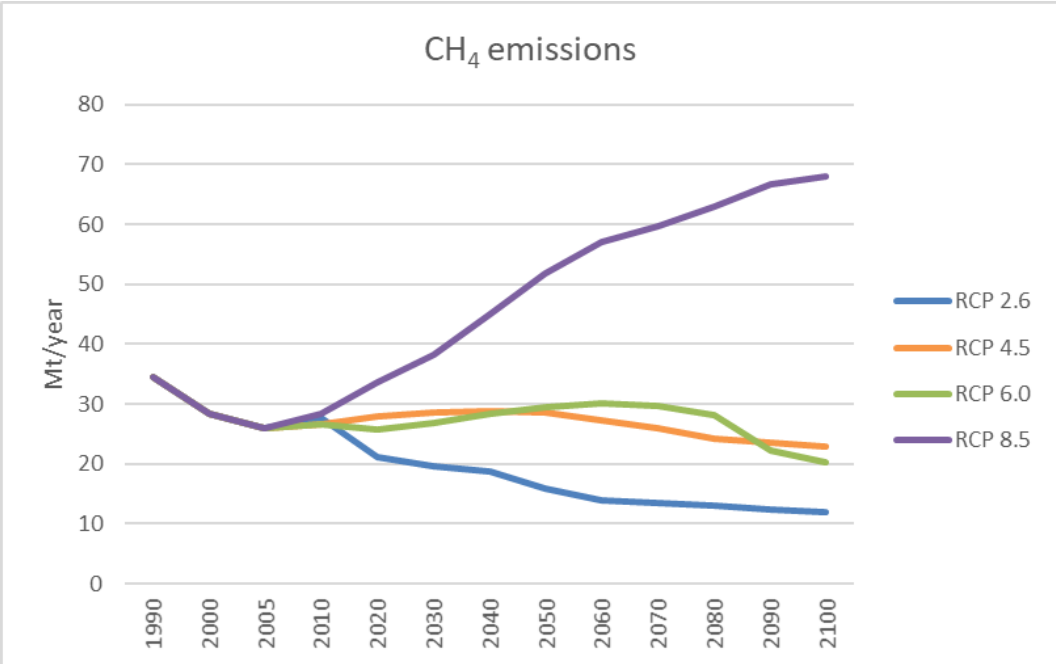

Figure 123. CH_4 emissions (1990 - 2100) for each RCP.

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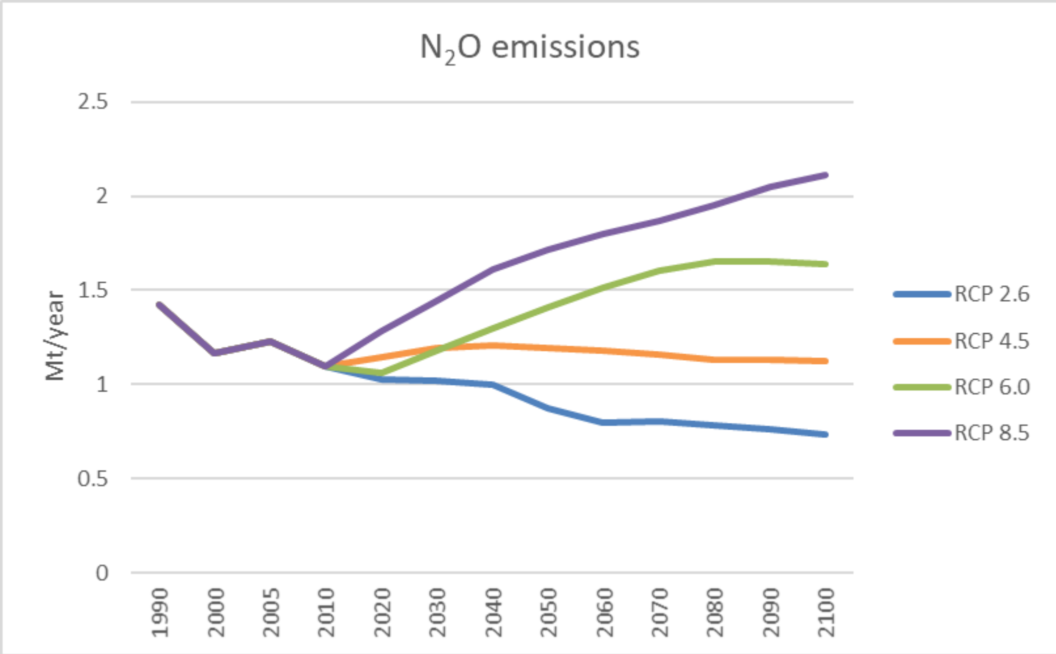

Figure 124. N_2O emissions (1990 - 2100) for each RCP.

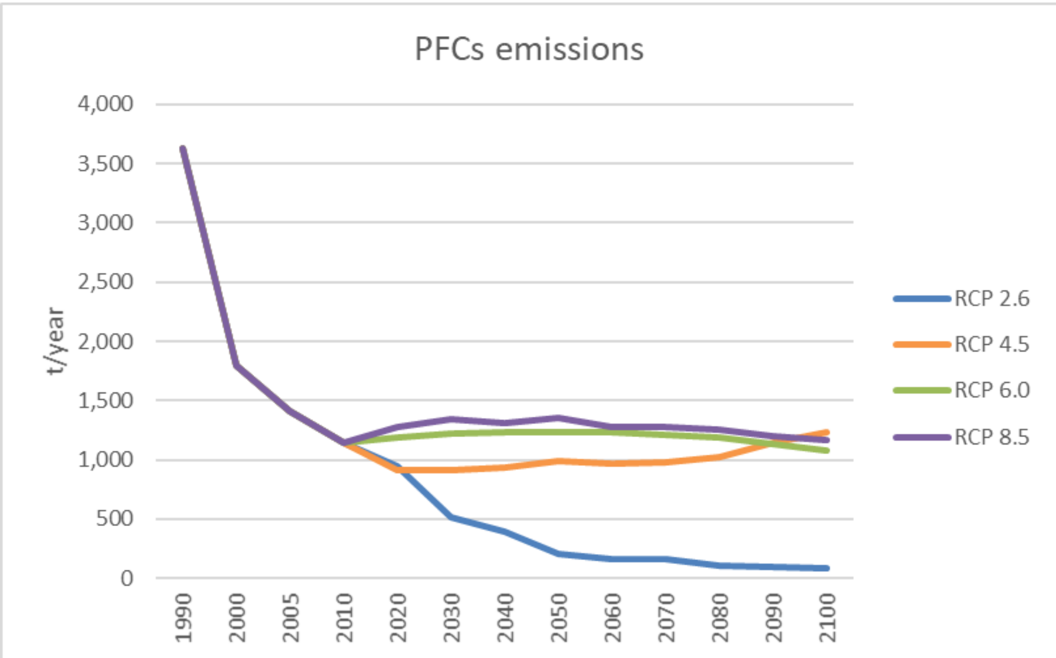

Figure 125. PFCs (CF_4) emissions (1990 - 2100) for each RCP.

