



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

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



**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 2.0.0

Due date of deliverable: 28/02/2017

Actual submission date: 28/02/2017



## Disclaimer of warranties and limitation of liabilities

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

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

- (a) makes any warranty or representation whatsoever, express or implied,
  - (i). with respect to the use of any information, apparatus, method, process, or similar item disclosed in this document, including merchantability and fitness for a particular purpose, or
  - (ii). that such use does not infringe on or interfere with privately owned rights, including any party's intellectual property, or
  - (iii). that this document is suitable to any particular user's circumstance; or
- (b) assumes responsibility for any damages or other liability whatsoever (including any consequential damages, even if Project Coordinator or any representative of a signatory party of the MEDEAS Project Consortium Agreement, has been advised of the possibility of such damages) resulting from your selection or use of this document or any information, apparatus, method, process, or similar item disclosed in this document.

# Table of Contents

<b>DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES.....</b>	<b>2</b>
<b>TABLE OF CONTENTS.....</b>	<b>3</b>
<b>ABSTRACT .....</b>	<b>7</b>
<b>LIST OF ABBREVIATIONS AND ACRONYMS .....</b>	<b>8</b>
<b>STRUCTURE OF THE CODE.....</b>	<b>9</b>
<b>MODEL.PY STRUCTURE .....</b>	<b>10</b>
<b>GENERAL PROPERTIES.....</b>	<b>16</b>
<b>SIMULATION PROCESS.....</b>	<b>17</b>
FUNCTIONALITY DETAILS .....	17
<b>INSTALLATION.....</b>	<b>18</b>
RUNNING THE MODEL IN SPYDER.....	19
RUNNING THE MODEL IN COMMAND LINE.....	21
<b>PLOTTING.....</b>	<b>22</b>
COMMAND LINE TOOL PLOT.PY .....	22
<b>VISUAL TOOL PLOT_TOOL.PY .....</b>	<b>23</b>
<b>TESTING PROCEDURE.....</b>	<b>25</b>
<b>LICENSE .....</b>	<b>26</b>
<b>REFERENCES .....</b>	<b>27</b>
<b>ANNEX: MEDEAS_W MODEL DESCRIPTION .....</b>	<b>28</b>
<b>ANNEX DOCUMENT INFO SHEET.....</b>	<b>28</b>
<b>ANNEX ABSTRACT .....</b>	<b>29</b>
<b>ANNEX LIST OF ABBREVIATIONS AND ACRONYMS .....</b>	<b>30</b>
<b>ANNEX EXECUTIVE SUMMARY.....</b>	<b>34</b>
<b>1. INTRODUCTION.....</b>	<b>37</b>
<b>2. METHODOLOGY .....</b>	<b>39</b>

<b>2.1. OVERVIEW OF MEDEAS-WORLD .....</b>	<b>40</b>
<b>2.2. ECONOMY MODULE .....</b>	<b>43</b>
2.2.1. LITERATURE REVIEW.....	44
2.2.2. OVERVIEW OF THE ECONOMY MODULE.....	48
2.2.3. DESCRIPTION OF THE ECONOMY MODULE.....	51
2.2.3.1. Sectoral demand function.....	51
2.2.3.2. Input-Output Analysis (IOA) .....	59
2.2.3.3. Energy-Economy feedback .....	62
2.2.4. DYNAMIC MODELING OF FINAL ENERGY INTENSITIES IN MEDEAS.....	68
2.2.4.1. Overview.....	68
2.2.4.2. Final energy intensity historic data.....	70
2.2.4.3. Final energy intensity trend evolution.....	71
2.2.4.4. Changes on inertial trend of final energy intensity.....	73
<b>2.3. ENERGY AND INFRASTRUCTURES MODULE.....</b>	<b>77</b>
2.3.1. ESTIMATION OF ENERGY DEMANDS.....	78
2.3.1.1. Historic final energy demands from WIOD and IEA balances.....	78
2.3.1.2. Energy losses .....	83
2.3.1.3. Adjustment of energy demands to account for all non-commercial heat.....	86
2.3.2. ENERGY SUPPLY IN MEDEAS .....	88
2.3.3. NON-RENEWABLE ENERGY RESOURCES AVAILABILITY .....	90
2.3.3.1. Modeling of primary non-renewable energy resources in MEDEAS.....	91
2.3.3.2. Literature review of depletion curves by fuel .....	95
2.3.3.3. Depletion curves available in MEDEAS.....	107
2.3.3.4. Constraints to the (growth) extraction of unconventional fuels .....	109
2.3.3.5. CTL and GTL .....	111
2.3.3.6. Waste-to-energy.....	112
2.3.4. RENEWABLE ENERGY SOURCES (RES) AVAILABILITY .....	113
2.3.4.1. Bioenergy.....	114
2.3.4.2. RES for heat other than biomass.....	122
2.3.4.3. RES for electricity generation other than bioenergy.....	125
2.3.4.4. Summary of RES sustainable potentials considered in MEDEAS.....	129
2.3.4.5. Modelling of intermittency of RES variables in MEDEAS.....	130
2.3.4.6. Employment factors of RES technologies .....	141
2.3.5. ELECTRICITY GENERATION .....	142
2.3.5.1. Electricity generation from RES.....	145
2.3.5.2. Electricity generation from oil.....	149
2.3.5.3. Nuclear power scenarios.....	150
2.3.5.4. Electricity generation from CHP plants.....	152
2.3.6. HEAT GENERATION .....	153



2.3.6.1.	<i>Heat generation from liquids</i>	155
2.3.6.2.	<i>Heat generation from RES</i>	156
2.3.6.3.	<i>Heat generation from CHP plants</i>	157
2.3.7.	TRANSPORTATION	159
2.3.7.1.	<i>Methodology</i>	161
2.3.7.2.	<i>Data and parameters of the transportation submodels</i>	171
2.3.7.3.	<i>Saving ratios</i>	176
2.3.7.4.	<i>Batteries for electrical vehicles</i>	179
2.3.8.	NON-ENERGY USE CONSUMPTION	180
<b>2.4.</b>	<b>MATERIALS MODULE</b>	<b>181</b>
2.4.1.	DEMAND OF MATERIALS	183
2.4.1.1.	<i>Demand of materials for key technologies for the transition to RES</i>	183
2.4.1.2.	<i>Demand of the rest of the economy of key materials for the transition to RES</i>	191
2.4.2.	SUPPLY OF MINERALS	192
2.4.2.1.	<i>Analysis of the potential importance of minerals scarcity</i>	192
2.4.2.2.	<i>Implementation in MEDEAS</i>	195
2.4.3.	MODELLING OF RECYCLING POLICIES IN MEDEAS	197
2.4.4.	EROI ESTIMATION PER ELECTRICITY GENERATION TECHNOLOGY	203
2.4.4.1.	<i>EROI of RES dispatchables for electricity generation</i>	204
2.4.4.2.	<i>EROI of RES variables for electricity generation</i>	207
2.4.4.3.	<i>Cumulative energy demand for new installed capacity and O&amp;M per technology of RES variables</i>	210
2.4.4.4.	<i>Summary of results</i>	214
2.4.5.	EROI AS CRITERIA FOR ALLOCATION OF RES TECHNOLOGIES FOR ELECTRICITY GENERATION	217
2.4.6.	EROI OF THE SYSTEM	220
2.4.7.	FEEDBACK OF THE EROI TO THE ECONOMIC AND ENERGY SYSTEM	222
<b>2.5.</b>	<b>GHG EMISSIONS AND CLIMATE SUBMODULE</b>	<b>225</b>
2.5.1.	ENDOGENOUS CALCULATION OF GHG EMISSIONS	225
2.5.2.	CARBON CYCLE AND CLIMATE MODEL	227
2.5.2.1.	<i>Structure of the climate module in MEDEAS-W</i>	229
2.5.3.	CLIMATE CHANGE IMPACTS	232
<b>2.6.</b>	<b>LAND-USE MODULE</b>	<b>237</b>
<b>2.7.</b>	<b>SOCIAL AND ENVIRONMENTAL IMPACTS INDICATORS</b>	<b>238</b>
2.7.1.	CONTEXT AND MEDEAS APPROACH	238
2.7.2.	LIST OF INDICATORS	239
2.7.3.	WATER USE	243
2.7.3.1.	<i>Context</i>	243
2.7.3.2.	<i>Data</i>	245

2.7.3.3.	<i>Methodology for estimating water use in MEDEAS</i> .....	247
2.7.3.4.	<i>Water potential</i> .....	249
<b>3.</b>	<b>POLICY OPTIONS AVAILABLE IN MEDEAS</b> .....	<b>250</b>
3.1.	CARBON CAPTURE AND STORAGE (CCS) AND NEGATIVE EMISSIONS .....	252
3.2.	HYDROGEN/« RENEWABLE HYDROGEN ECONOMY» .....	259
3.3.	NUCLEAR FAST BREEDERS AND NUCLEAR FUSION.....	261
<b>4.</b>	<b>LIMITATIONS AND FURTHER DEVELOPMENTS OF MEDEAS-WORLD MODEL</b> .....	<b>262</b>
4.1.	STRUCTURE OF THE MODEL.....	263
4.2.	POLICY OPTIONS .....	268
<b>5.</b>	<b>CONCLUSIONS</b> .....	<b>269</b>
	<b>ACKNOWLEDGEMENTS</b> .....	<b>271</b>
	<b>REFERENCES</b> .....	<b>272</b>
	<b>LIST OF TABLES</b> .....	<b>296</b>
	<b>LIST OF FIGURES</b> .....	<b>299</b>

## Abstract

This document provides the user's manual for the python implementation of Medeas-World model with the ***pymedeas\_w*** freeware tool. The document also contains the description of the model as annex.

## List of abbreviations and acronyms

**BAU** Business As Usual

**IDE** Integrated Development Environment

**IO** Input/output

**PySD** Python System Dynamics library

## Structure of the code

- The code of the integrator is stored in the *pysd/py\_backend* folder.
- *pysd/py\_backend/functions.py* contains the definitions of the functions.
- *model.py* file contains the definition of the model in python terms.
- *plot.py* file implements the command-line plotting capabilities
- *plot\_tool.py* file implements the plotting graphic interface (GUI) based on tkinter library.

## Model.py structure

The model makes use of the following basic functional elements:

- Constants in the format of a function : *def constant\_a()*:
- Vectors and matrices in the format of a function, xarray.DataArray type: *def matrix\_a()*:
- Lookups (tabular functions) in the format of a function with argument: *def lookup\_a(x)*:
- Non-constant functions: *def nonconstant\_function\_a()*:
- Integration functions using lambda-expressions: *integ\_some\_function = functions.Integ ...*
- Delay function using lambda-expressions: *delay\_some\_function = functions.Delay ...*

These are arranged in the following shape:




```
from __future__ import division
import numpy as np
from pysd import utils
import xarray as xr
import inspect

from pysd.py_backend.functions import cache
from pysd.py_backend import functions

from debugutils import interrupt, round_sig, single_precision, less_thr_func

equality_threshold = 1e-4
_subscript_dict = {
    'households vehicles':
        ['liq 4wheels', 'hib 4wheels', 'elec 4wheels', 'gas 4wheels', 'liq 2wheels', 'elec 2wheels'],
    'vehiclet': [
        'hv liq', 'hv hib', 'hv gas', 'lv liq', 'lv elec', 'lv hib', 'lv gas', 'bus liq',
        'bus elec', 'bus hib', 'bus gas', 'train liq', 'train elec'
    ],
    'final sources': ['electricity', 'heat', 'liquids', 'gases', 'solids'],
    'final sources1': ['electricity', 'heat', 'liquids', 'gases', 'solids'],
    'water': ['xcleanx pumped waterx', 'xdistilledx deionized waterx'],
    'materials': [
        'adhesive', 'aluminium', 'aluminium mirrors', 'cadmium', 'carbon fiber', 'cement',
        'chromium', 'copper', 'diesel', 'dy', 'xelectricx electronic componentsx',
        'evacuation lines', 'fiberglass', 'foam glass', 'galium', 'glass',
        'glass reinforcing plastic', 'gravel', 'indium', 'iron', 'kno3 mined', 'asphalt', 'lime',
        'limestone', 'lithium', 'lubricant', 'magnesium', 'manganese', 'heavy equipment'
    ]
}
```

 =<> condition threshold  
vector indices dictionary

Header with the definition of used libraries and the equality threshold. Here we also define the dictionary of subscripts available for the matrices of the model.



```
78     'renting od meq and other business activities',
79     'public admin and defence compulsory social security', 'education'
80     'health and social work', 'other community social and persona serv
81     'private households with employed persons'
82 ],
83 'res elec': [
84     'hydro', 'xgeotxelec', 'xsolid bioxelec', 'oceanic', 'wind onsh
85     'solar pv', 'csp'
86 ],
87 'gtco2 ipcc emissions': ['gtco2e a1', 'gtco2e a2', 'gtco2e b1', 'gtco2
88 'gtc cumulated': ['gtc a2', 'gtc a1g', 'gtc b1']
89 }
90
91 _namespace = {
92     'ifthenelse dummy 3766 Implementatio policy to change final energy':
93     'ifthenelse_dummy_3766_implementation_policy_to_change_final_energy',
94     'ifthenelse dummy 7365 real extraction conv gas EJ':
95     'ifthenelse_dummy_7365_real_extraction_conv_gas_ej',
96     'ifthenelse dummy 4447 max extraction conv gas EJ':
97     'ifthenelse_dummy_4447_max_extraction_conv_gas_ej',
98     'ifthenelse dummy 6020 max extraction coal EJ':
99     'ifthenelse_dummy_6020_max_extraction_coal_ej',
100     'ifthenelse dummy 8153 scarcity conv gas':
101     'ifthenelse_dummy_8153_scarcity_conv_gas',
102     'ifthenelse dummy 1949 URR uranium':
103     'ifthenelse_dummy_1949_urr_uranium',
104     'ifthenelse dummy 4618 Xshare natX gas dem for ElecX':
105     'ifthenelse_dummy_4618_xshare_natx_gas_dem_for_elec',
```

Namespace: the correspondence between the verbose names and the python names of the functions and values.





```
@cache('run')
def ia_matrix_2002():
    """
    IA matrix 2002

    constant

    """

    ret = xr.DataArray(
        data=[[
            8.68684171e-01, -9.33669000e-04, -2.57643610e-01, -3.94381980e-02, -3.66334540e-02,
            -1.29627905e-01, -1.21232260e-02, -1.56225600e-03, -4.95520600e-03, -1.40601000e-02,
            -6.23449000e-04, -2.71843000e-04, -2.76016000e-04, -1.88636000e-04, -1.49733000e-04,
            -9.52747100e-03, -5.10374000e-04, -1.02566090e-02, -4.55947000e-04, -3.13305400e-03,
            -2.64502400e-03, -3.86784270e-02, -1.33808600e-03, -1.27999600e-03, -3.07578000e-04,
            -3.93945100e-03, -2.52928000e-04, -1.41304000e-04, -3.71861000e-04, -6.27869000e-04,
            -1.90611800e-03, -2.01888000e-03, -2.15198400e-03, -2.33462200e-03, -1.53724580e-02
        ]], [
            -3.52914000e-03, 9.26812613e-01, -2.61520200e-03, -2.01922000e-03, -8.51768000e-04,
            -3.65366900e-03, -4.38863700e-03, -4.42566481e-01, -3.18202300e-02, -2.93755700e-03
        ])
```

Definition of constant matrices (with `@cache('run')` decorator)

```
# Transportation
# TRANSP - Total number vehicles
@cache('step')
def share_of_electric_light_vehicles():
    """
    share of electric light vehicles

    component

    """

    ret = total_number_elec_light_vehicles() / total_number_light_vehicles()
    try:
        name = 35
        ret.name = 35

        if (True in np.isnan(ret).values):
            interrupt('NaN occurred at:', True in np.isnan(ret).values, ret.name, ret)
    except:
        if np.any(np.isnan(ret)):
            interrupt('NaN occurred at:', ret, name)
    return round_sig(x=ret, name=name)
```

Each matrix is defined with its subscript lists.



```
-1.88441000e-05, -3.94316000e-05, -4.90602000e-05, -2.42861000e-04, -6.11539000e-05,  
-7.05908000e-05, -3.89425000e-05, -6.60497000e-05, -1.10022000e-04, 9.99904553e-01  
]],  
coords={  
  'sectors': [  
    'agriculture hunting forestry and fishing', 'mining and quarrying',  
    'food beverages and tobacco', 'textiles and textile products',  
    'leather leather and footwear', 'wood and products of wood and cork',  
    'pulp paper printing and publishing', 'coke refined petroleum and nuclear fuel',  
    'chemicals and chemical products', 'rubber and plastics',  
    'other non metallic mineral', 'basic metals and fabricated metal', 'machinery nec',  
    'electrical and optical equipment', 'transport equipment',  
    'manufacturing nec recycling', 'electricity gas and water supply', 'construction',  
    'sale maintenance and repair of motor vehicles and motorcycles retail sale of fuel',  
    'wholesale trade and commissions trade except of motor vehicles and motorcycles',  
    'retail trade except of motor vehicles and motorcycles repair of household goods',  
    'hotels and restaurants', 'inland transport', 'water transport', 'air transport',  
    'other supporting and auxiliary transport activities activities of travel agencies',  
    'post and telecommunications', 'financial intermedation', 'real estate activities',  
    'renting od meq and other business activities',  
    'public admin and defence compulsory social security', 'education',  
    'health and social work', 'other community social and persona services',  
    'private households with employed persons'  
  ],  
  'sectors1': [  
    'agriculture hunting forestry and fishing', 'mining and quarrying',  
    'food beverages and tobacco', 'textiles and textile products',
```

Constant values (computed upon the initialization phase only)

```
def pop_ssp2(x):  
    """  
    Pop SSP2  
  
    lookup  
  
    """  
    ret = functions.lookup(x, [2010, 2020, 2030, 2040, 2050, 2060, 2070, 2080, 2090, 2100, 2110],  
                           [  
                               6867.39, 7611.25, 8261.99, 8787.12, 9169.11, 9384.7, 9456.88,  
                               9407.26, 9253.95, 9032.42, 9032.42  
                           ])  
    try:  
        name = 62
```

Lookups





```
# Integration definitions

integ_evol_final_energy_intensity_h = functions.Integ(
    lambda: _devol_final_energy_intensity_h_dt(), lambda: _init_evol_final_energy_intensity_h())

integ_installed_capacity_phs_tw = functions.Integ(
    lambda: phs_capacity_under_construction() - wear_phs(), lambda: initial_instal_cap_phs())

integ_phs_planned_capacity = functions.Integ(lambda: new_phs_capacity_under_planning() + replacement_capa

integ_required_capacity_phs = functions.Integ(
    lambda: new_required_phs_capacity() - new_phs_capacity_under_planning(),
    lambda: initial_required_capacity_phs())

integ_battery_storage_capacity = functions.Integ(
```

Integration function definitions *functions.Integ(derivative, initial)*

```
# Delay definitions

delay_tfec_intensity_until_2009_roundtime_step__time_step__time_step_0_time_step__time_step = functions.Delay(
    lambda: tfec_intensity_until_2009(), lambda: time_step(),
    lambda: 0, lambda: 1)

delay_annual_gdp_growth_rate_round3__time_step__time_step_0_3__time_step = functions.Delay(
    lambda: annual_gdp_growth_rate(), lambda: round(3 / time_step()) * time_step(), lambda: 0,
    lambda: 3 / time_step())

delay_annual_gdp_growth_rate_round1__time_step__time_step_0_1__time_step = functions.Delay(
    lambda: annual_gdp_growth_rate(), lambda: round(1 / time_step()) * time_step(), lambda: 0,
    lambda: 1 / time_step())
```

Delay function definitions *functions.Delay(function, aux\_vars)*

```
delay_extraction_unconv_oil_ej_roundtime_step__time_step__time_step_105__time_step__time_step = functions.Delay(
    lambda: extraction_unconv_oil_ej(), lambda: time_step(),
    lambda: 1.09, lambda: 1)

# Playground

integ_my_random = functions.Integ(lambda: population(), lambda: initial_pes_waste())

@cache('step') # updated on every time step
def my_random_function():
    return gdppc() / gdppc_annual_growth_ssp2(time()) + integ_my_random()
```

Code modifications in the bottom of the file: testing routines, additional functionality. *@cache('step')* makes the function dynamic.