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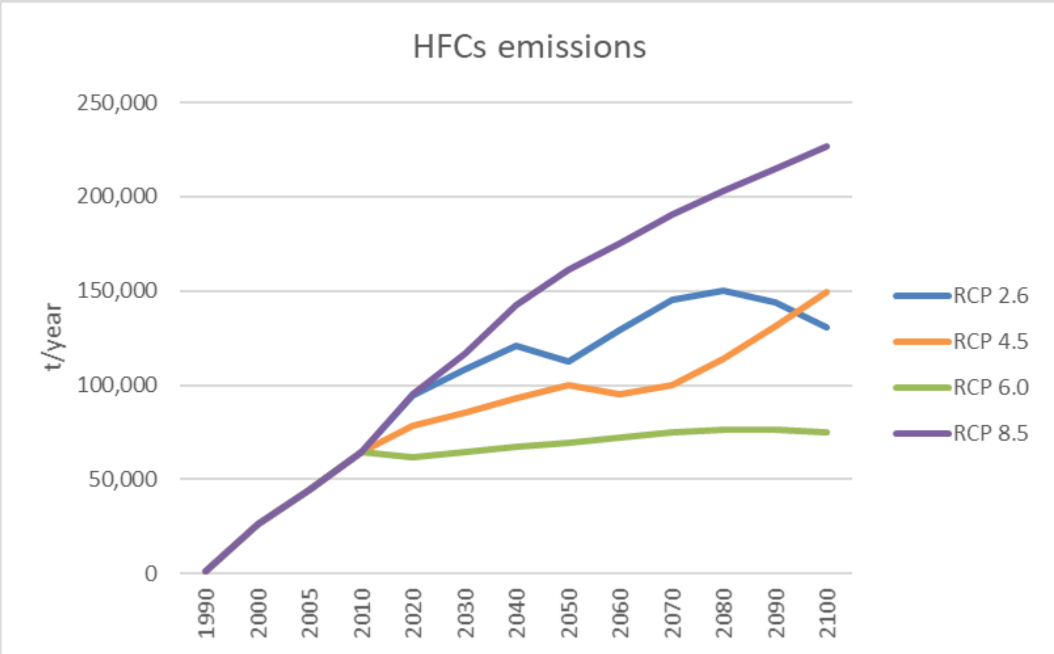

Figure 126. HFCs emissions (1990 - 2100) for each RCP.

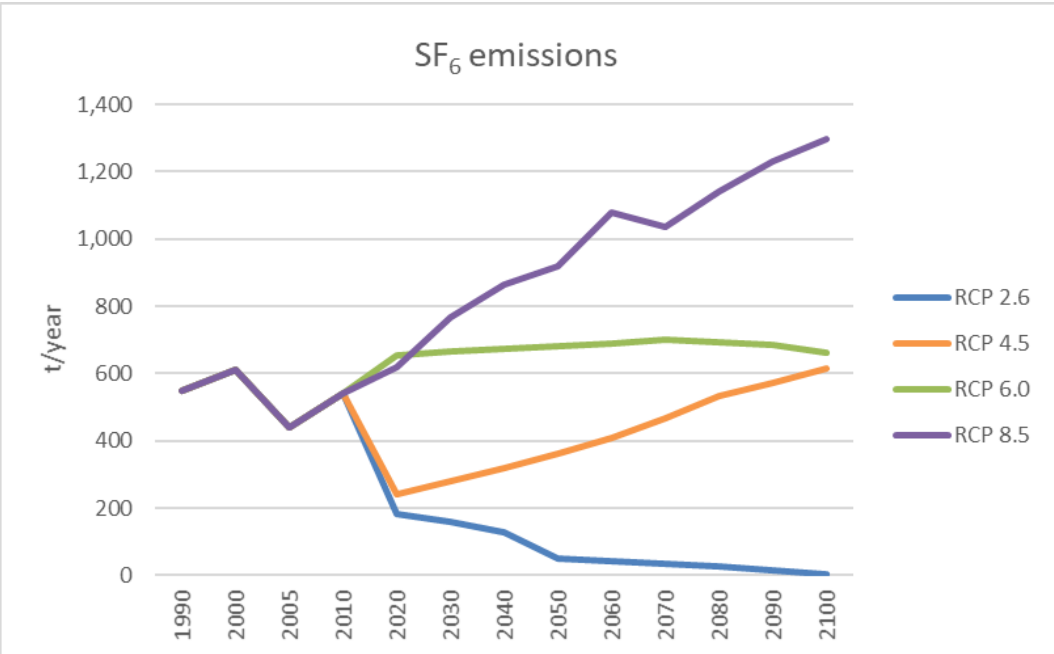

Figure 127. SF_6 emissions (1990 - 2100) for each RCP.

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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/).

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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).