## General properties

1. Medeas model relies heavily on the extraction of data from a database. In the current implementation the data is kept in an Excel file *inputs.xlsx*.
2. pymedeas performs the interpolation for any array by default (as this is probably required in most applications and cases). The lookups (tabular functions) are by default extrapolated using the leftmost and rightmost values for the lower and upper extrapolated ranges, correspondingly.
3. Currently, we the variable names can contain 'X' symbol where non-standard symbols were used in the original naming to facilitate a possible comparison in the debugging phase. Later on, this will be replaced by a cleaner representation of the variables.
4. The scenario used in the simulation is the one defined in inputs.xlsx PythonScenario sheet. By default, this scenario is equivalent to the Business-as-usual (BAU) scenario and can be overridden directly in this sheet. The *run.py* script updates automatically the input data in the initialization phase prior to simulation. A user-defined scenario can also be saved as a separate sheet (e.g. NewSheet); in order to invoke it, a user must add it as a key in the command line, as `python run.py -u NewSheet`.
5. In order to modify the input in the default configuration (without `run.py -u` option), open inputs.xlsx and PythonScenario sheet. The modifications of data in this and only this sheet, if changed by a user, is taken in account by run.py.

## Simulation process

### Functionality details

- Math functions: *numpy.roll*, *logical\_or*, *logical\_and*, *numpy.where*, and similar. They were rewritten to include all the possible combination of xarray matrices, vectors and scalars, where the broadcasting rules of xarray apply.
- Matrices in partial definitions get the corresponding coordinates, or collapsed along the corresponding dimension, if needed. The information for the coordinates is taken by a syntactic analysis of the initial *model.mdl* model file.
- SUM function is implemented using the native *xarray.sum()*, with the inclusion of the dimensional parameter (tuple of dimensions, over which the sum is computed). The information for the coordinates is taken by a syntactic analysis of the initial *model.mdl* model file.
- Vector lookups and delays are represented in the expanded way, in order to comply with the demands of PySD.
- *run.py* application generates the tab-delimited file, containing all the data converted from pandas.DataFrame internal format.
- *plot.py* provides a simple command line functionality to pick and graph the required values, using *matplotlib*.
- *plot\_tool.py* provides a graphic user interface (GUI) to graph the required values, using *matplotlib* and *tkinter*.

## Installation

1. Prior to the installation, it is recommended to uninstall and erase any prior Python installations, if possible.
2. Download and install Anaconda Python 3.6 version for your operating system: <https://www.anaconda.com/download> using the default parameters that the installer proposes.
3. Extract the zip archive of pymedeas to some path, e.g. PathTopymedeas/pymedeasFolder
4. Run the installation script:
  - a) Windows: click on *install\_windows.bat* given in PathTopymedeas/pymedeasFolder
  - b) MacOS/Linux:
    - i. Open Terminal (or any other command line tool) and execute:
    - ii. `cd PathTopymedeas/pymedeasFolder`
    - iii. `chmod +x install_macos_linux.sh`
    - iv. `./install_macos_linux.sh`

## Running the model in Spyder

A user can run the simulation from an environment, for example, Spyder. This is how it is done.

1. Open Spyder application, installed with Anaconda. This is a freeware multiplatform IDE (development environment), that allows to run the code directly from it.
2. Download pymedeas and extract it to a suitable location as in (3) of the previous paragraph, for example, to PathToppymedeas/pymedeasFolder
3. In Spyder, open “*run.py*” file from this location and press F5 (or click the green arrow icon in the menu). This launches the script, and the output arises in the “Terminal” on the right.
4. Follow the suggestions given in the terminal:
  - a) Enter the variables that you are interested in: comma-separated, using their names or number codes from the list, 0’ for all variables, ‘r’ to repeat the last choice, +var1,var2... to add variables to the last choice. The numerical indices and actual variable names can be used together, in any order. If an input is incorrect (e.g. an index or a variable doesn’t exist), the prompt will offer to input the variables again.
  - b) wait for the run to finish at the final time stamp.
  - c) the output data is saved in ‘data.log’ file in the same folder as ‘run.py’ with the structure: variable[index (if present)],value1,value2,....
  - d) data.log that existed before (if it existed) is copied to data1.log, and data1.log (if existed) copied to data2.log. The files data.log and data.log1 are used for comparison plotting.
  - e) the basic parameters of the simulation can be given as command line options: in Spyder: Run > Configuration per file > Command line options
  - f) available options are:
    - -i initial\_time
    - -f final\_time
    - -t time\_step
    - -h help
    - -u NewSheet (the sheet in inputs.xlsx where the scenario data is)

- -r return\_timestep (time step for the output data in data.log, default=time\_step)
  - -s silent\_mode (no prompt, using the last used configuration)
5. The options can be put in arbitrary order. For example, the options: -s -i 1995 -f 2050 -t 0.125  
run the code with initial\_time=1995, final\_time=2050, time\_step=0.125 in “silent” mode.
6. Spyder also allows to edit and debug the actual model code written in Python. For further details and documentation see <https://pythonhosted.org/spyder/>



## Running the model in command line

Like any other Python program, it might be run without an IDE, but by executing it as a script in a command line (also called terminal or prompt). Anaconda installation provides its own command line, called Anaconda Prompt.

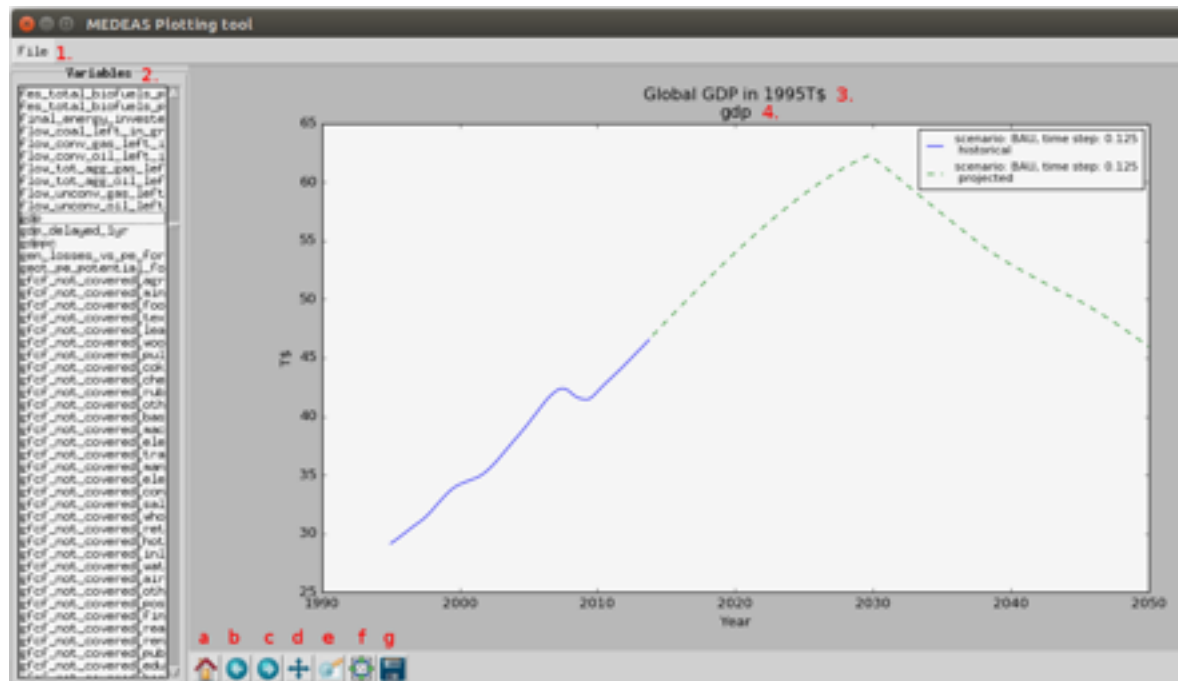
1. In Anaconda Prompt (for Windows) or any other command line/terminal tool (for MacOS or Linux) open the location of pymedeas folder by executing `cd PathTopymedeas/pymdeasFolder`
2. Run the model by executing the command: `python run.py`
3. The running is equivalent to the described in the previous section, part (4). That is, the basic parameters can be set in the command line, for example, the command:
  - `python run.py -i 1995 -s -f 2050`
  - launches a simulation with `initial_time=1995`, `final_time=2050` in the “silent” mode.
4. The last used configuration is kept in `last_output_conf.txt` file together with `run.py` as a list of values (in python notation), comma-separated, spaces ignored. It might be edited manually to add required values, if needed.
5. In the “silent” mode (`-s` option) the output values are chosen from the last configuration, or all the values are kept, if no last configuration available. The run options are taken from the command line (if the options are provided), the rest of the initial configuration is kept by default.

## Plotting

### Command line tool `plot.py`

1. Run `plot.py` in the same fashion as `run.py` (press F5 in Spyder or `python plot.py` from the command line).
2. Enter the required values that you want to plot. The script will plot in a one by one every variable that contains the given string as a part of its name, or exactly the given value, if preceded by `#`. The plot of the next variable emerges upon closing the previous plot window.
3. The input names can also contain free spaces and special symbols, native to the denominations used in the original model, these are translated into the internal Python names automatically, if needed. For example: `#gdp` plots only GDP, while `gdp` plots `GDP`, `GDPpc`, `GDP delayed`, etc.
4. The plot window allows to modify the image (zoom and pan), and export the image in a suitable format.
5. Press a **Enter** to output all available values or e **Enter** to end the execution.
6. In the default configuration, `plot.py` tries to plot the same function from `data.log` and `data1.log` datasets (for comparison). The file `data1.log` contains the results of the penultimate simulation.

## Visual tool `plot_tool.py`



- It can be run from the command line by executing the command `python plot_tool.py` or in Spyder by opening `plot_tool.py` and pressing F5.
- Notice that the tool is also invoked automatically upon the completion of a simulation. Once the tool is launched, a window emerges. The design of the window is given in the screenshot (see Figure).
- In order to load the data, click *File* (mark 1 on Figure), then *Load* and pick the file `data.log`. It contains the results of the last simulation. Notice that any other dataset file can be taken, if needed.
- Pick the variable in the window on the left panel (mark 2). The plot arises on the right side of the window. The historical data (until 2014) is separated visually as a solid line.

- A user can add the variables of most interest in the header of the list by editing medeas\_var.txt file. The variable should be typed in a separate line of this file before '-----' line.
- The title (mark 3) and the units are generated automatically from the available metadata for the chosen variable. The variable name (mark 4) is shown beneath the title.
- The panel on the bottom (buttons a-g) of the window allows to visually modify the image (zoom, pan) and save it in the lossless png format.

## Testing procedure

1. Create a log file: *log-pymedeas-<version>-<your name or organization>.docx*
2. Save the parameters of your system in the header of the log file. These include the OS version and the general description of your computer, if known (example: *Windows 10, quad-core Intel Core i5 2.5 GHz*).
3. Keep in the log file the user experience, your comments, suggestions in a structured format:
  - a) Installation: whether any installation procedure steps failed, error output, did you manage to solve it by yourself and how.
  - b) Running: failed runs (with initial parameters and error output), did you manage to solve the problem by yourself and how, incorrect results and similar.
  - c) Input/output: IO errors, suggestions to improve IO.
  - d) Visualization: wrong graphs, suggestions to improve the visualization
  - e) Running time in the format: *initial\_time, final\_time, time\_step, total\_time*
  - f) Other comments and suggestions
  - g) Add your own chapters if you like.
4. It is strongly recommended to add screenshots to the documents to clarify the matter, if an issue arises.

## License

Copyright (C) 2018 MEDEAS Project.

Permission is granted to copy, distribute and/or modify this document under the terms of the GNU Free Documentation License, Version 1.3 or any later version published by the Free Software Foundation; with no Invariant Sections, no Front-Cover Texts, and no Back-Cover Texts. A copy of the license is included in the section entitled "GNU Free Documentation License".

## References

<https://github.com/JamesPHoughton/pysd>

<https://www.anaconda.com/download>

<https://pythonhosted.org/spyder/>

<https://pypi.python.org/pypi/parsimonious/>

<http://xarray.pydata.org/en/stable/plotting.html>

[pysd-cookbook.readthedocs.io/](https://pysd-cookbook.readthedocs.io/)

[http://pysd-cookbook.readthedocs.io/en/latest/analyses/getting\\_started/Hello World Teacup.html](http://pysd-cookbook.readthedocs.io/en/latest/analyses/getting_started>Hello World Teacup.html)

## 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

*Authors:* University of Valladolid

Iñigo Capellán-Pérez

Ignacio de Blas

Jaime Nieto

Carlos de Castro

Luis Javier Miguel

Margarita Mediavilla

Óscar Carpintero

Paula Rodrigo

Noelia Ferreras Alonso

Fernando Frechoso

Santiago Cáceres

*Dissemination level:* Public



## 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.

## Annex List of abbreviations and acronyms

BAU: Business-as-usual

BECCS: Bioenergy and CCS

BEV: Battery electric vehicle

BG: Best 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

EROI<sub>ext</sub>: EROI extended

EROI<sub>pou</sub>: EROI point of use

EROI<sub>st</sub>: EROI standard

ESOI: Energy stored on energy invested

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



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



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

## 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 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.
- 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 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.

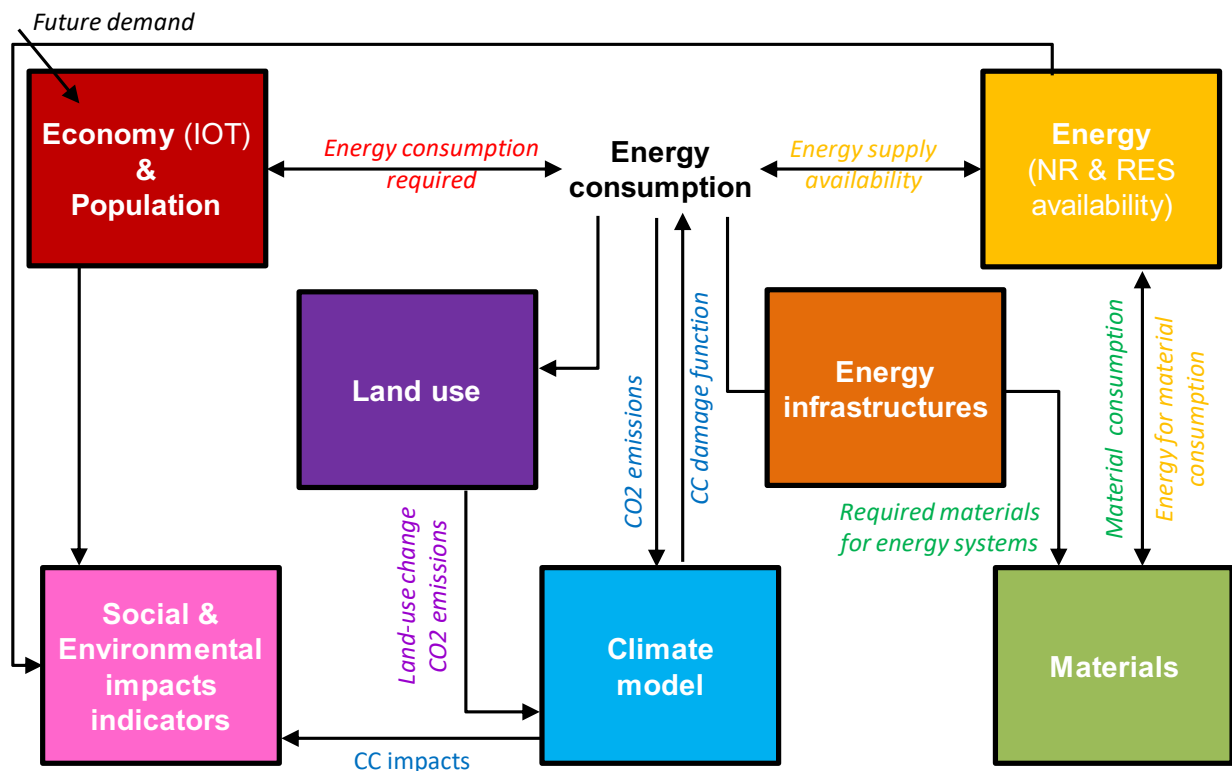


Figure 1: Overview of MEDEAS-World by modules and the modelled linkages between them

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.

- 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.



# 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

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.

## 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)

## 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 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.
- **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.

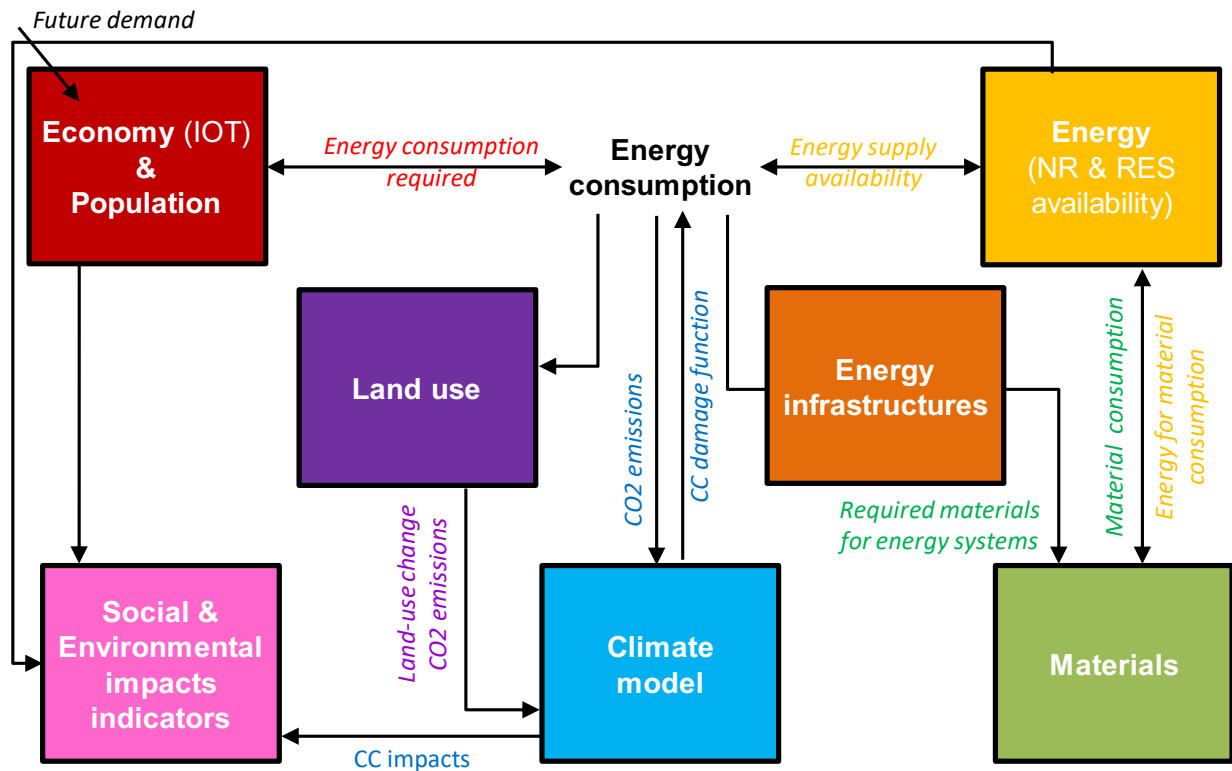


Figure 2: Overview of MEDEAS-World by modules and the modelled linkages between them

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 through 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

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.