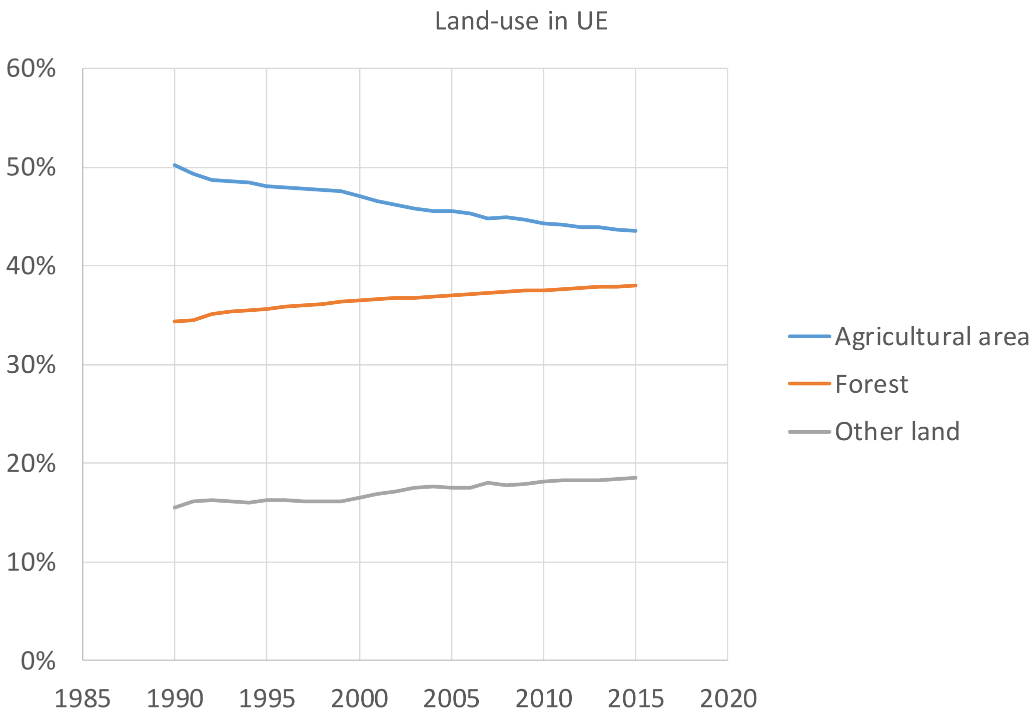

Figure 128. Historical evolution of land-use shares (1990-2015) for agricultural area, forest and other land.

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

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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).

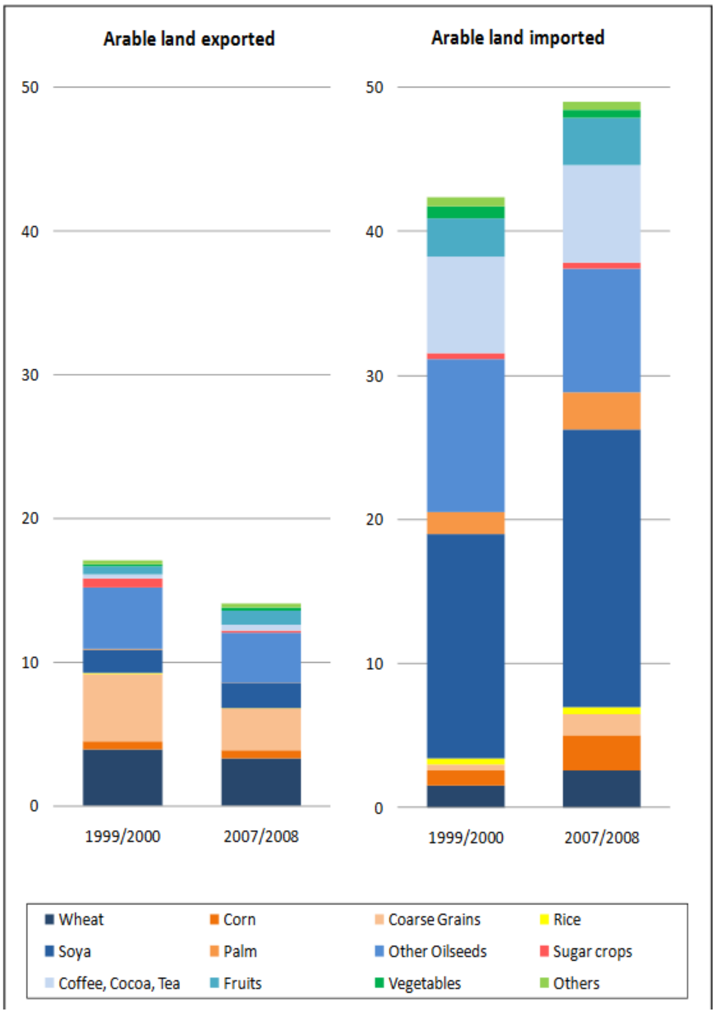

Figure 129. EU arable land virtually traded (in Mha).

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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).

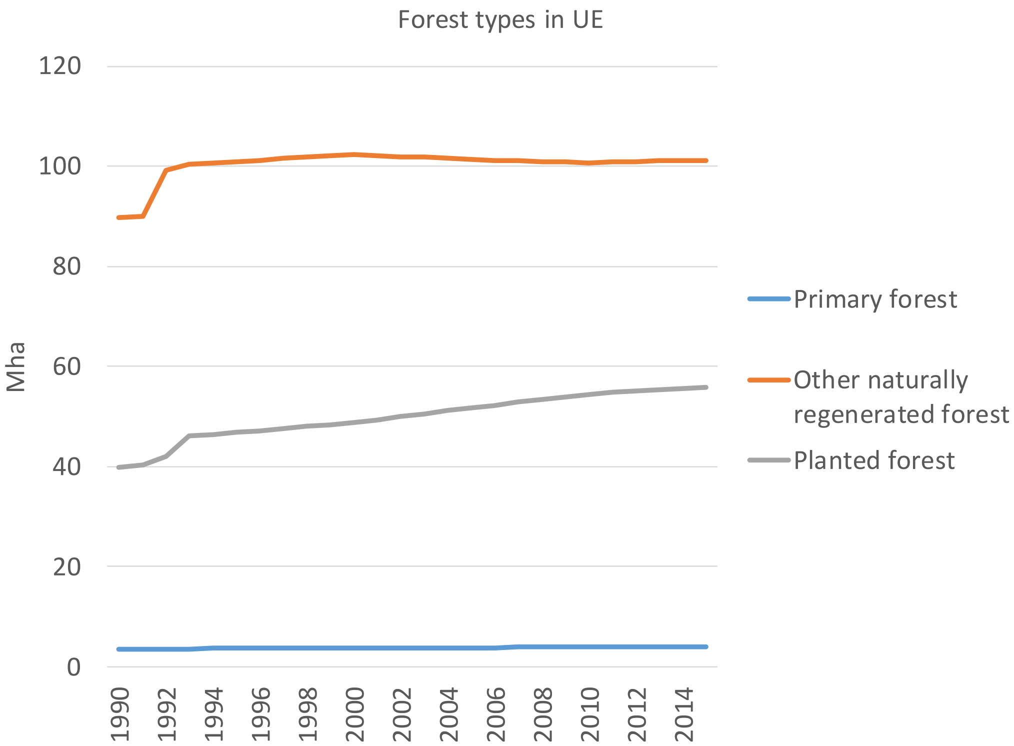

Figure 130. Historical evolution of area covered of forest by type in EU (1990-2015).

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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).

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- 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.

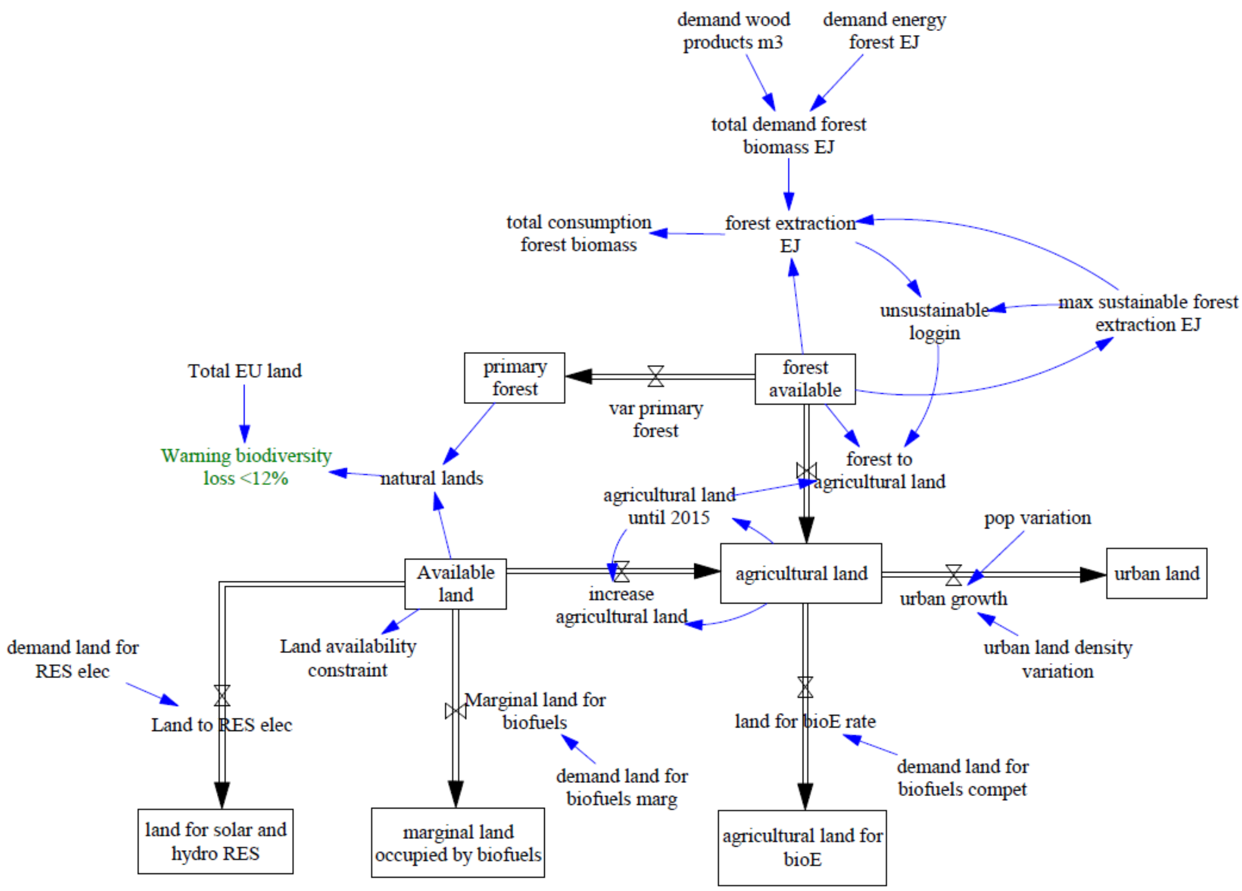

Figure 131. Overview of the Land Module in MEDEAS-EU.

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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.

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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).

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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.

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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 75. 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

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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.

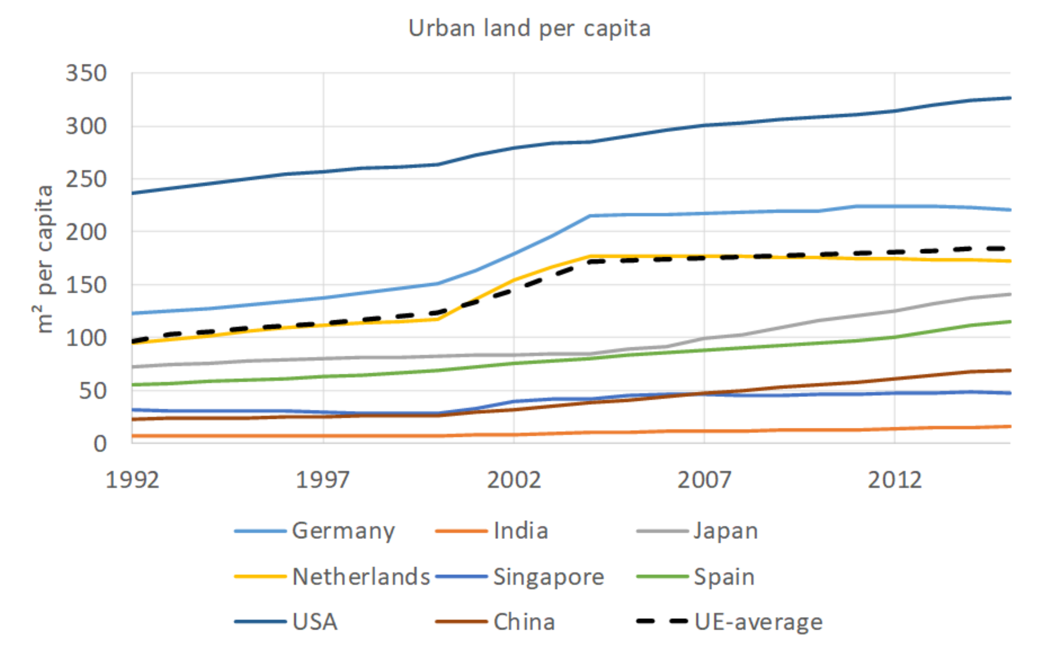

Figure 132. Urban land per capita.