## 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\$<sup>1</sup> 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-Output 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.

---

<sup>1</sup> Note: all dollars in MEDEAS refer to constant 1995\$US.

## 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 were dominant, critical remarks 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, 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 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, 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.

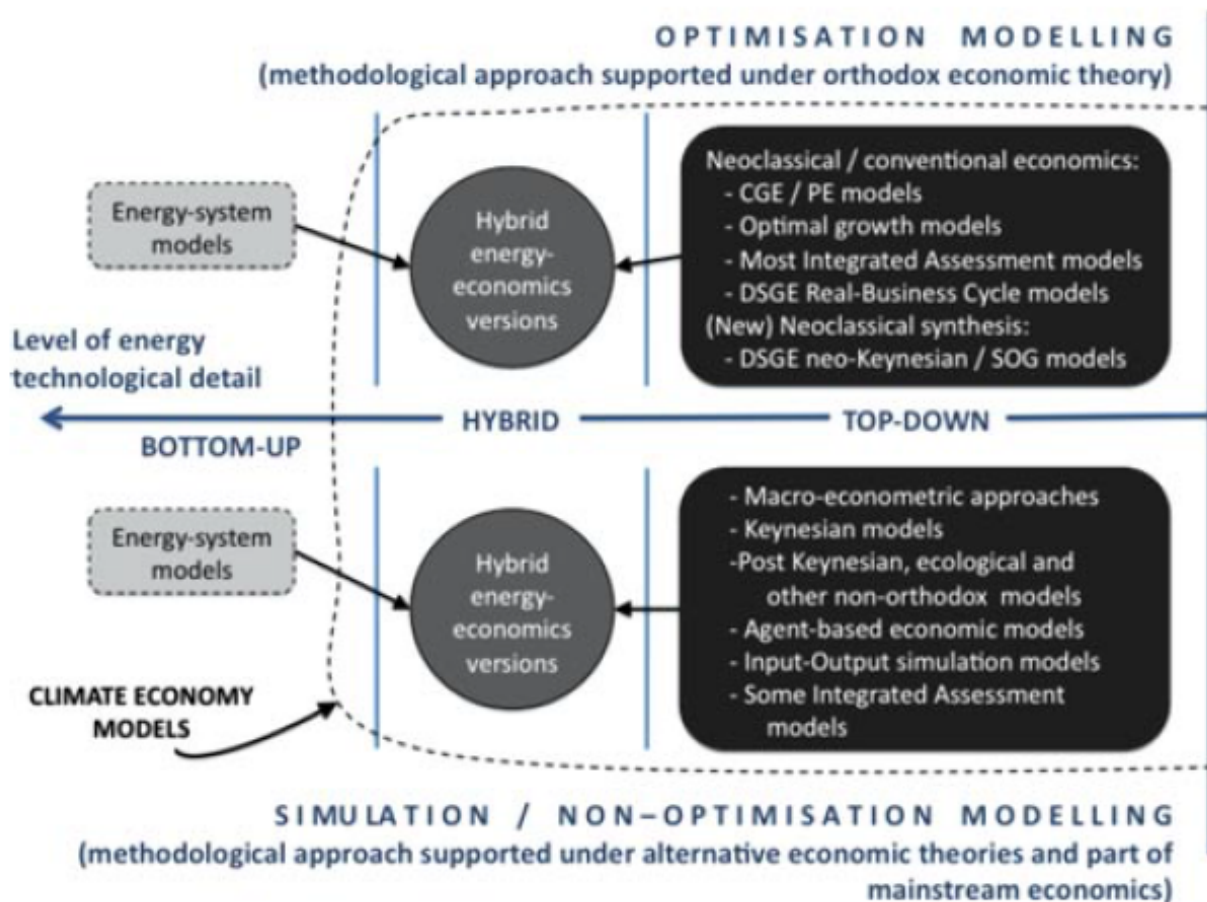


Figure 3. Macro-economic modelling in IAMs. Source: (Scrieciu et al., 2013b)

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 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).

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

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).

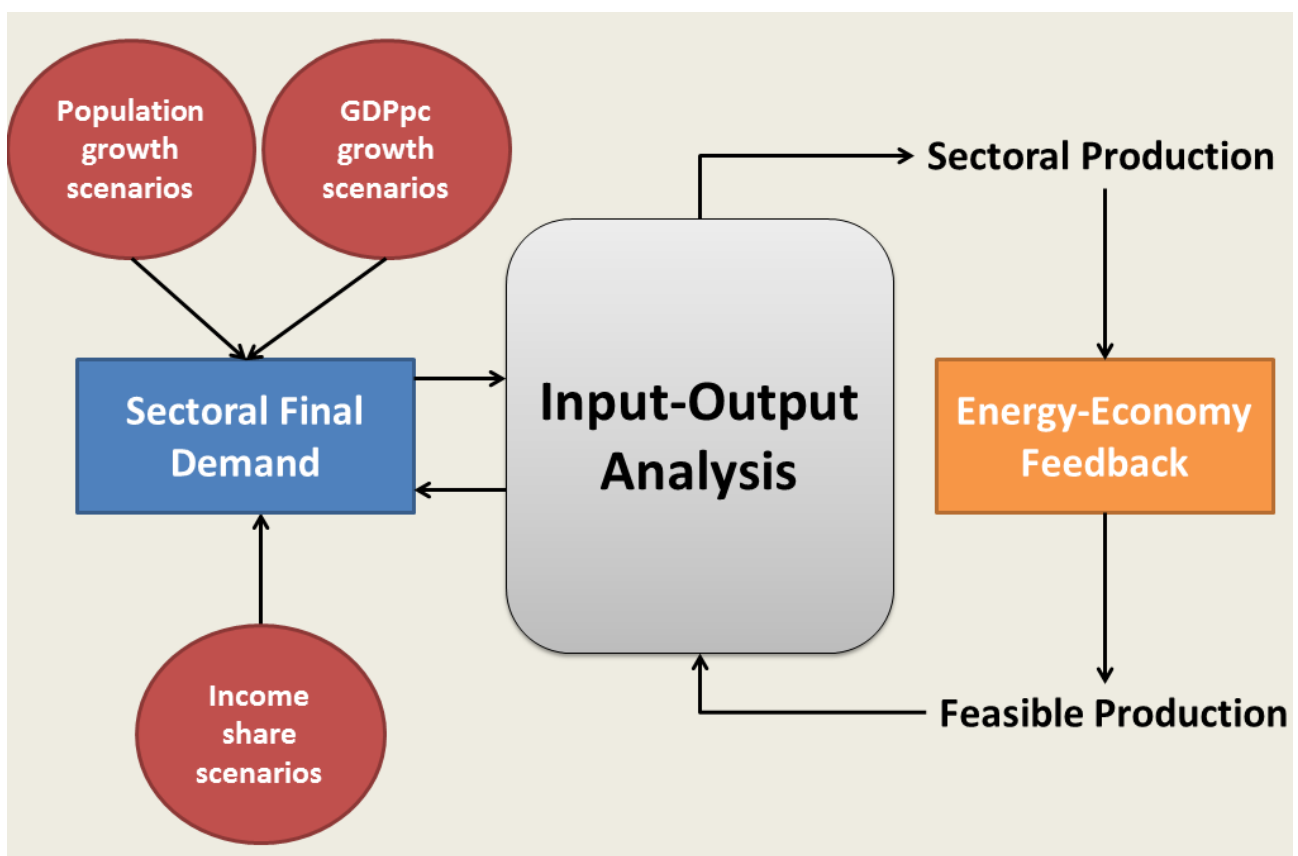


Figure 4. Schematic overview of MEDEAS Economy module. Own elaboration

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.

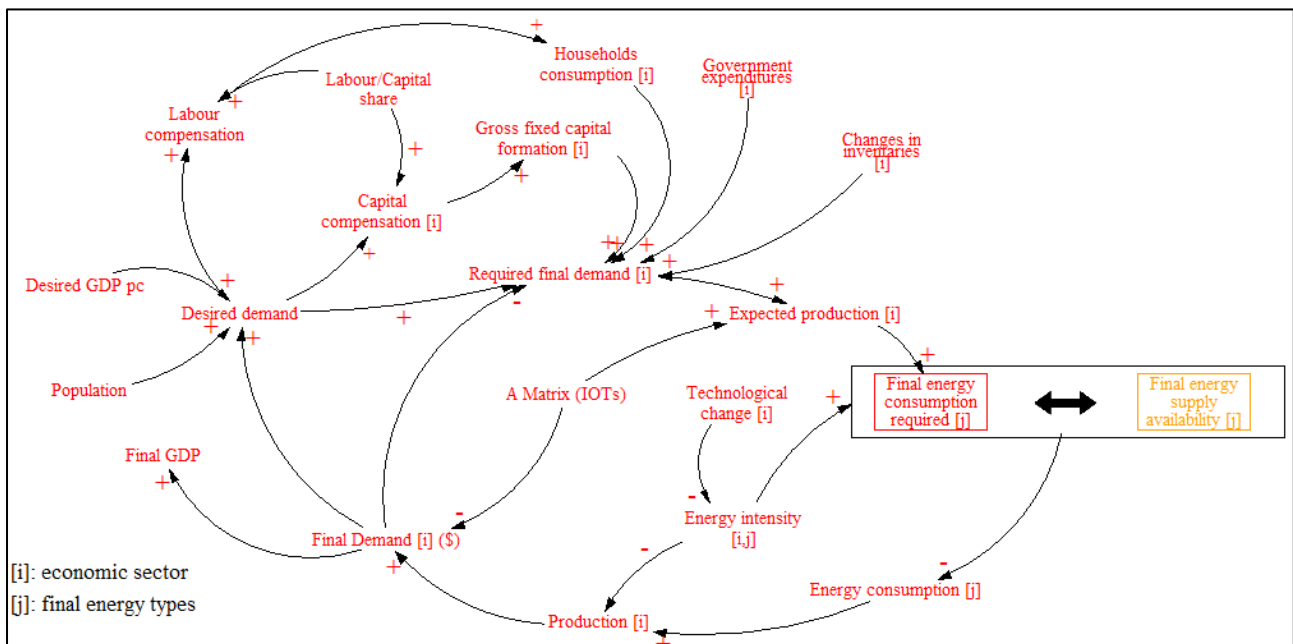


Figure 5. Causal loop map of MEDEAS Economy module. Source: own elaboration.

## 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:

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

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:

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

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:

$$\ln HH_i = \beta_0 + \beta_{1,i} Sec_i + \beta_2 \ln LAB. \quad i \in 1...35$$

$$\ln GFCF_i = \beta_0 + \beta_{1,i} Sec_i + \beta_2 \ln CAP_i. \quad i \in 1...35$$

$Sec_i$  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  $\beta_1$  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 spent 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.  $\beta_0$  value is that in the first column (Coef.) and the last row (\_cons).  $\beta_1$  values are given in the first column (Coef.) from sector 2 to 35. For sector 1,  $\beta_1$  is always



equal to 0.  $\beta_2$  is provided by the value in the first column and first row (log\_labworld for Lab and log\_capworld for Cap). All  $\beta_1$  are significant at 5%, but sectors 6 and 19 for GFCF and, in that cases,  $\beta_1$  equals 0.

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

log_hh	Panel-corrected					
	Coef.	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					

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

log_fbc	Panel-corrected					[95% Conf. Interval]
	Coef.	Std. Err.	z	P> z		
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					

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:

$$GDP = FD = \sum GVA$$

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

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).<sup>2</sup> 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  $1 - \alpha_{lab}$ . 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.

---

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

Table 4. Income share scenarios

Scenario	Labour share (2050)	Capital share (2050)
<b>BAU</b>	52%	48%
<b>Increased inequality</b>	45%	55%
<b>Decreased inequality</b>	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:

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

### 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				Interregional IOT						
Industry demand	Final demand		Total	Industry demand			Final demand			Total
$IC^N$	$FD^N$	$FD^{FN}$	$X^N$	$IC^{1,1}$	$IC^{1,...}$	$IC^{1,n}$	$FD^{1,...}$	$FD^{1,1}$	$FD^{1,n}$	$X^1$
$IC^F$	$FD^{NF}$			$IC^{...,1}$	$IC^{...,...}$	$IC^{...,n}$	$FD^{...,1}$	$FD^{...,...}$	$FD^{...,n}$	$X^{...}$
				$IC^{n,1}$	$IC^{n,...}$	$IC^{n,n}$	$FD^{n,1}$	$FD^{n,...}$	$FD^{n,n}$	$X^n$
$VA^N$				$VA^1$	$VA^{...}$	$VA^n$				
$X^N$				$X^1$	$X^{...}$	$X^n$				

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 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.

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



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:

$$\Delta X = L \Delta FD$$

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.

### 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:

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

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

Let's  $\hat{e}$  be the diagonal matrix of energy coefficients and  $\hat{E}$  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).

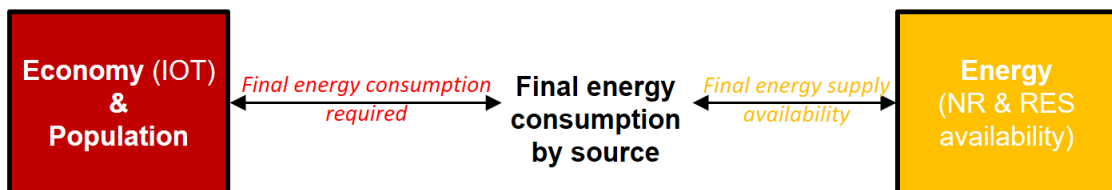


Figure 8. Energy-Economy feedback in MEDEAS. Source: own elaboration.

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:

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

$$\text{If shortage coefficient}_j \left\{ \begin{array}{l} = 1: \text{no energy constraints} \\ < 1: \text{energy constraints of fuel } j \end{array} \right.$$

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

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

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 ( $\hat{I}_e^{-1}$ ) 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.

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

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

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

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.

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

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.

## 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  $E = I_e \times E_o$ . 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 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.

## 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.

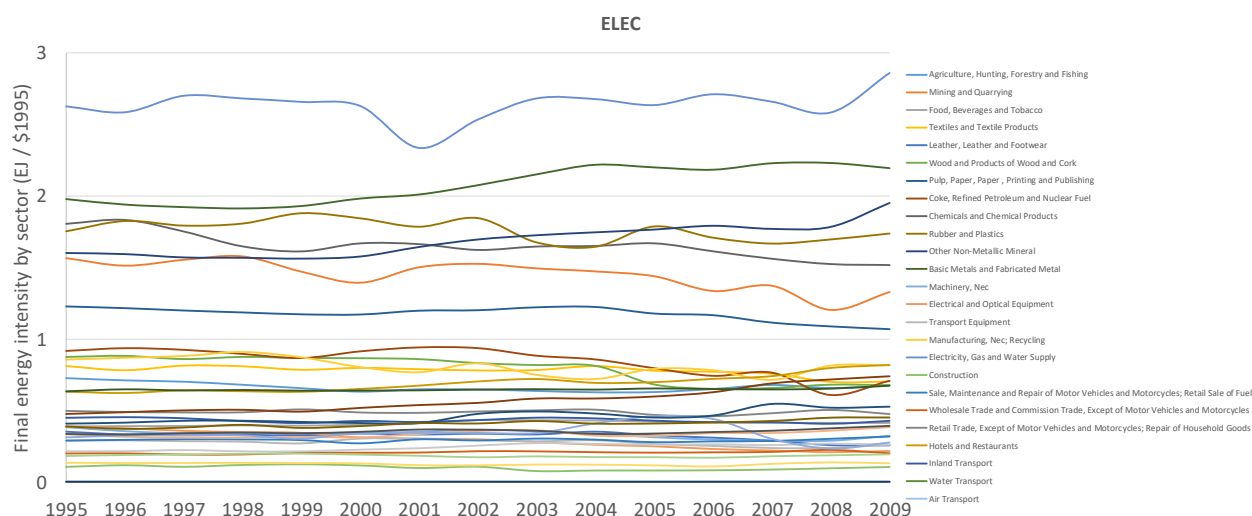


Figure 9: Historical evolution of electricity intensity by sector for the period 1995-2009. Source: WIOD and own work.

### 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 ( $I_t$ ) decreases each year at a constant rate ( $a=1-AEI$ ) in relation to the previous year ( $I_{t-1}$ ):

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

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.

<b>OLS for the estimation of the model: <math>I(t)=a*I(t-1)</math></b>	<b>ELEC</b>	<b>HEAT</b>	<b>LIQUIDS</b>	<b>GASES</b>	<b>SOLIDS</b>
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 Motorcycles	0,9996	0,9809	0,9587	0,9727	0,9210
Retail Trade, Except of Motor Vehicles and Motorcycles; Repair of Household Goods	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.

#### 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:

$$a' = a - 1$$

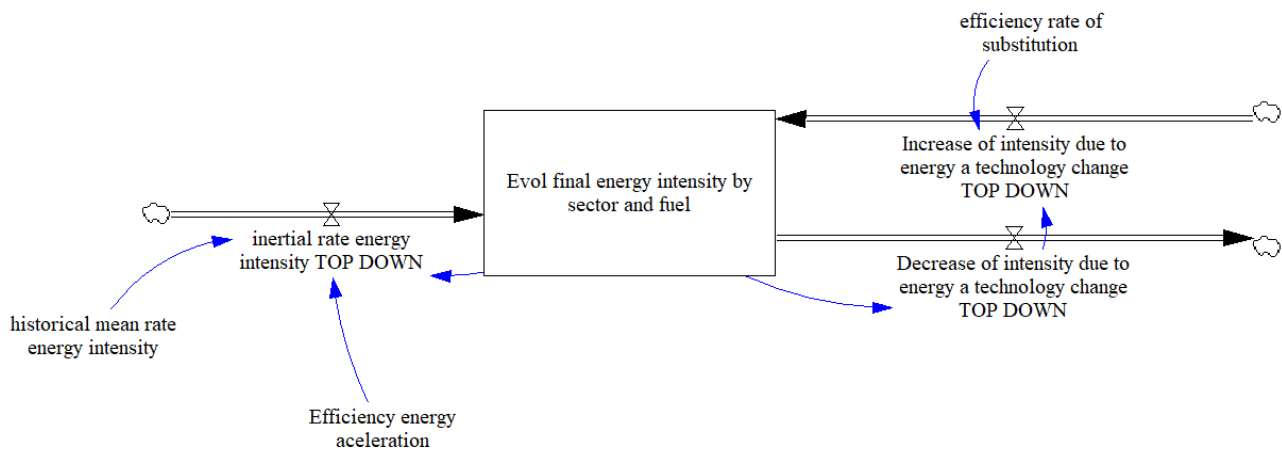


Figure 11: Simplified structure of the energy intensities model.