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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).

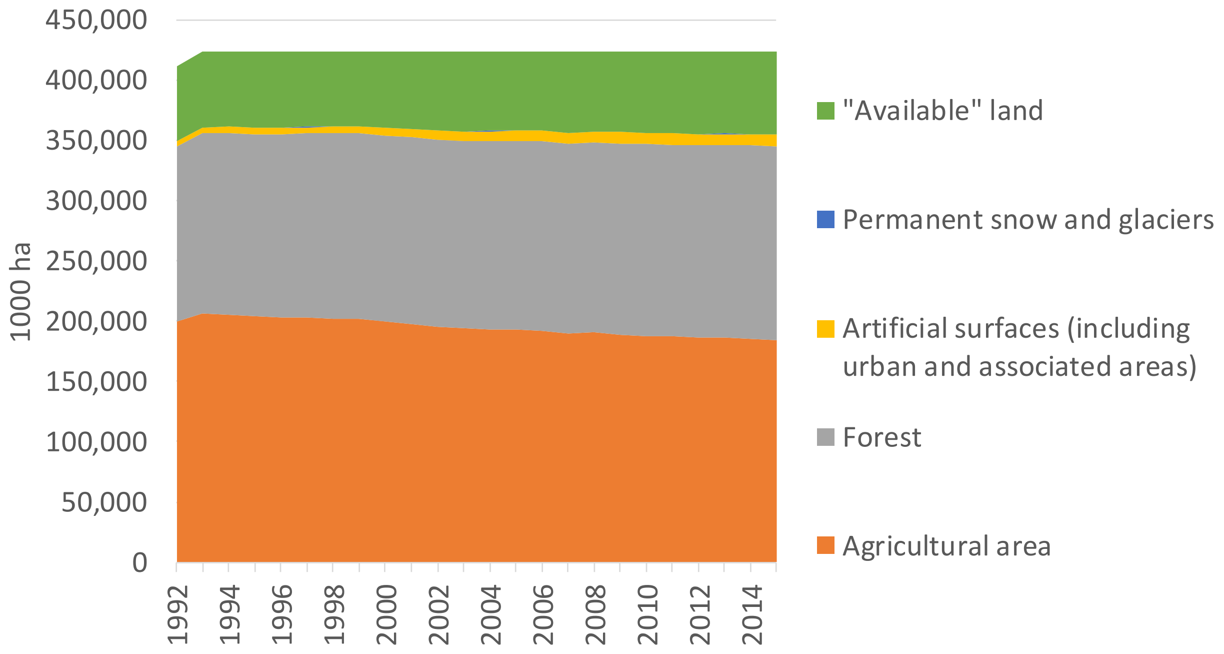

Figure 133. Historical evolution of the main stocks of land considered in the Land Module of MEDEAS-EU (1992-2015).

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)).

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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%.

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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).

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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.

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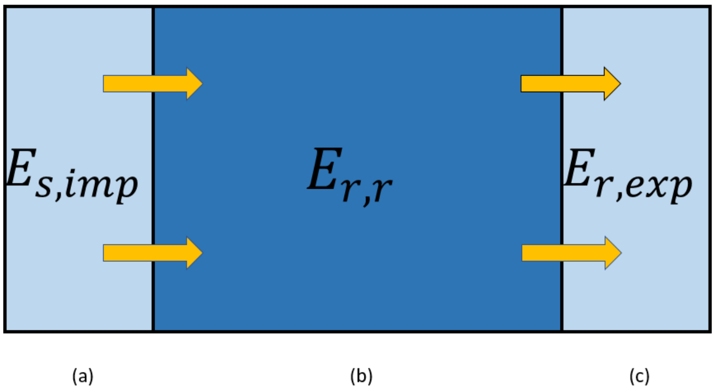
2.7.3. Energy footprint

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):

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

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 134. 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

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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):

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

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:

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

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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.

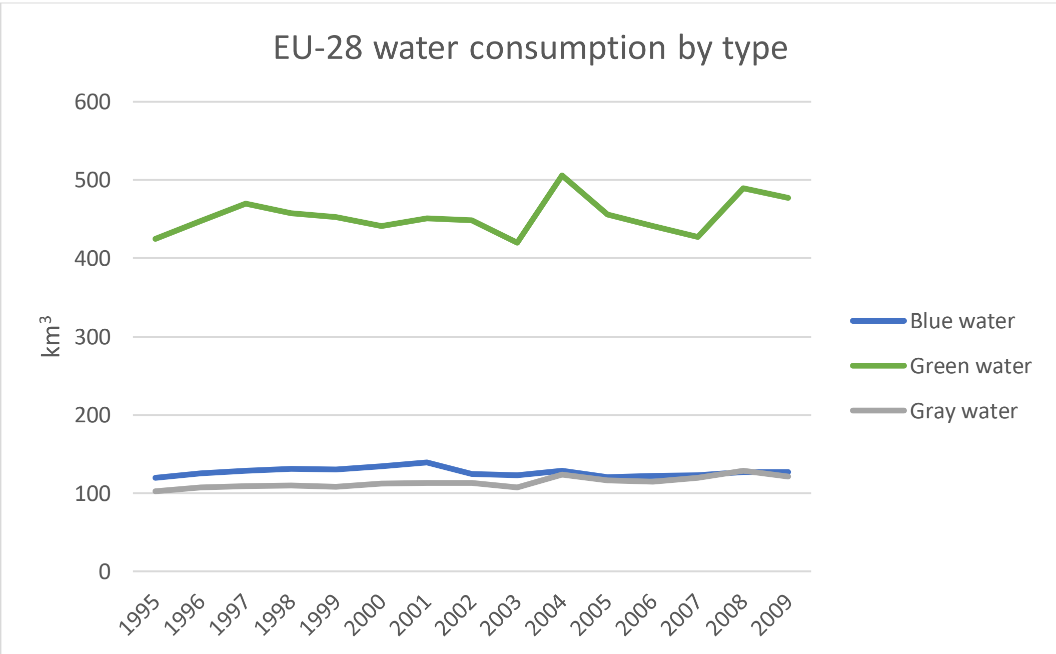

Figure 135. EU-28 water consumption (1995-2009) by type from WIOD database.