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

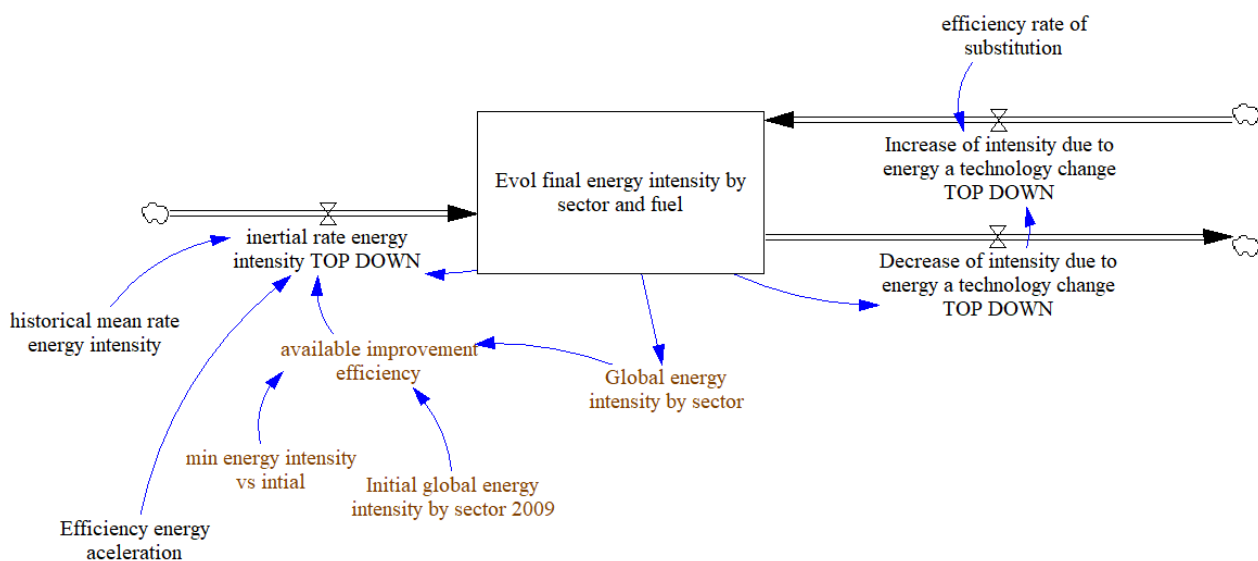


Figure 12: Simplified structure of the energy intensities model with a limit in energy intensity.

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).

$$\text{Available improvement efficiency} = \frac{\text{IF THEN ELSE}(\text{Time} < 2009, 1, (\text{Global energy intensity by sector} - (\text{min energy intensity vs initial} * \text{Initial global energy intensity by sector 2009})))}{(1 - \text{min energy intensity vs initial}) * \text{Initial global energy intensity by sector 2009}}$$

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.

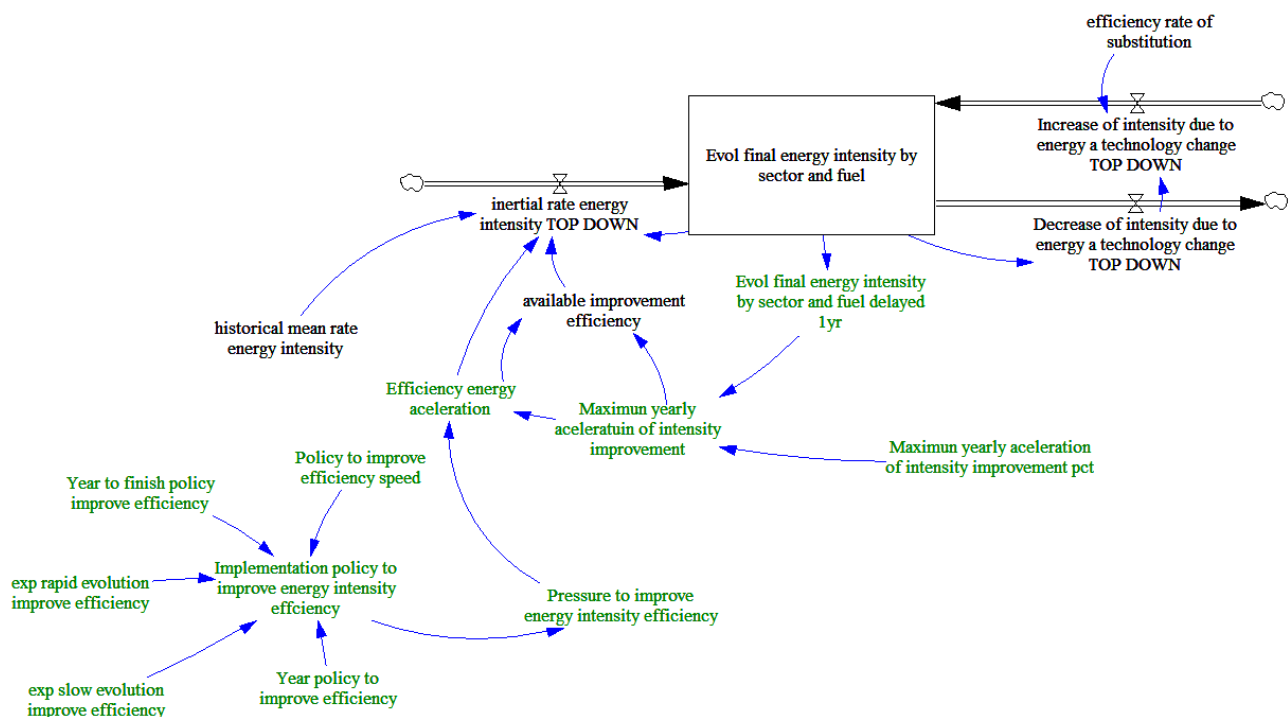


Figure 13: Simplified structure of the energy intensities model with efficiency energy acceleration.

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

### *Inertial rate energy intensity TOP DOWN*

$$= \text{Evol final energy intensity by sector and fuel} \\ * (\text{historical mean rate energy intensity} \\ + \text{Efficiency energy aceleration}) * \text{available improvement efficiency}$$

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.

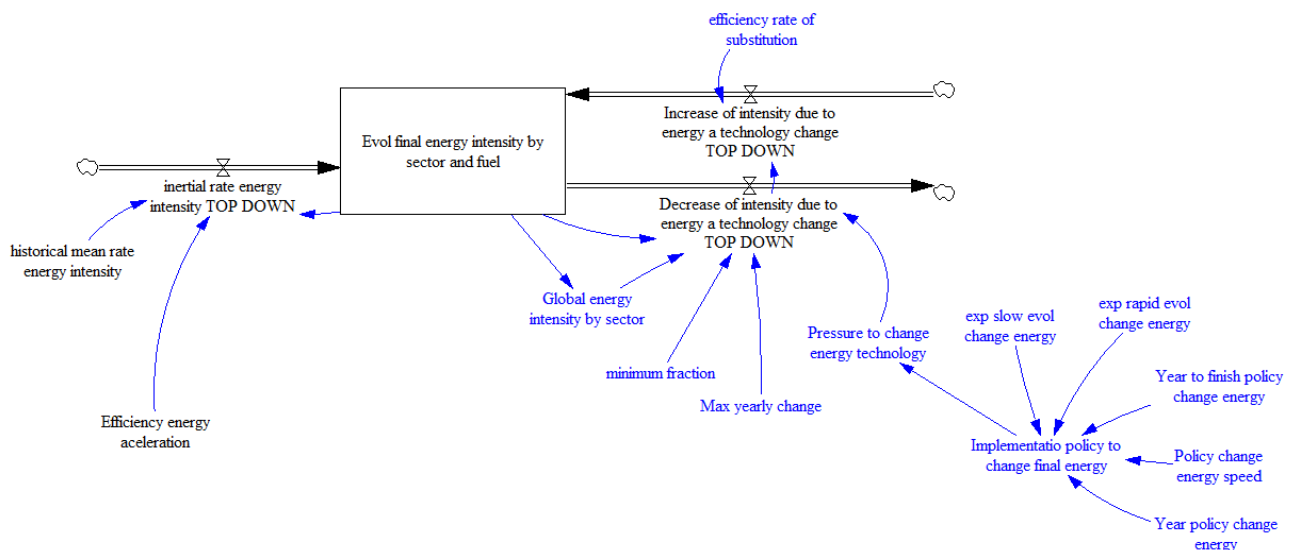


Figure 14: Simplified structure of the energy intensities model with the change in energy source.

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



## 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.<sup>3</sup>

---

<sup>3</sup> 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).

## 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-bituminous 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

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 (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.

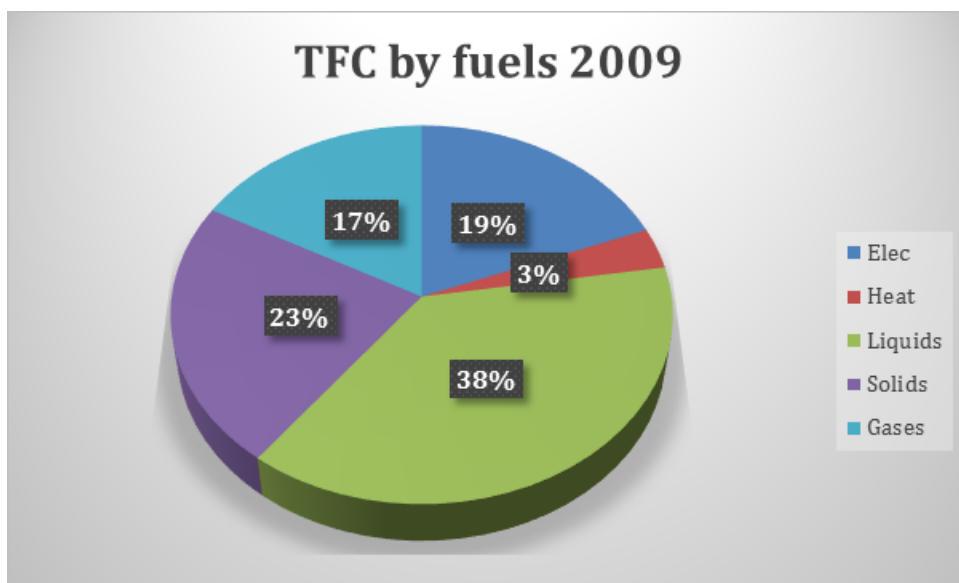


Figure 15: TCF by fuels 2009. Source: WIOD database.

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

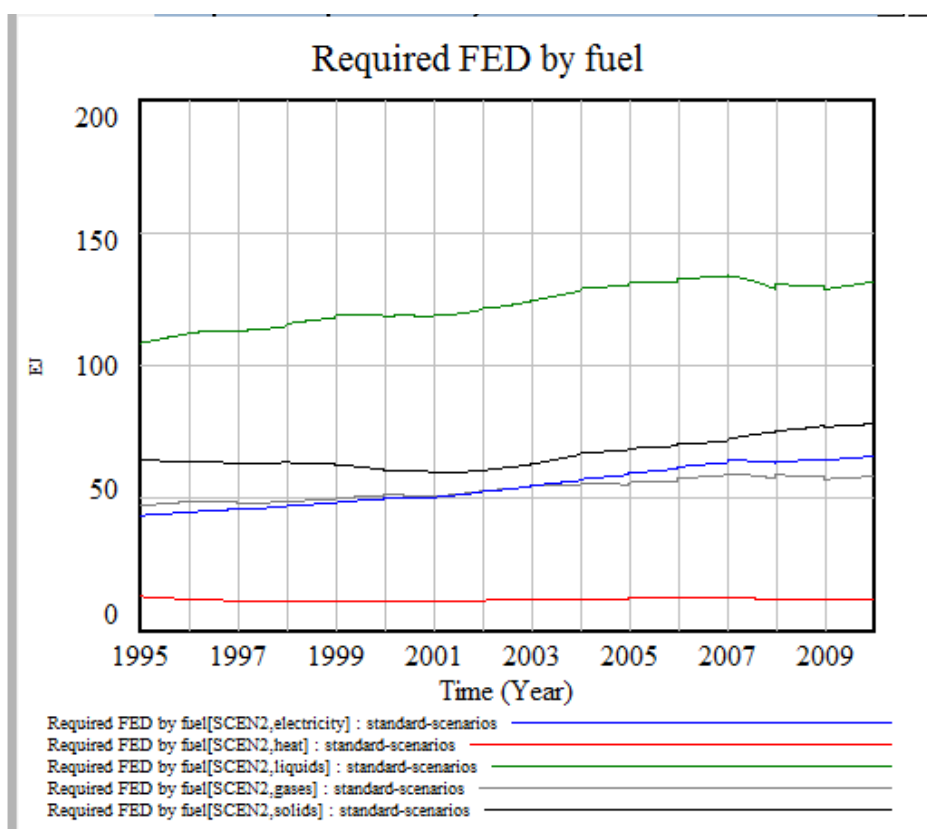


Figure 16: Historic FED by fuel after adjusting WIOD data from IEA balances. Heat refers solely to commercial heat.

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).

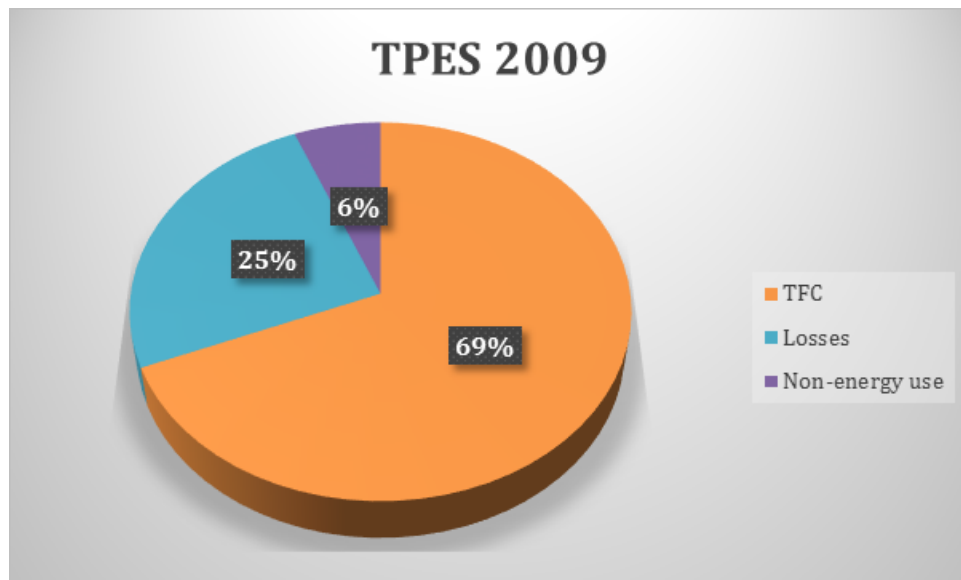


Figure 17: TPES 2009. Source: (IEA, 2018).

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

### 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:

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

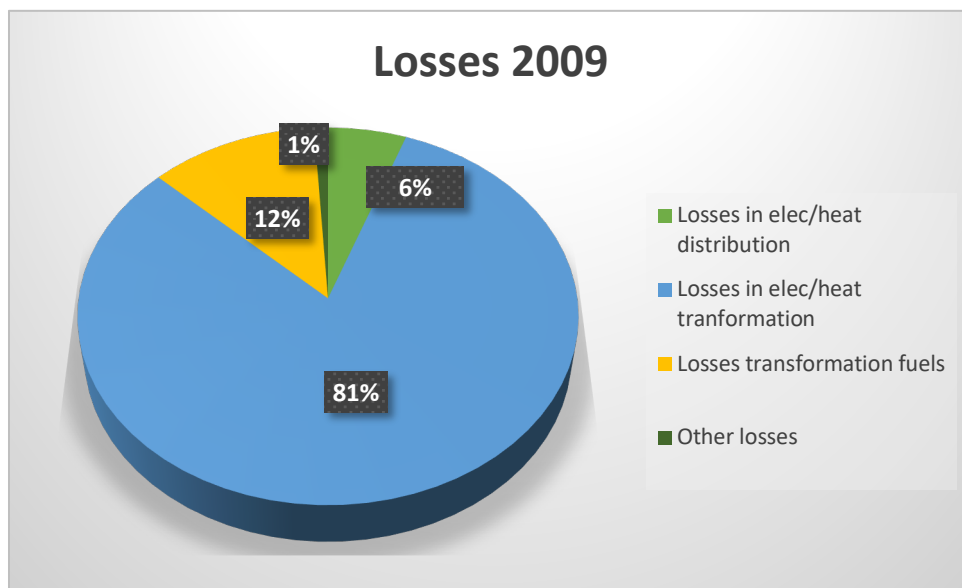


Figure 18: Losses in 2009. Source: (IEA, 2018).

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.

Table 7. Parameters for the modelling of energy distribution losses

	<b>MEAN</b>	<b>SDEVIATION</b>
<b>COAL share dist. losses vs total extraction</b>	0.00159169	0.00112364
<b>OIL share dist. losses vs total extraction</b>	0.00162263	0.0001716
<b>NAT GAS share dist. losses vs total extraction</b>	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.

	<b>MEAN</b>	<b>SDEVIATION</b>
<b>OIL share transf. losses vs total extraction</b>	0.01172461	0.00302965
<b>COAL share transf. losses vs total extraction</b>	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 Blast 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 transformation 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.



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

	<b>MEAN</b>	<b>SDEVIATION</b>
<b>Ratio gain gas vs lose solids in tranf processes</b>	-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 processes. In this way we will obtain a more realistic approximation and even better to the actual approximation in which we have assumed several hypothesis.

### 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).

Figure 19 shows the obtained modified energy demands accounting for non-commercial heat for the historical period 1995-2009. It can be observed that after the adjustment, 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.

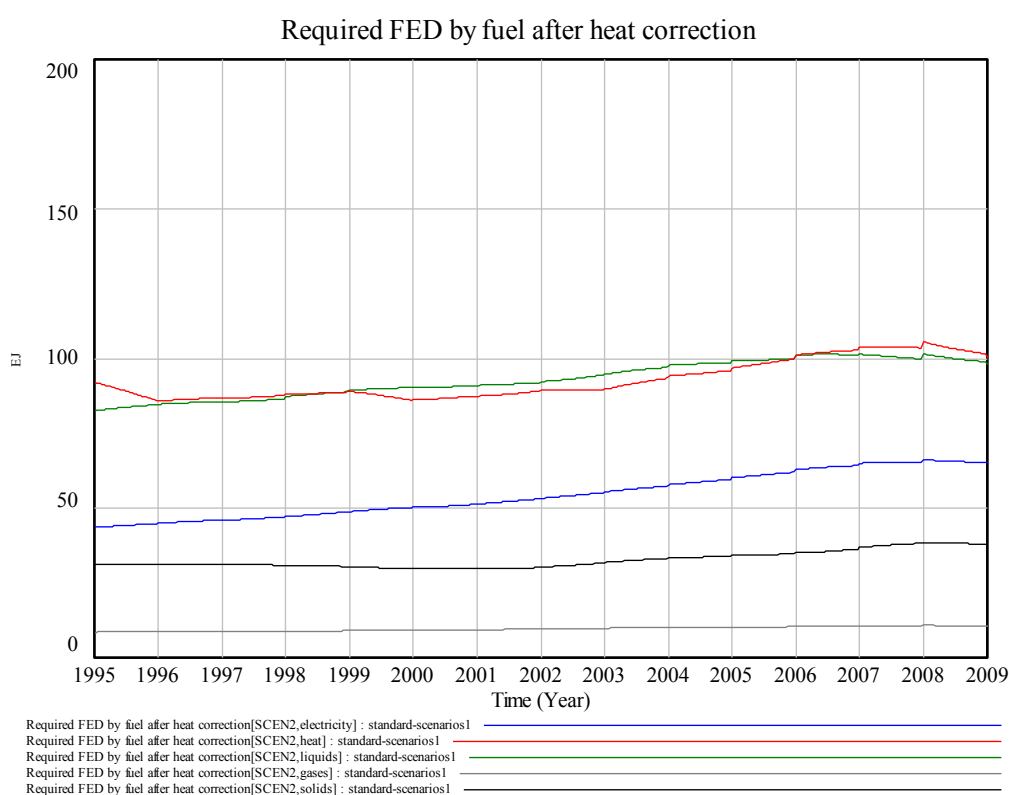


Figure 19: FED by fuel after heat correction

## 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

		Waste
	RES	Geothermal
		Solar
		Solid biomass
		Biogas

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

---

<sup>4</sup> 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).