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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,[36] 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.

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

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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.

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)).

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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).

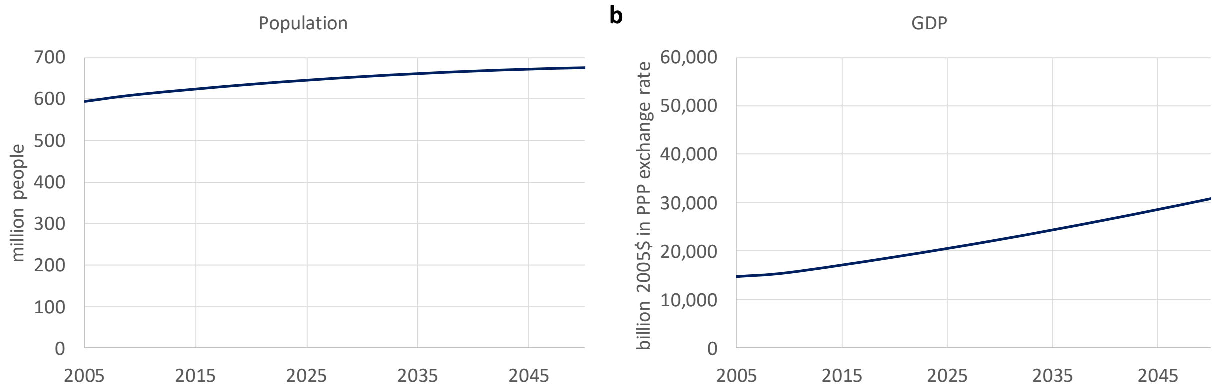

Figure 136. Population growth and GDP quantification of the SSP2 from D3.3.

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

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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.

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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).

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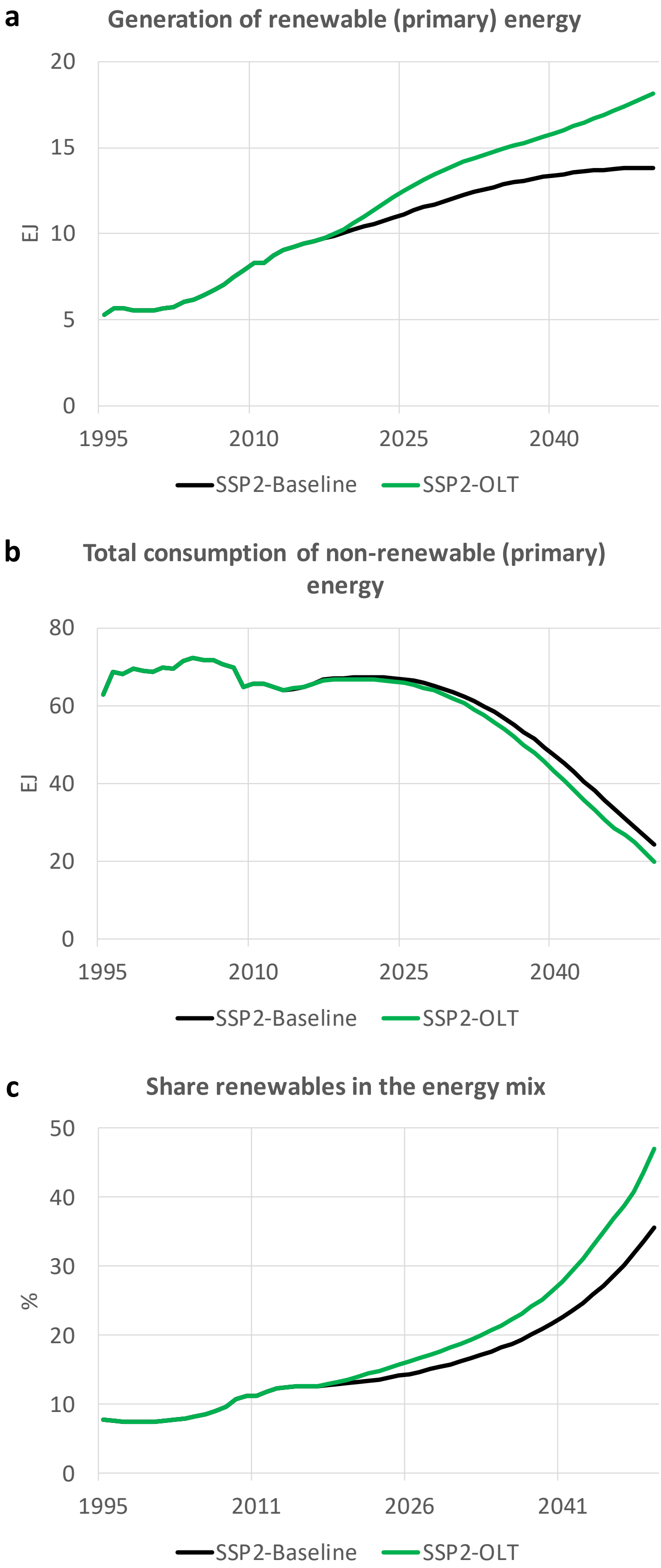

Figure 137. Primary energy mix: (a) generation of renewables; (b) non-renewables (oil, gas, coal and uranium) and (c) share of renewables in the energy mix.

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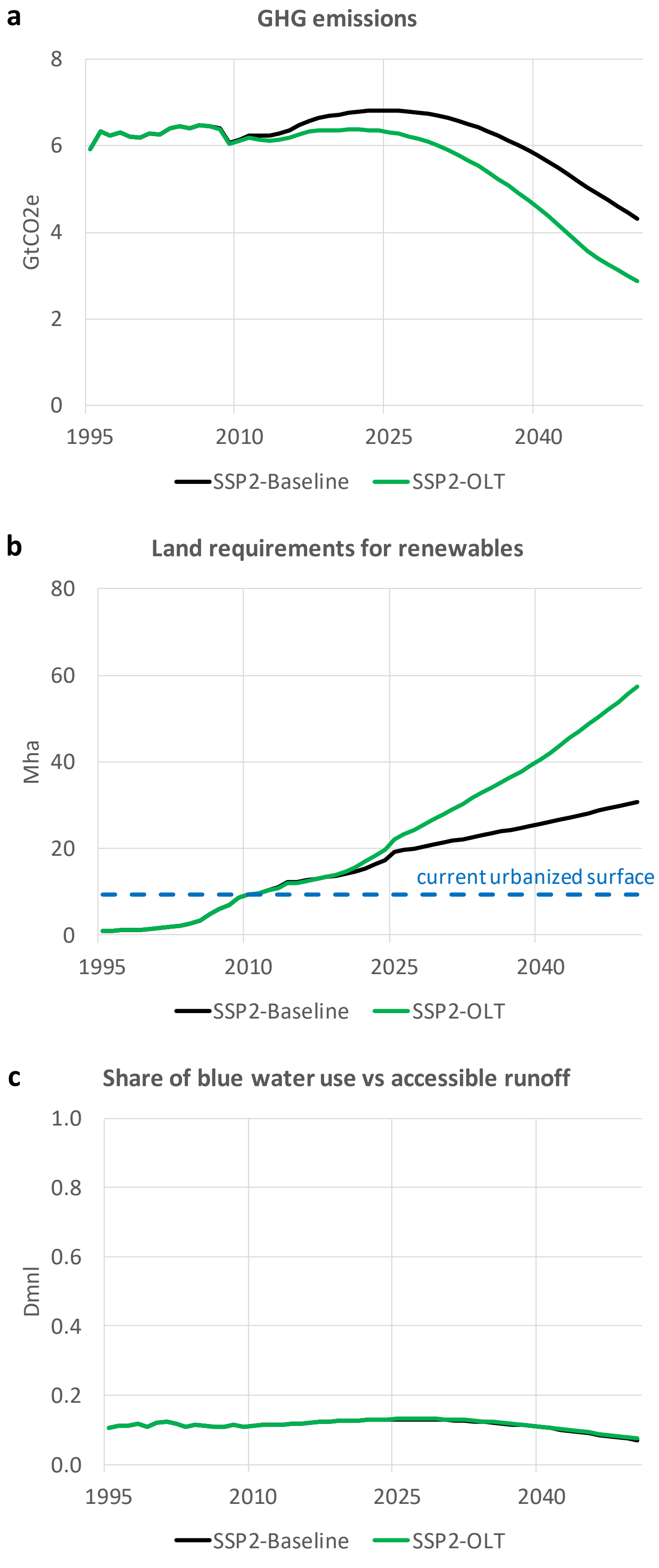

Figure 138. Environmental impacts: (a) GHG emissions; (b) Land requirements for renewables and (c) share of blue water use vs. accessible runoff.

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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.).

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Table 76. 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 technology of

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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.

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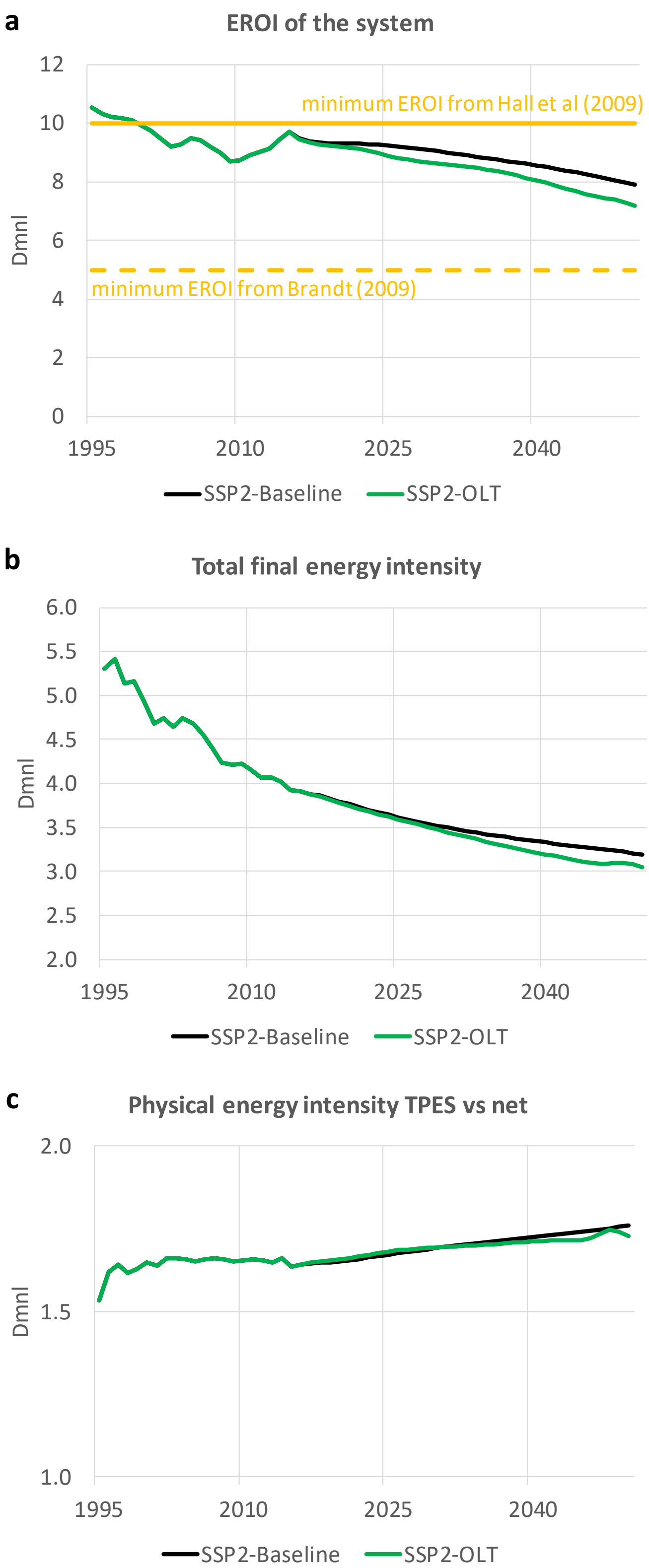

Figure 139. Efficiency of the system: (a) EROI of the system; (b) Total final energy intensity and (c) Physical energy intensity TPES vs net.