### 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! Reference source not found.**). 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.

### 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.

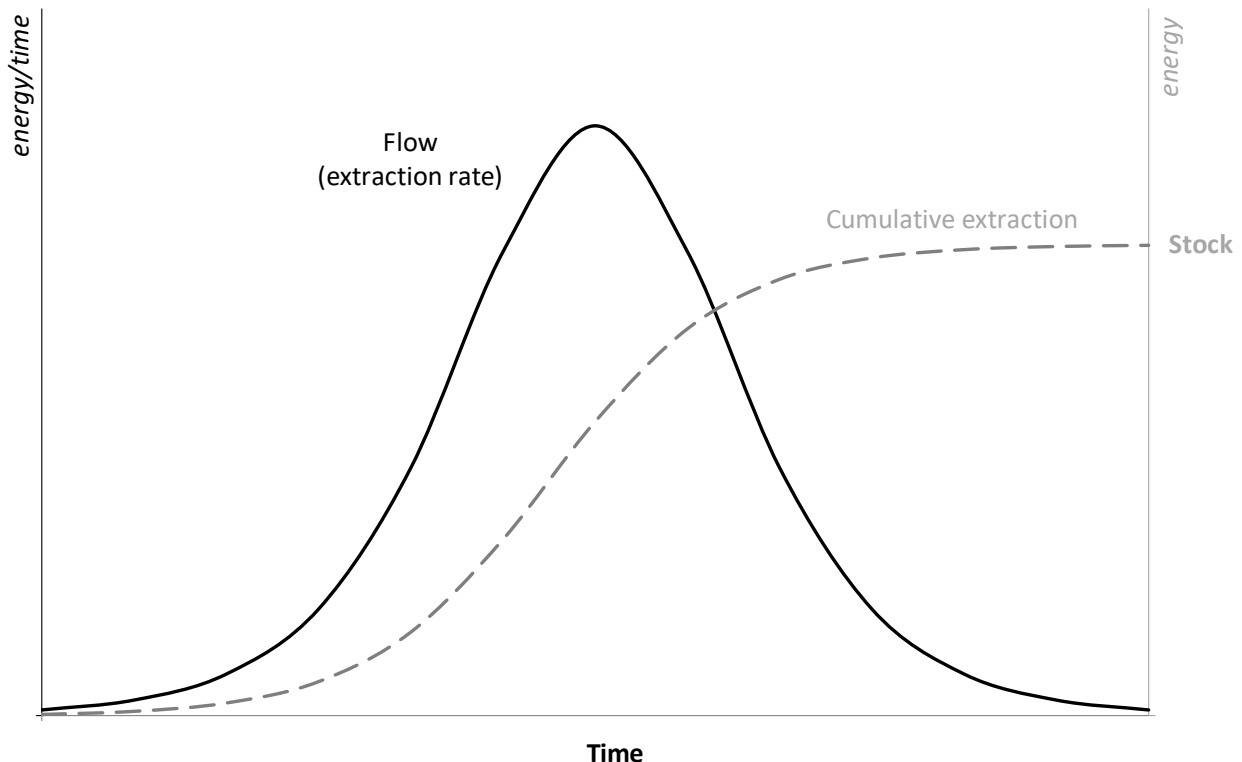


Figure 20 : (Kerschner and Capellán-Pérez, 2017): Simplified representation of the depletion of a non-renewable resource in the absence of non-geologic constraints. Stocks and flows of energy relative to time.

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  $t$ :

$$RURR_t = URR - cumulative\_extraction_t$$

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 (Alekklett 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).

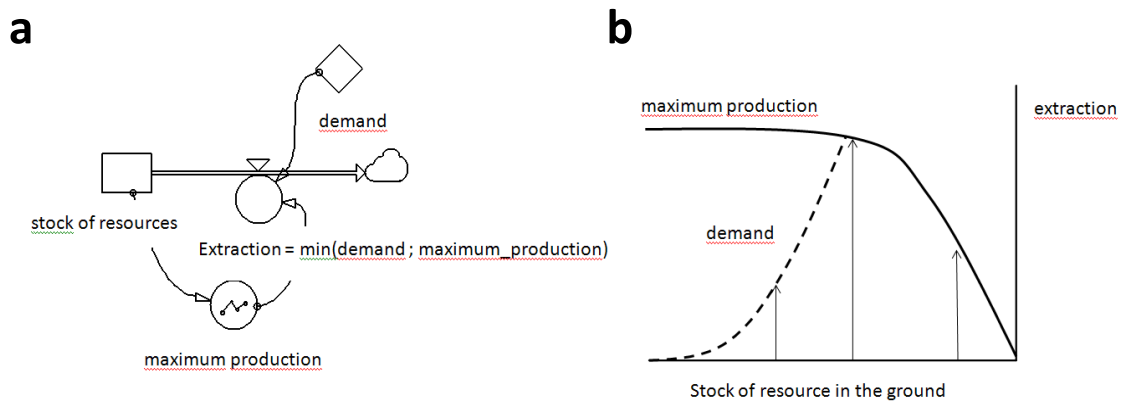




Figure 21 : (Mediavilla et al., 2013): Integration of depletion curves in the model. (a) SD model. (b) A curve of maximum extraction (solid) compared with the demand (dashed).

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).

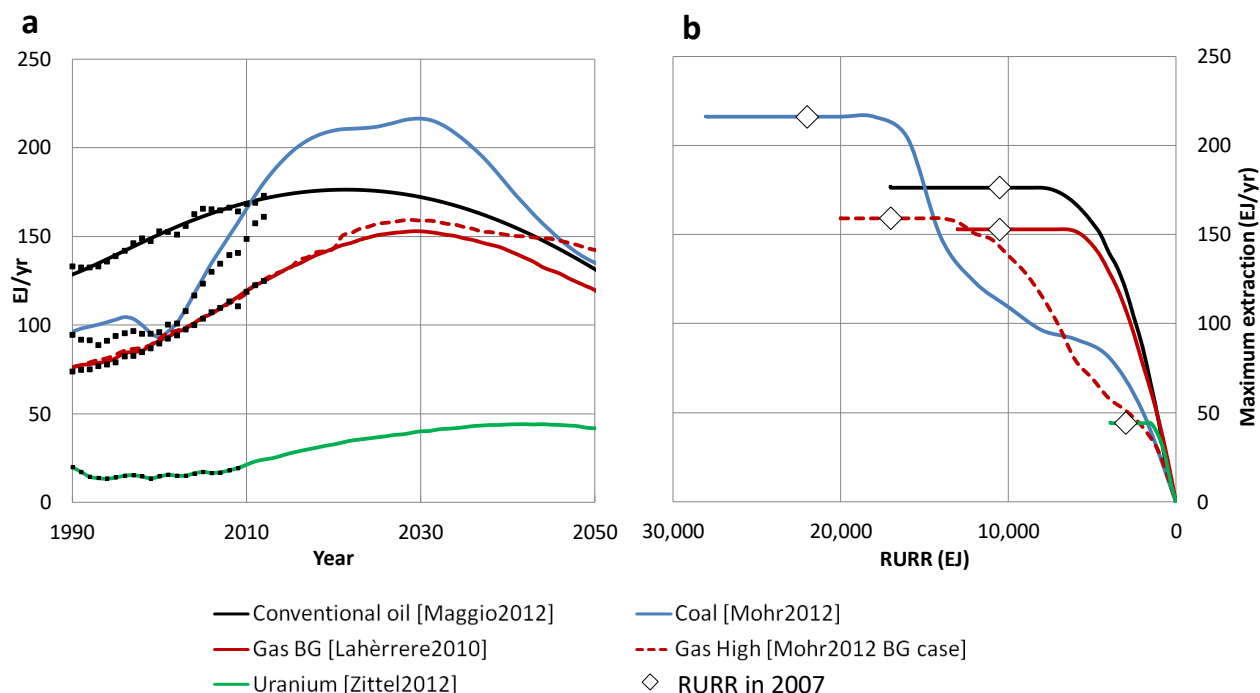


Figure 22 : (Capellán-Pérez et al., 2014): Non-renewable primary energy resources availability: (a) depletion curves as a function of time from the original reference; (b) curves of maximum extraction in function of the RURR as implemented in the model. The y-axis represents the maximum achievable extraction 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).

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! Reference source not found.**).

### 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.

### 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 (Alekklett 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.<sup>5</sup> Alekklett 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.

---

<sup>5</sup> 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.

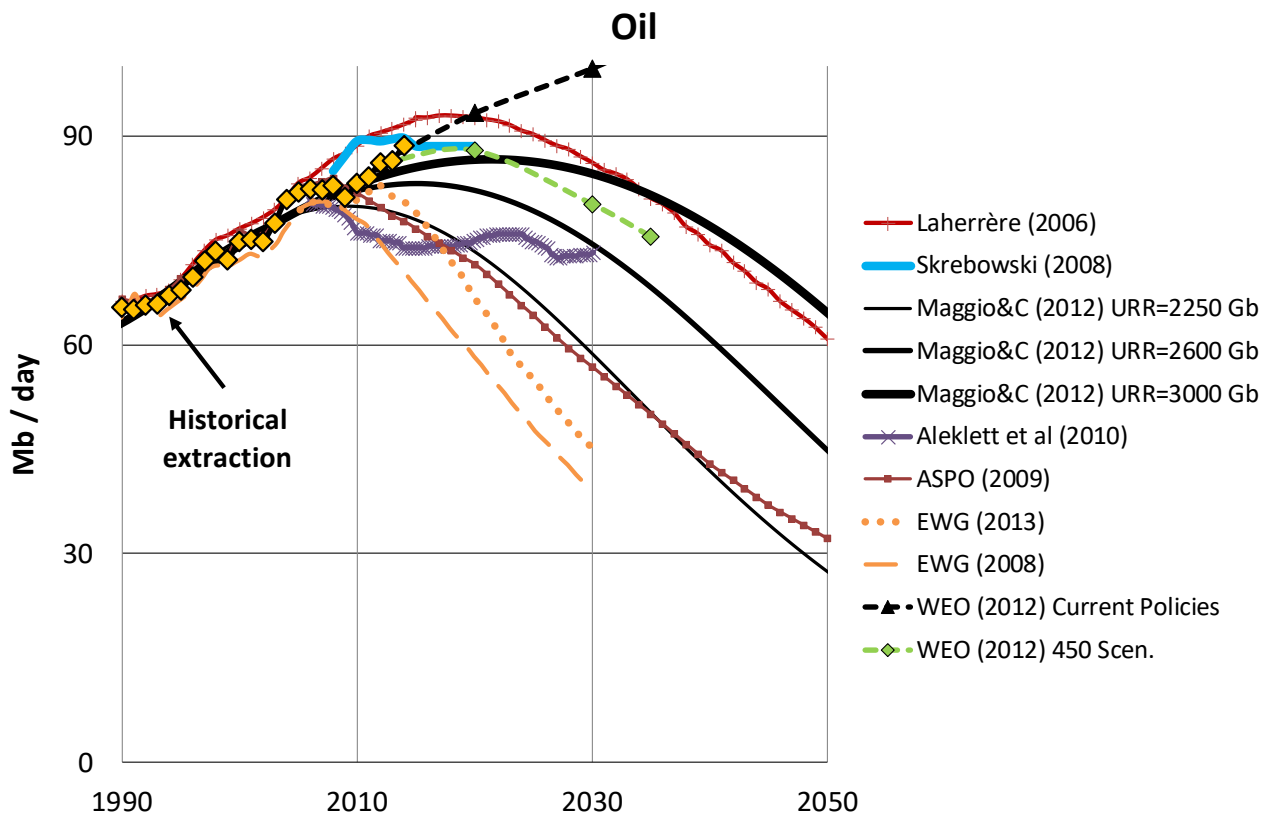


Figure 23: Depletion curves for oil by different authors and comparison with (WEO, 2012) scenarios “Current Policies” and “450 Scenario”. Historical data (1990-2014) from BP (2015). There is a lack of standardization in the literature. For each study, “oil” refers to only crude oil (including NGLs) (Maggio 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).

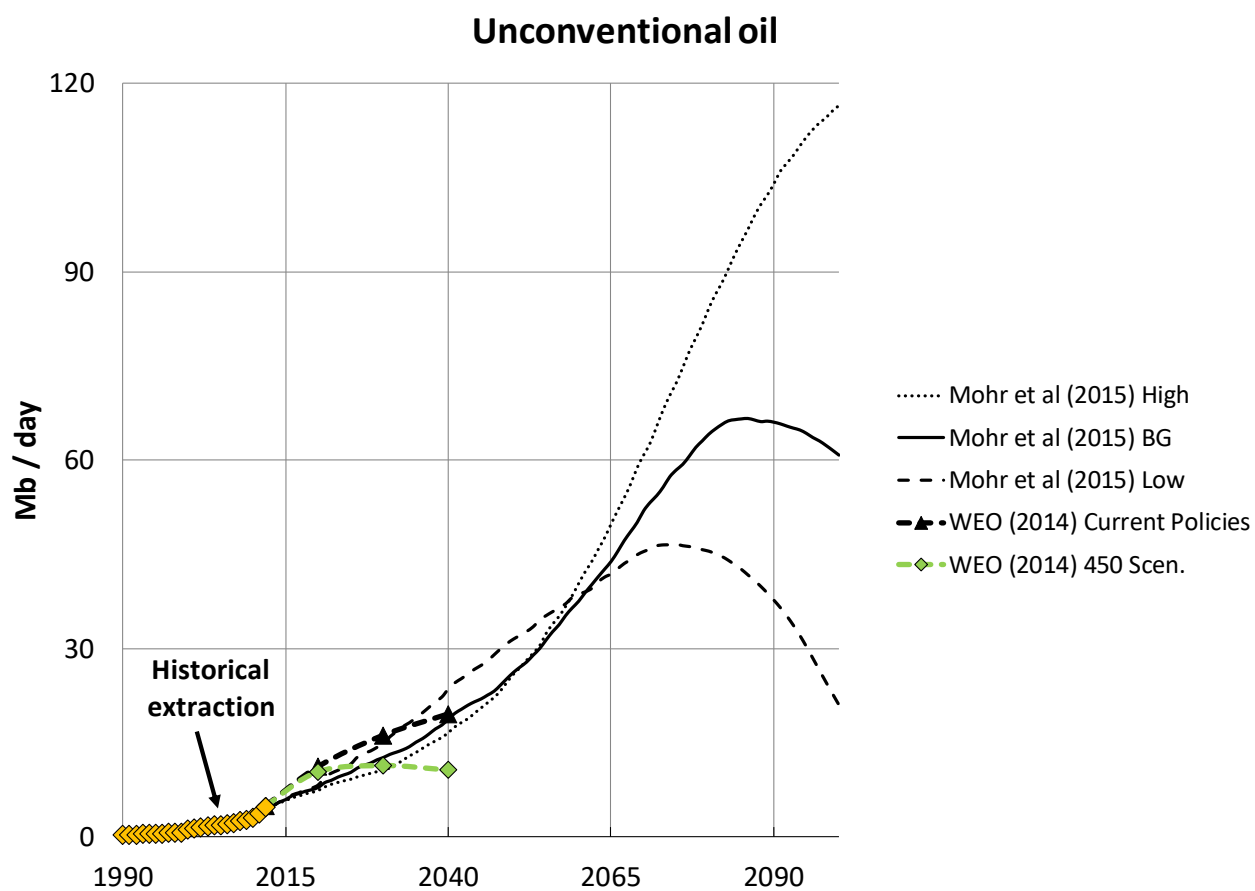


Figure 24: Depletion curves for unconventional oil from Mohr et al. (2015), WEO (2014) projections and historical extraction (1990-2012) from Mohr et al (2015).

### 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. Laherrère'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 Laherrère (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.

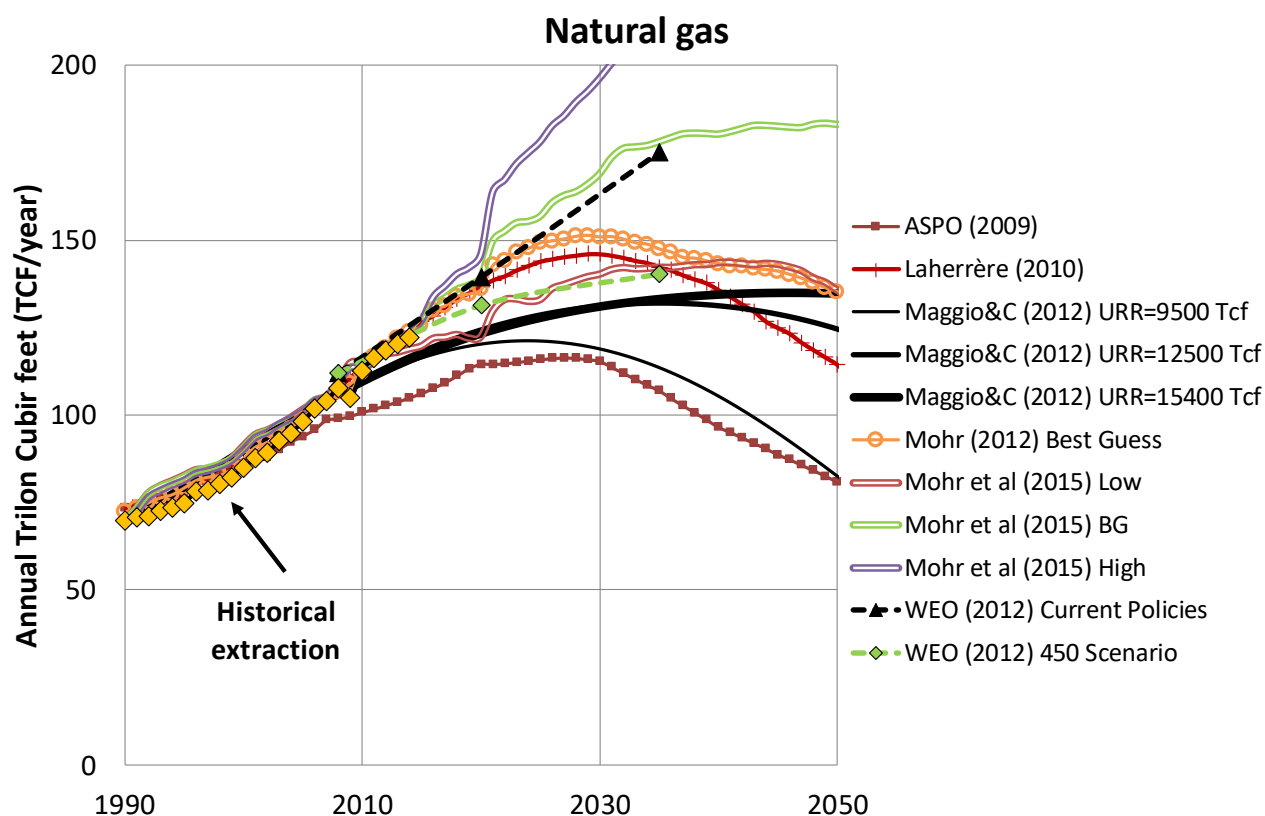


Figure 25: Estimations of total natural gas extraction by different authors and comparison with (WEO, 2012) scenarios "Current Policies" and "450 Scenario". Historical data (1990-2014) from BP (2015).