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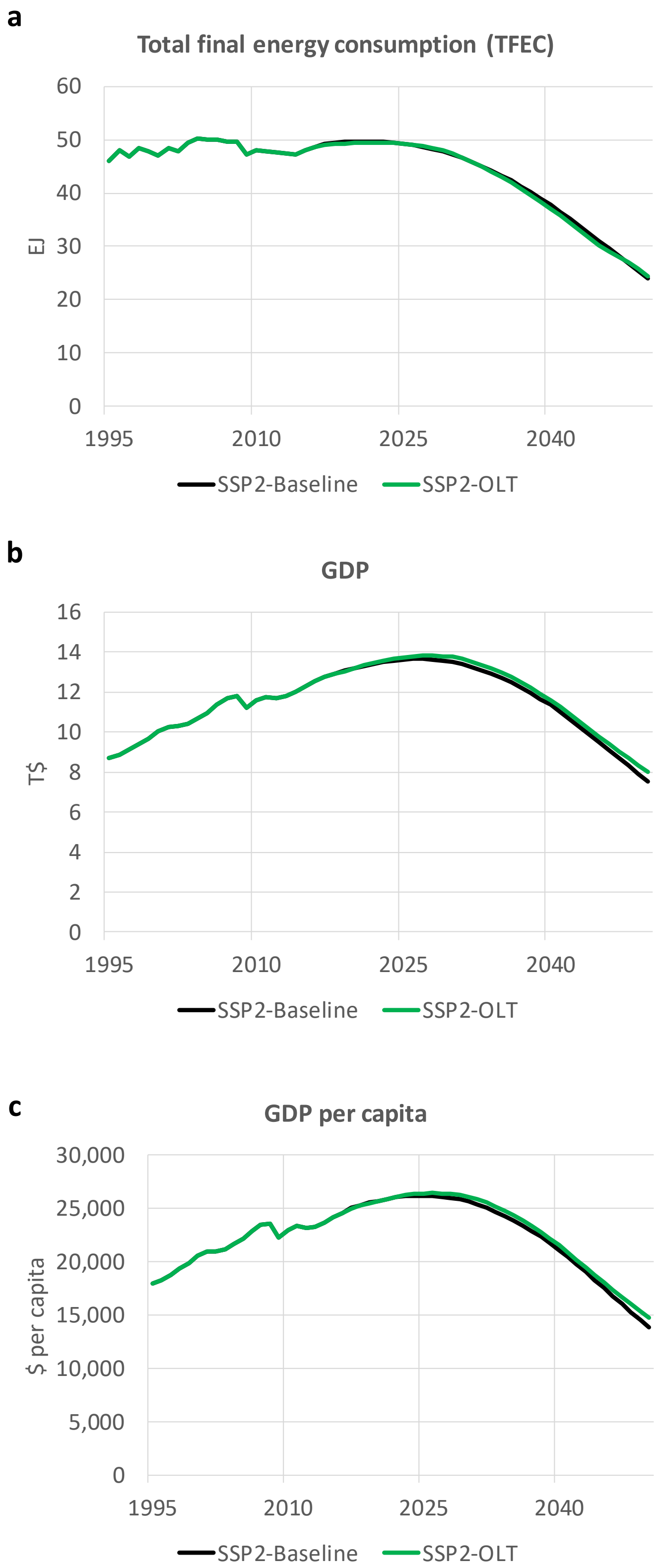

Figure 140. Aggregated variables: (a) Total Final Energy Consumption, (b) GDP and (c) GDP per capita.

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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%.

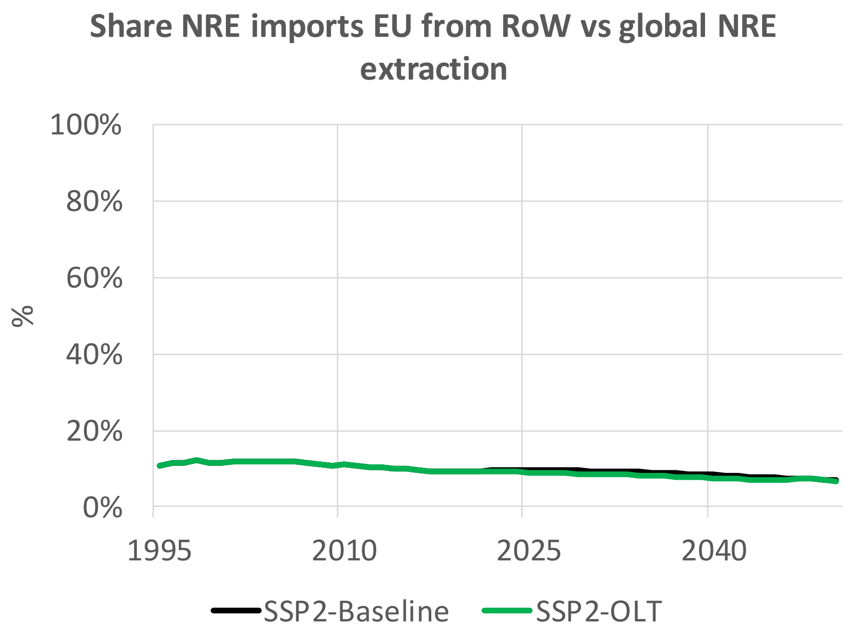

Figure 141. Share of non-renewable energy imports of EU from RoW as a share of the global non-renewable energy extraction.

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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,

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- 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

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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.[37]

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

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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).

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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.

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- 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

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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.

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