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).



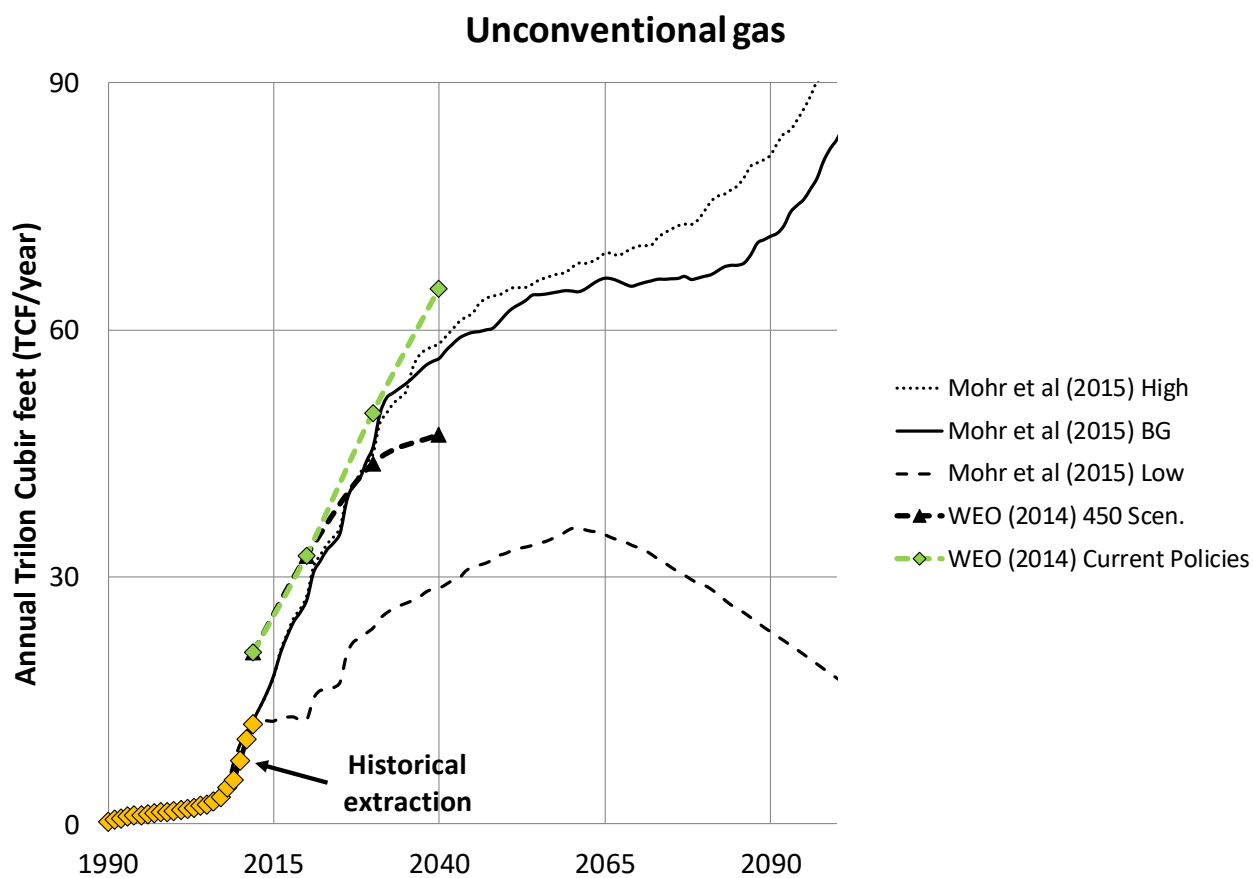


Figure 26: Estimations of unconventional natural gas extraction from Mohr et al (2015), WEO (2014) projections and historical extraction (1990-2012) from Mohr et al (2015).

## Natural gas energy content per volume

Gas reserves are usually reported in volume units (e.g. tcf<sup>6</sup>). 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*.

<sup>6</sup> tcf: trillion cubic feet, that equals  $10^3$  bcf ( $10^9$  cf).

### 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)).

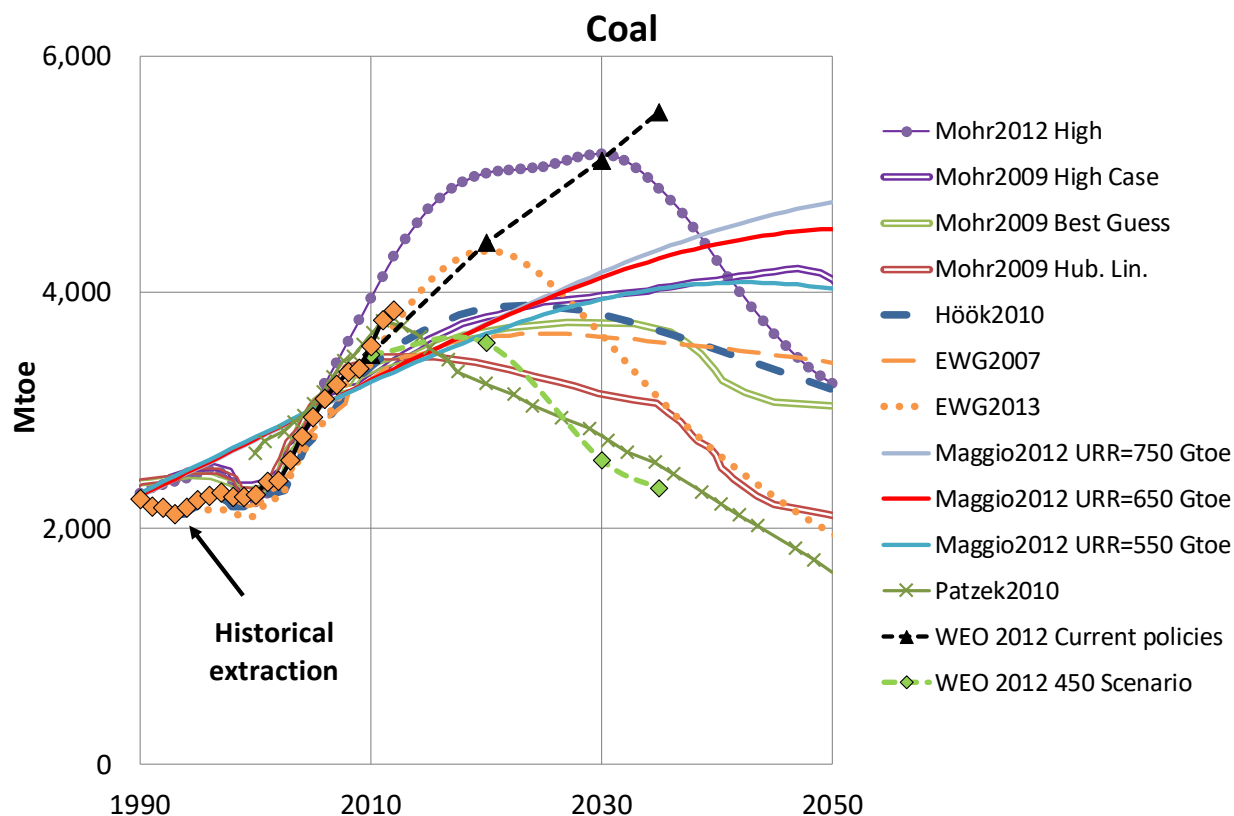


Figure 27: Estimations of coal extraction by different authors and comparison with (WEO, 2012) scenarios “Current Policies” and “450 Scenario”. Historical data (1990-2014) from BP (2015). (1 Mt = 0.4844 Mtoe (Höök et al., 2010)).

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”.

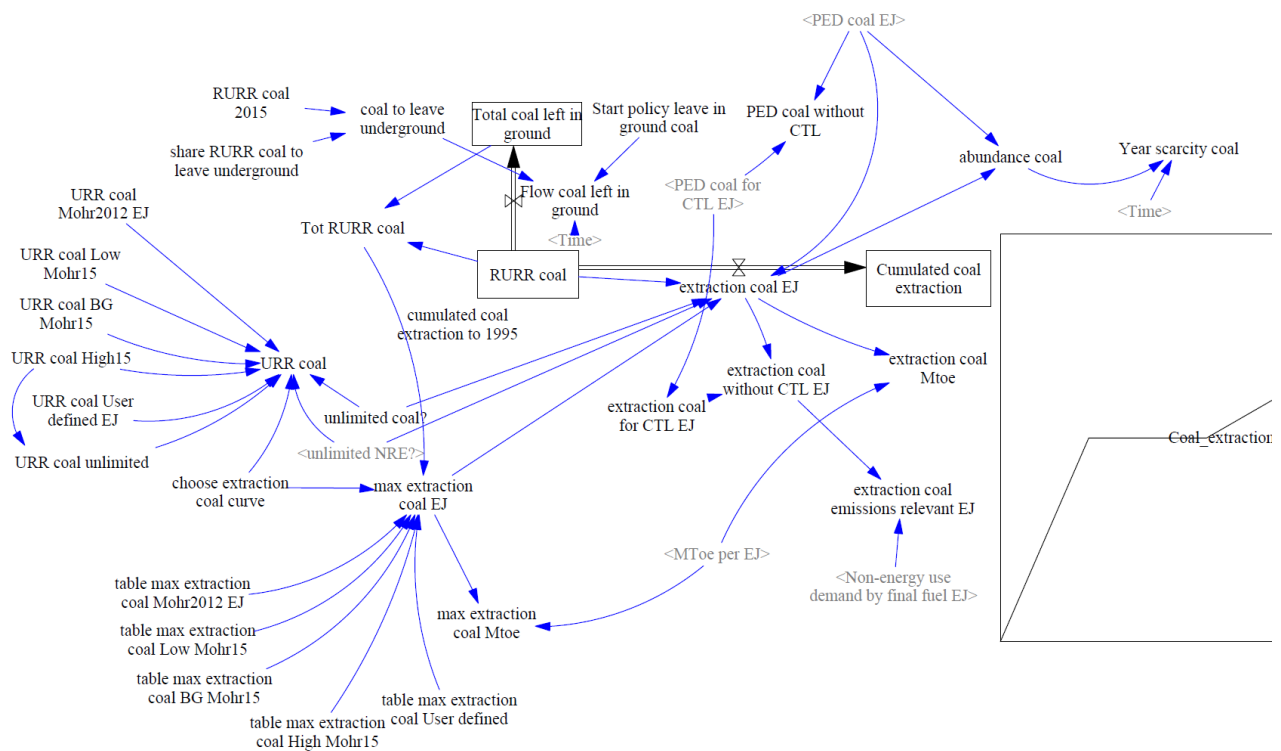


Figure 28: Stock and flow map diagram of coal extraction.

### 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).

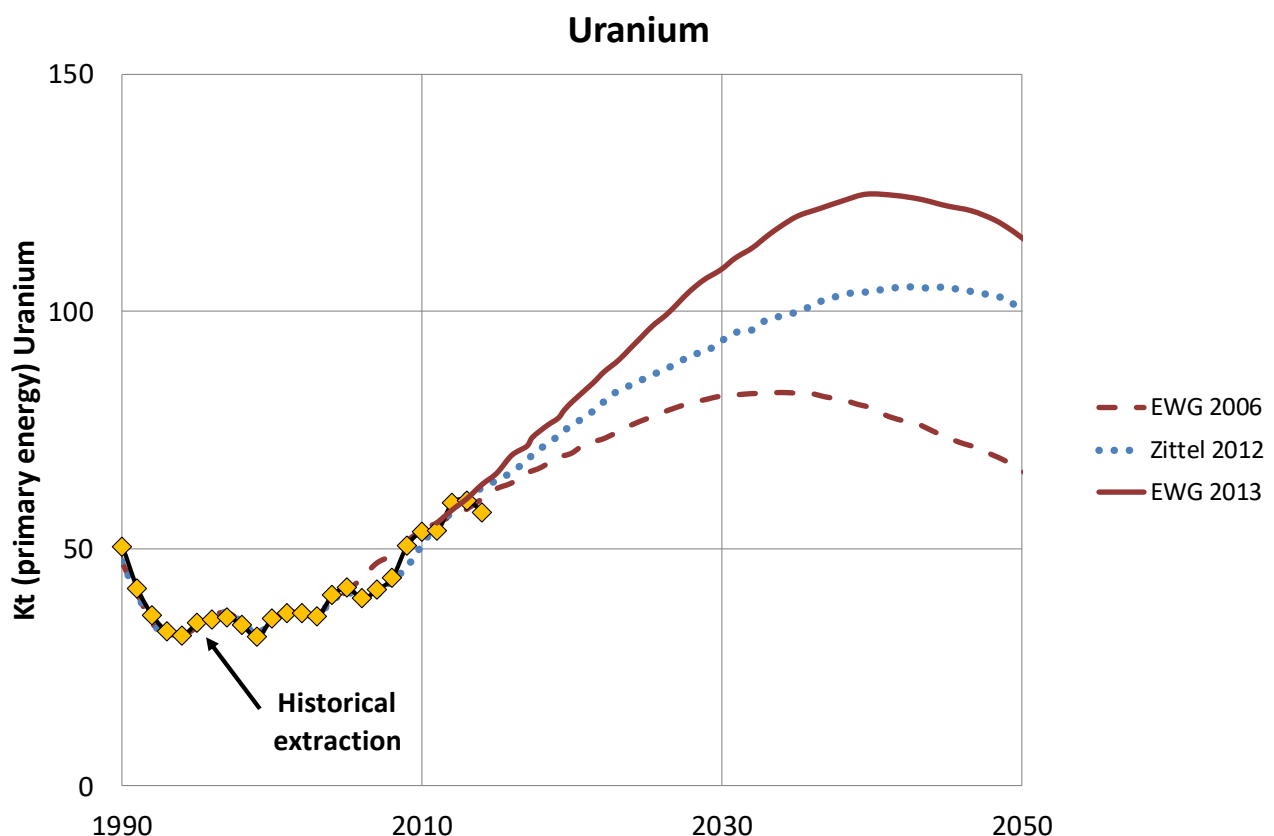


Figure 29: Estimations of uranium extraction by different authors. Historical data (1990-2014) from WMD (2016); conversion from kt U<sub>3</sub>O<sub>8</sub> to ktU following EWG (2006).

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

### 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

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.



### 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.

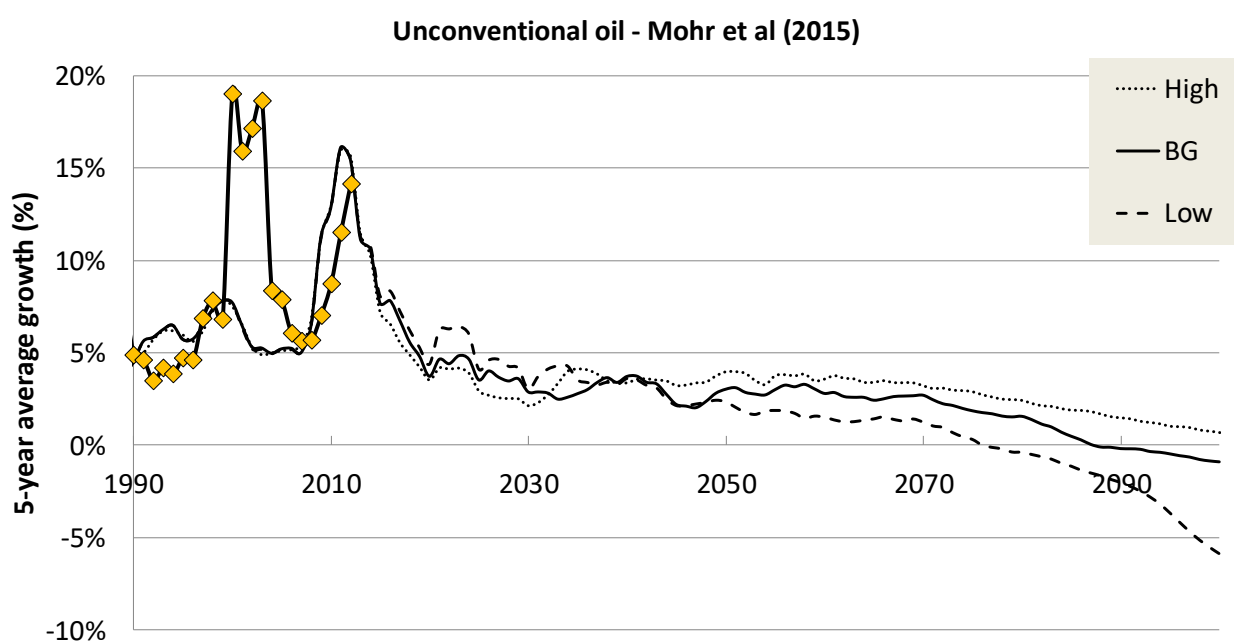


Figure 30: 5-year average growth (%) of unconventional oil for the high, BG and low scenarios from Mohr et al (2015). Historical extraction (1990-2012).

## Unconventional gas

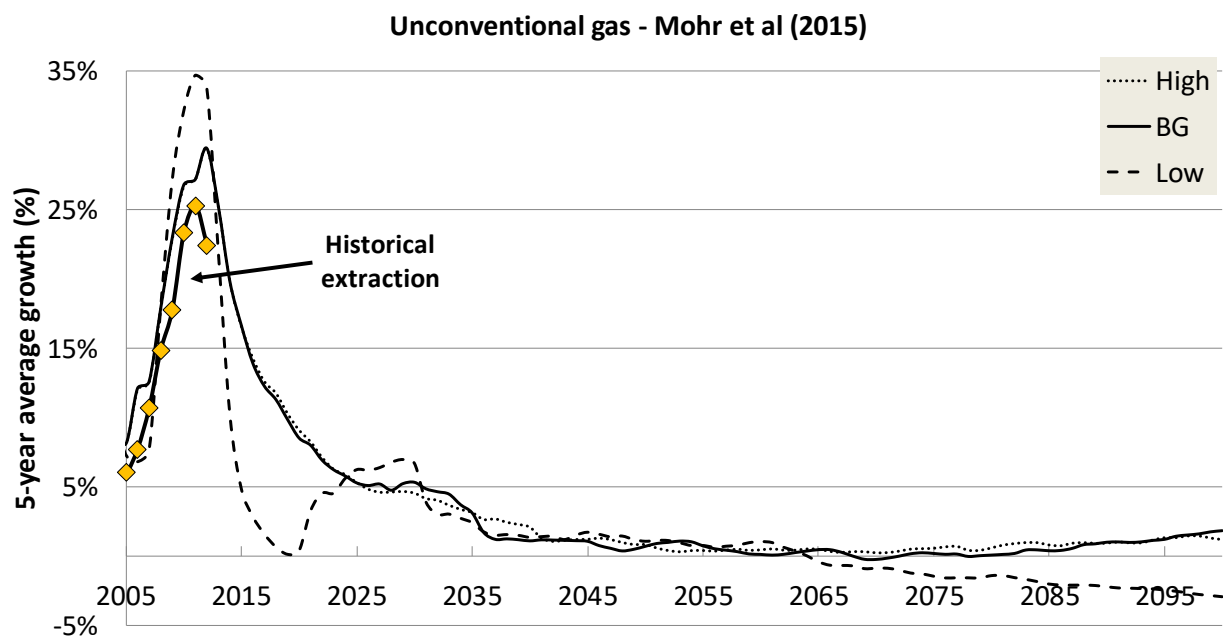


Figure 31: 5-year average growth (%) of unconventional gas for the high, BG and low scenarios from Mohr et al (2015). Historical extraction (1990-2012).

### 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,<sup>7</sup> 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). Moreover, 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 Moss gas 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).

---

<sup>7</sup> 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).

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.<sup>8</sup>

### 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).

---

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

## 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.

### 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.<sup>9</sup> Peatlands<sup>10</sup> 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 consider 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.

---

<sup>9</sup> 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 CO<sub>2</sub> 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).

<sup>10</sup> 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 (CO<sub>2</sub>), the leading greenhouse gas, than other ecosystems. As such, the world's peat bogs represent an important "carbon sink"—a place where CO<sub>2</sub> 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.

### 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 assume 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 2<sup>nd</sup> 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 2<sup>nd</sup> generation (WBGU, 2009).

4- Residues (agricultural, forestry, municipal, industry, etc.). Currently, only biogas and MSW<sup>11</sup> 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

---

<sup>11</sup> 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! Reference source not found.**).

past evolution. The 3rd generation biofuels (cellulosic) are still in R&D and doesn't appear in the standard 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.



### 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 2<sup>nd</sup> 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 <2°C 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.

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/m<sup>2</sup>. 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! Reference source not found.**).

Figure 32 represents the Forrester diagram of the 2<sup>nd</sup> and 3<sup>rd</sup> generation biofuel production in land competing with other uses, as well as the biofuel production in marginal lands:

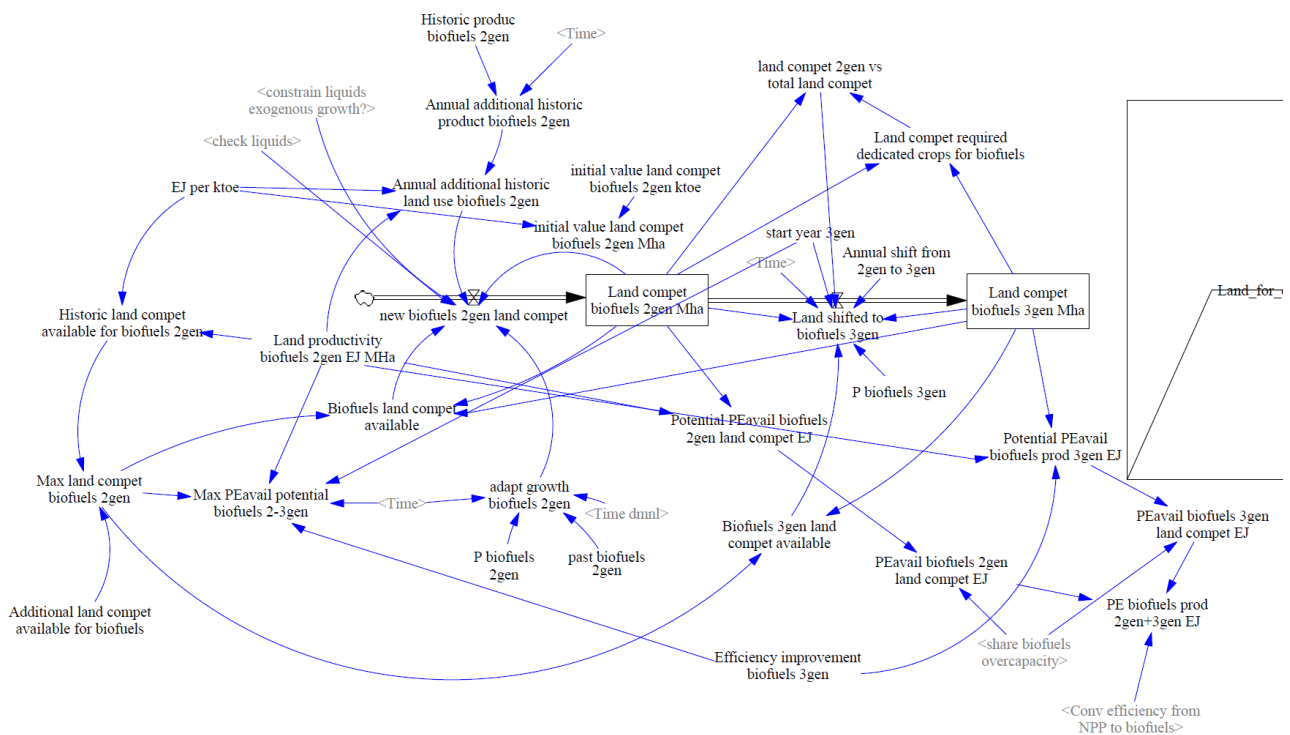


Figure 32: Stock and flow map of the model of the bioenergy in land subject to competition in MEDEAS.

### 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/m <sup>2</sup>	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 <sup>a</sup>	27	4.1	Biofuels
Dedicated crops (competition with other uses)	2 <sup>nd</sup> gen.	(de Castro et al., 2013a)	100 (standard scenario)	0.155 <sup>b</sup>	33	4.9	Biofuels
	3 <sup>rd</sup> gen. (from 2025)	(WBGU, 2009)	0 <sup>c</sup>	0.18	+5.0 <sup>c</sup>	+0.7 <sup>c</sup>	Biofuels
Residues	Agriculture & Forestry residues 3 <sup>rd</sup> gen. (from 2025)	(WBGU, 2009)	-	-	18.75	3.75-15 (0% heat-100% heat)	75% <sup>e</sup> Heat&Elec
			-	-	6.25	0.95	25% biofuels
	Biogas	Own estimation	-		5	3	Heat, Elec and TFC <sup>d</sup>
<b>Total</b>					125	21.4-52.65	All uses

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

<sup>b</sup> 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/m<sup>2</sup> 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.<sup>12</sup> 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.

---

<sup>12</sup> “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).

### 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.

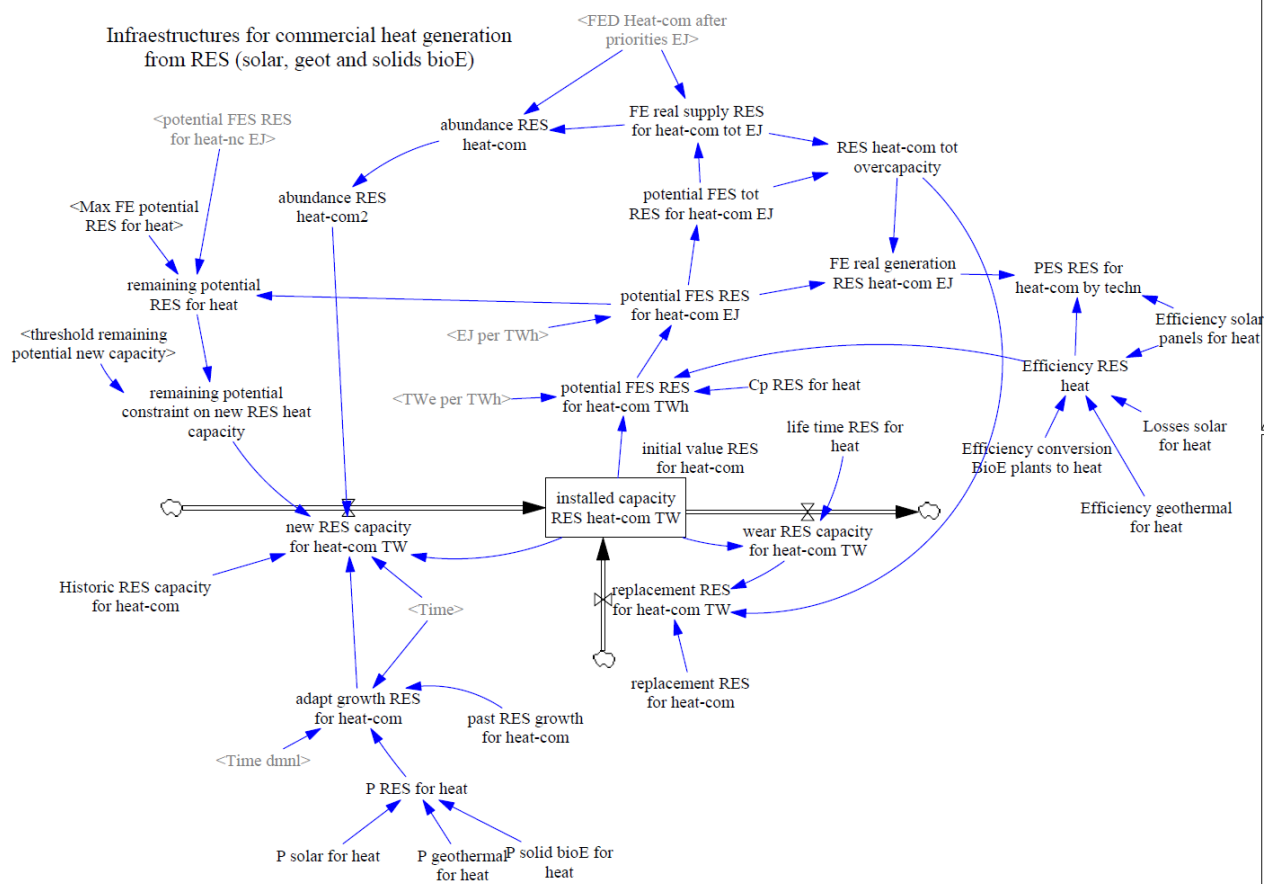


Figure 33: Stock and flow diagram of the extraction of (primary energy) from thermal commercial RES.

## 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

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 <sub>th</sub>
Geothermal for heat	(de Castro, 2012)	0.3
Solar for heat	Own estimation (see (Capellán-Pérez et al., 2017b))	0.7
<b>Total</b>		<b>1.0</b>

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).



### 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/m<sup>2</sup> 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<sub>e</sub><sup>13</sup>) (de Castro et al., 2013b) in 60-120 MHa.<sup>14</sup>

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<sub>e</sub> 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 scenario (i.e. final energy demands, policies, etc.), the model will assign a different use for heat

<sup>13</sup> “TW<sub>e</sub>” 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.

<sup>14</sup> 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).

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

<sup>a</sup>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. <sup>b</sup>(Boccard, 2009; BP, 2016; De Castro and Capellán-Pérez, 2018; EIA, 2009; IRENA db, 2017; REN21, 2016). <sup>c</sup>We assume that offshore wind has a +50% higher Cp than onshore wind. <sup>d</sup>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.  
<sup>e</sup>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. Bocard (2009) found that, although for more than two decades, the Cp of wind power measuring the average energy 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 Bocard (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.

## 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
<b>TOTAL</b>	<b>6.3 – 9.3</b>

## 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.

### 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  $C_p$ ). 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 (“dispatchable”) load such as hydro,<sup>15</sup> 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.<sup>16</sup> To cope with their intermittency, MEDEAS incorporates 4 mechanisms:

1. Storage
2. Overcapacities of dispatchable 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% substantially increases these requirements, i.e., there is an exponential relationship when

---

<sup>15</sup> Hydroelectricity is not a fully dispatchable RES due to the interannual (e.g. droughts) and seasonal variability and the fact that water is also used for other purposes (irrigation, control floods, human consumption, industrial use, navigability, etc.).

<sup>16</sup> 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.

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).<sup>17</sup> 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.

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

<sup>17</sup> 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 they 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.



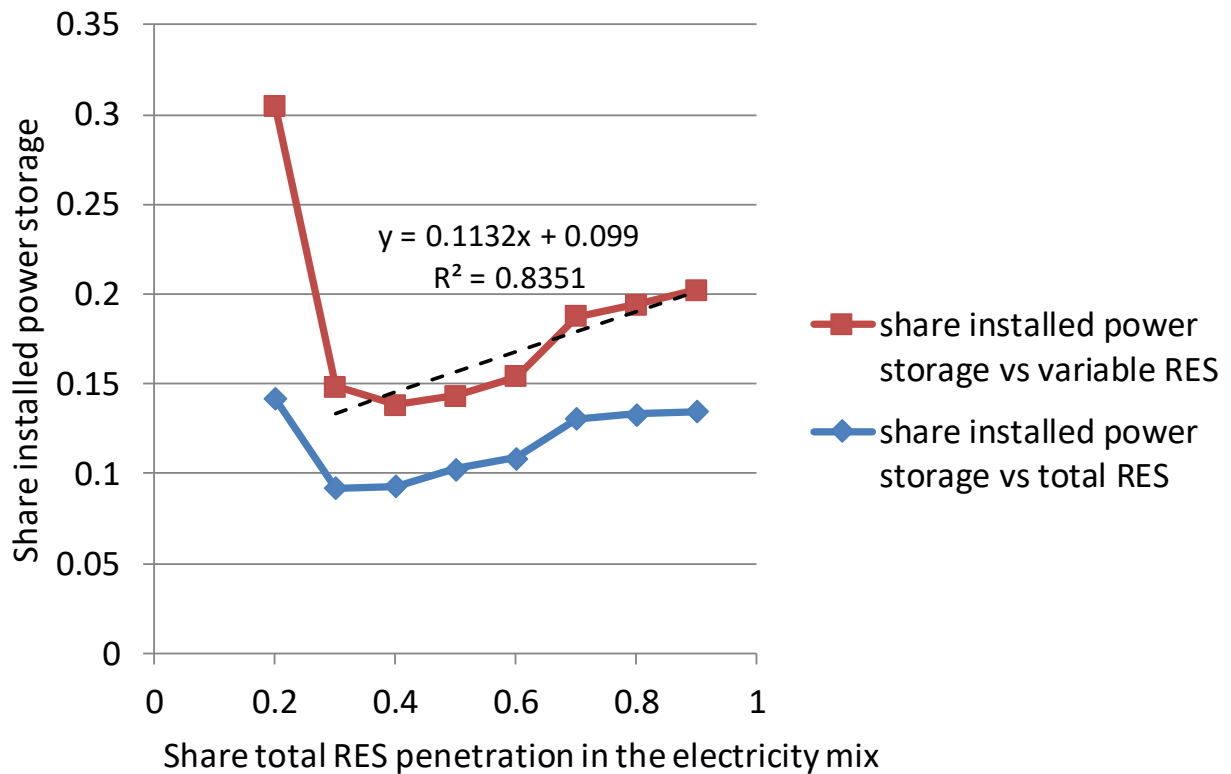


Figure 34: Share of installed power storage vs. (1) variable RES installed capacity (red curve), and vs. (2) total RES installed capacity (blue curve) as a function of the share of total RES penetration in the electricity mix.

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-Aránegui, 2015).<sup>18</sup> 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.

<sup>18</sup> However, the identified total technical potential for hydropower in Europe only doubles current installed capacity (IPCC, 2011).

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  $C_p$  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  $C_p$  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  $C_p$  of the RES power plants as a function of the penetration of variable RES in the electricity generation.

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.<sup>19</sup>

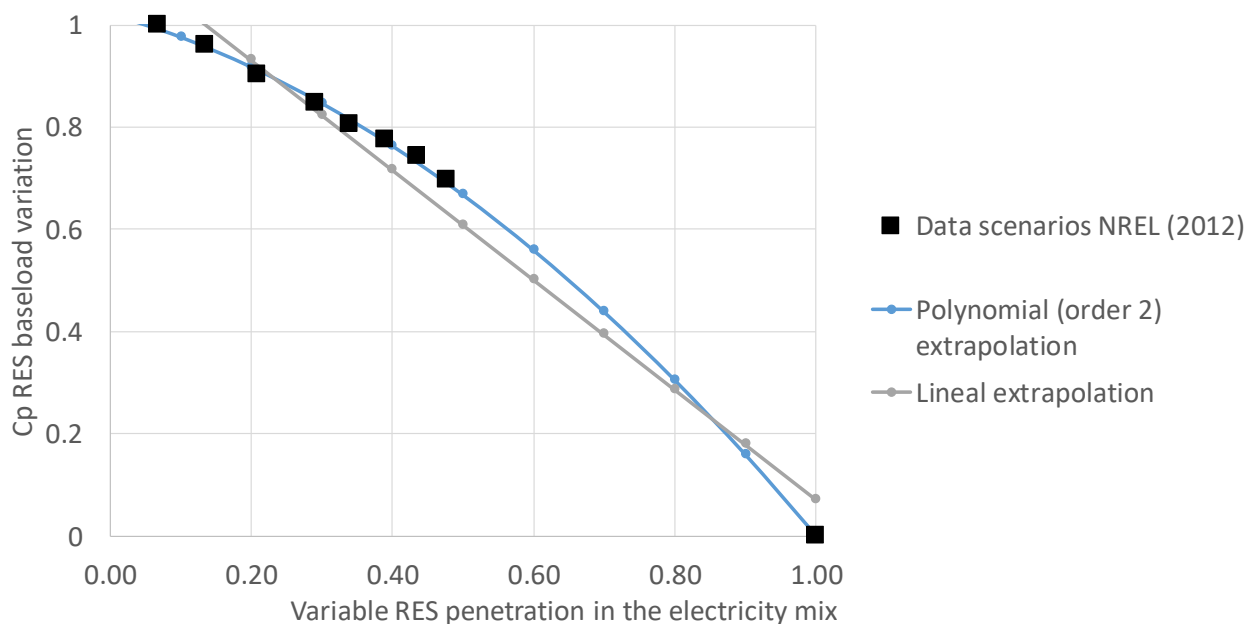


Figure 35: Capacity factor reduction of baseload plants (including RES and non-RES power plants) in relation to the initial point of “negligible” variable RES penetration as a function of the increasing level of penetration of the electricity generation of RES variables. Source: own calculations from 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

<sup>19</sup> This was explicitly modelled only for dispatchable RES sources and nuclear, since capacity for electricity generation from fossil fuel resources is not modelled in this model version.

source 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  $C_p$  of the variable RES power plants and interpolation assuming that  $C_p = 1/(1 + \text{overcapacity})$ . 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  $C_p$ . 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).

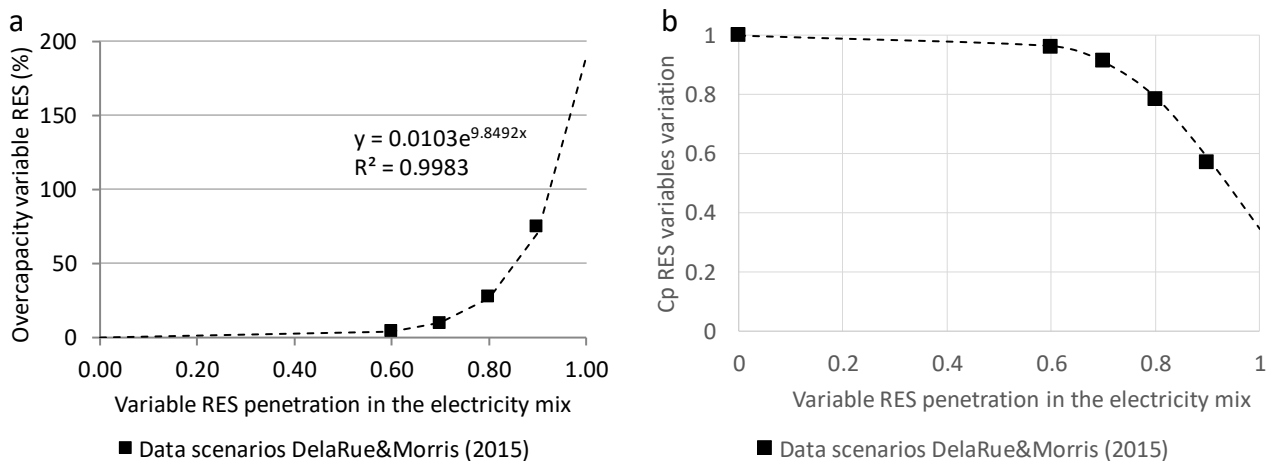


Figure 36: Overcapacities of RES variables: (a) Overcapacities of variable RES as a function of the variable RES penetration in the electricity mix from (Delarue and Morris, 2015) and exponential fit; (b) Reduction in the  $C_p$  of the variable RES power plants and interpolation.

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

## Grid development

MEDEAS-World does not explicitly model electricity grids given that these infrastructure 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

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.

### 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<sup>20</sup>) 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

<sup>20</sup> Increase in reserve requirements is not computed since the investments for non-renewable electricity production are not modeled.

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.

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

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



## 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 where there 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 cancel 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 be low (2.2 jobs/MW for manufacturing, construction and installation, and in this case data for this technology from (REN21, 2017) was used instead.

	<b>C+I+M</b>	<b>O&amp;M</b>
	<b>job year/MW</b>	<b>job year/MW</b>
<b>RES elec</b>		
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
<b>RES heat</b>		
solar-heat	8.4	0
geot-heat	6.9	0
solid bioE-heat	16.9	1.5

## 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.

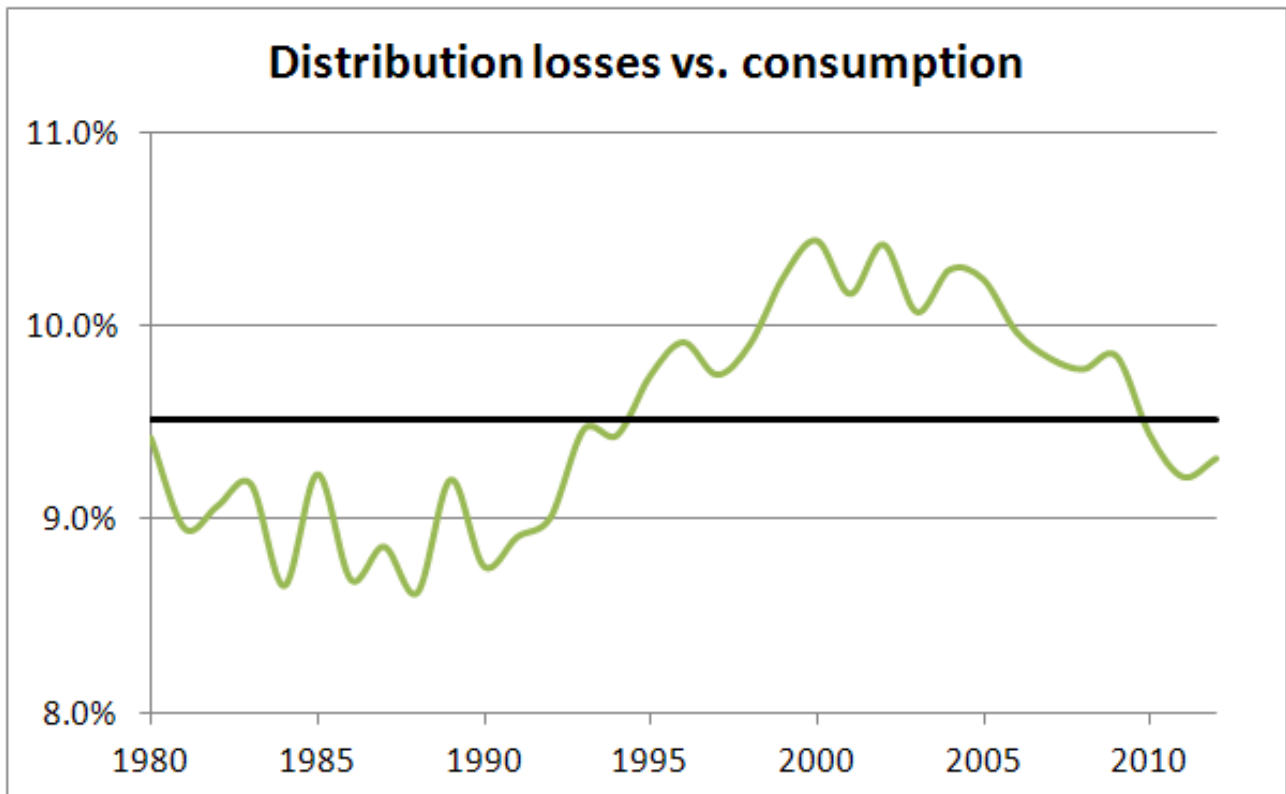


Figure 37: Distribution losses vs. consumption at global level (1980-2012) (US EIA db, 2015).

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):

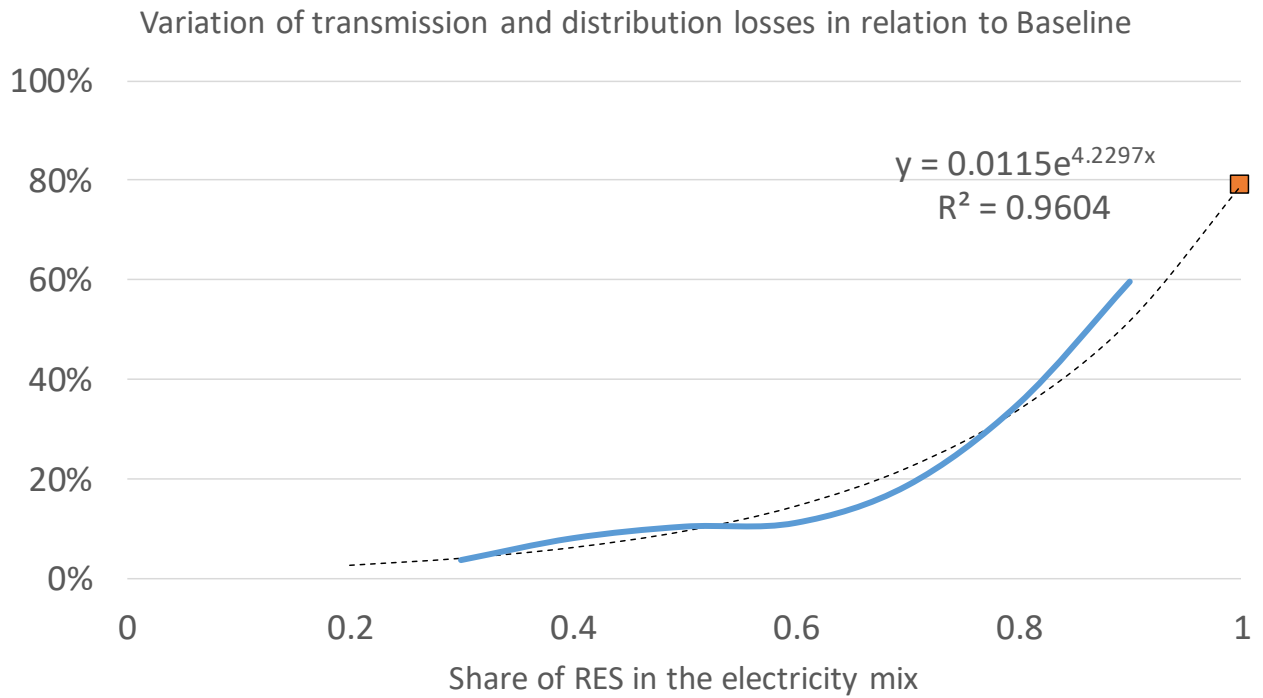


Figure 38: Variation of electricity transmission and distribution losses as a function of the share of RES in the electricity mix. Source: own work from (NREL, 2012).

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

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

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):

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

<b>Fuel</b>	<b>Efficiency of power plant</b>	<b>Comment</b>
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.

### 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 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).

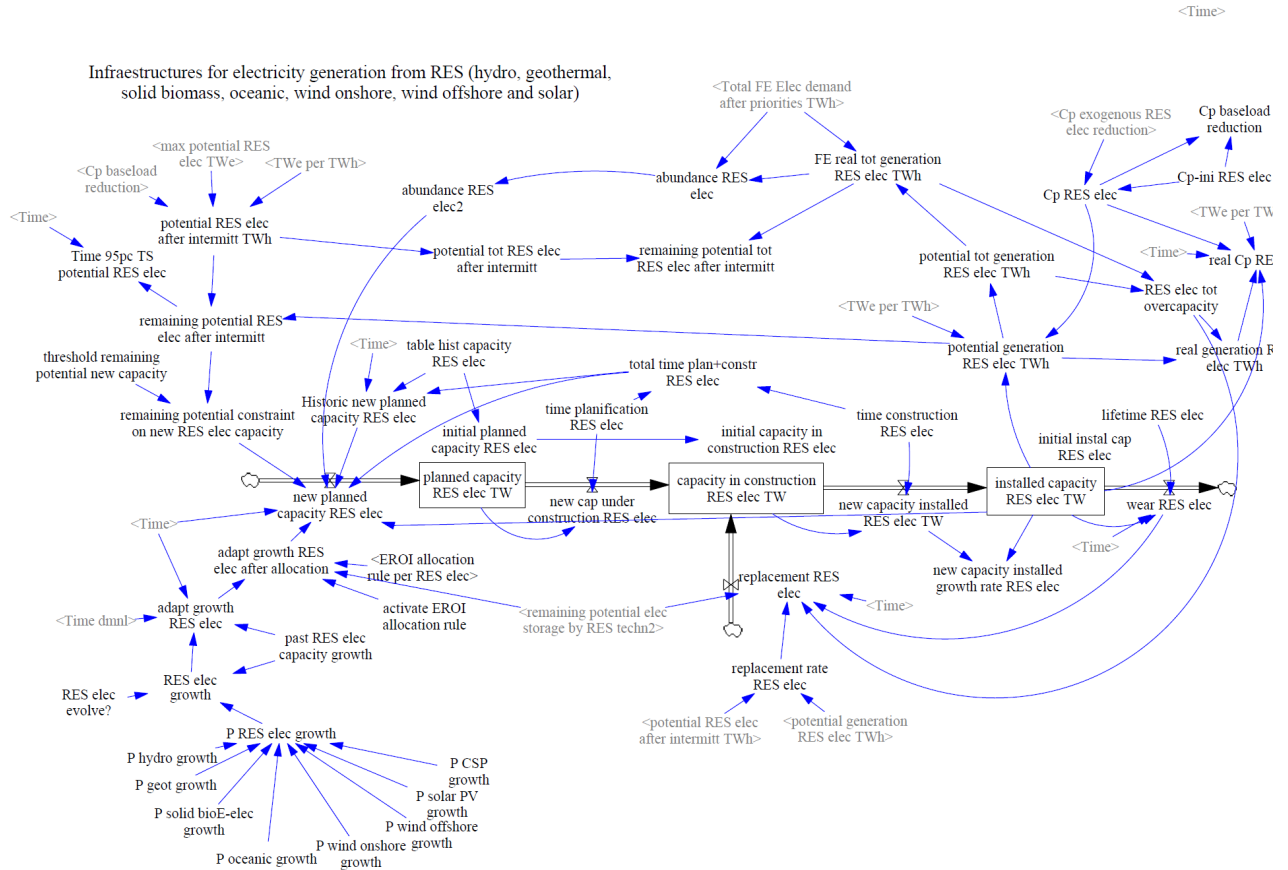


Figure 39: Infrastructure of RES technologies for the generation of electricity (vectorial programming).

$P1_{solar}$  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):

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

*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).

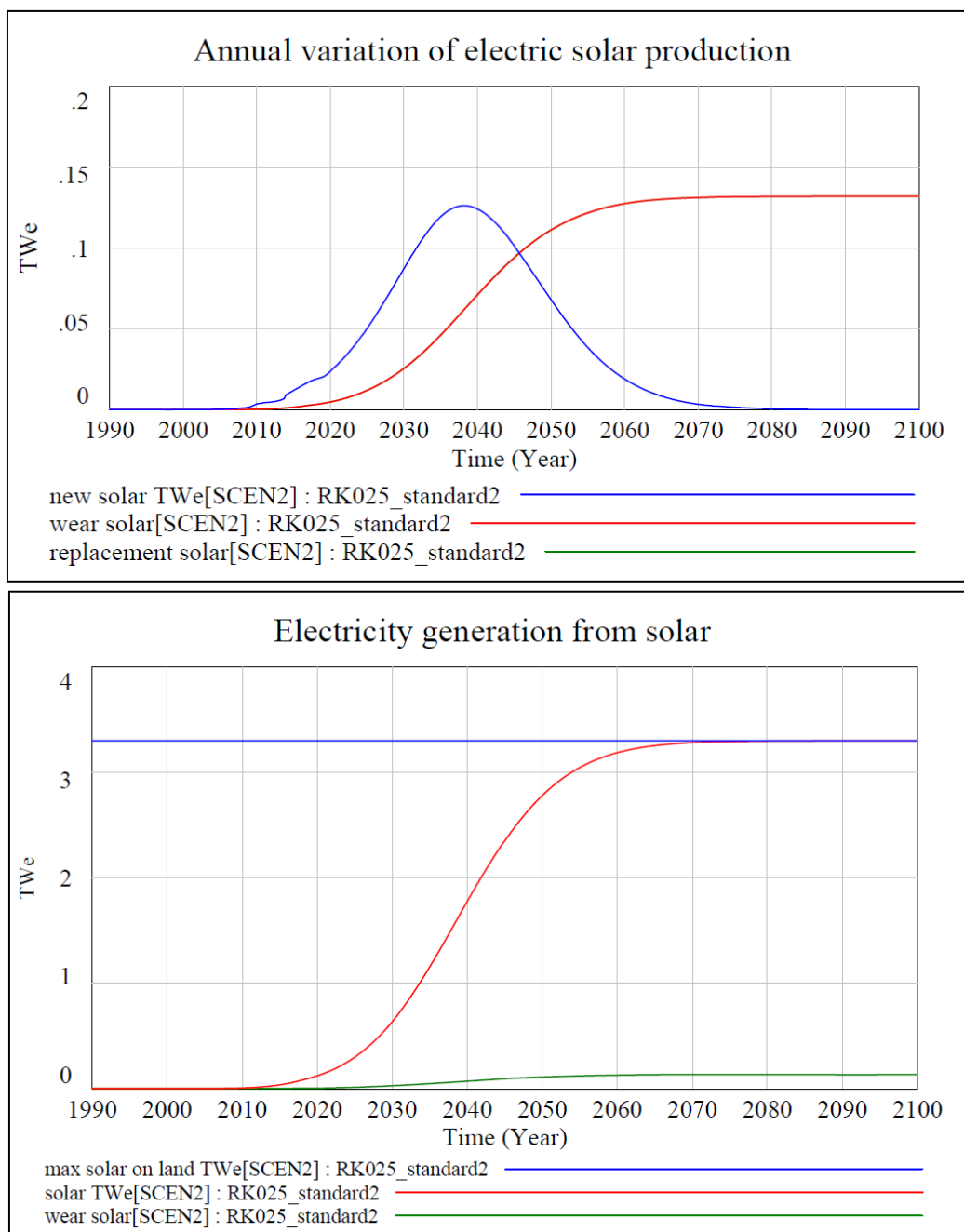


Figure 40: Total electric solar production (TWe). In this figure we represent the dynamics of the previous equation considering a very rapid growth of solar (+19%, as in scenario 1). While being far from the potential limit, exponential growth drives the growth of new solar power. As the total solar 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.



### 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.).

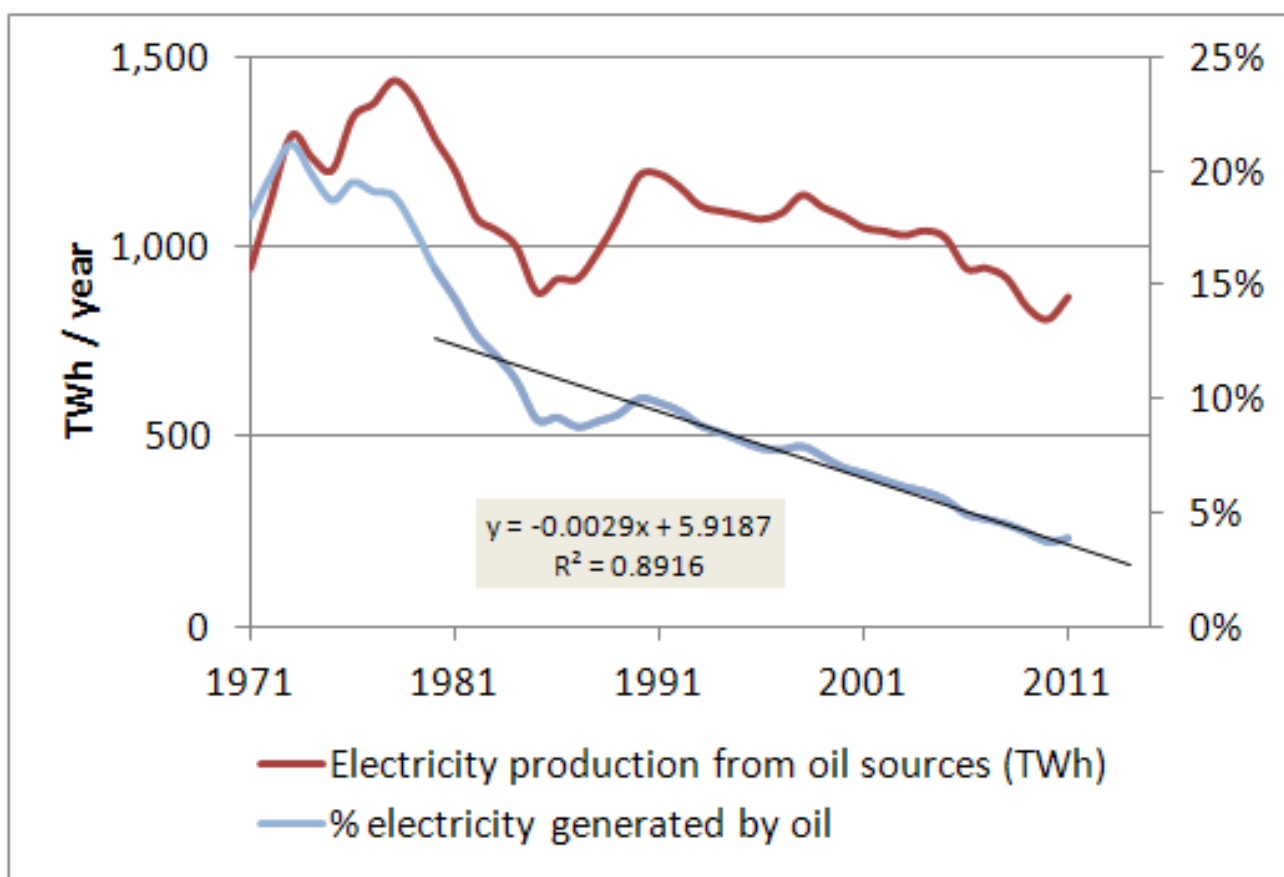


Figure 41 (own analysis from (World Bank database, 2018)): Electricity production from oil sources (TWh) and as percentage of the total electricity production.



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  $C_p$  of the nuclear plants falls which ultimately causes the decrease in the annual average output per installed capacity. A  $C_p$  minimum of 60% is set due to the specific characteristics of nuclear power plants which cannot operate at low  $C_p$  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).

#### 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.

## 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 end-use 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).

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.

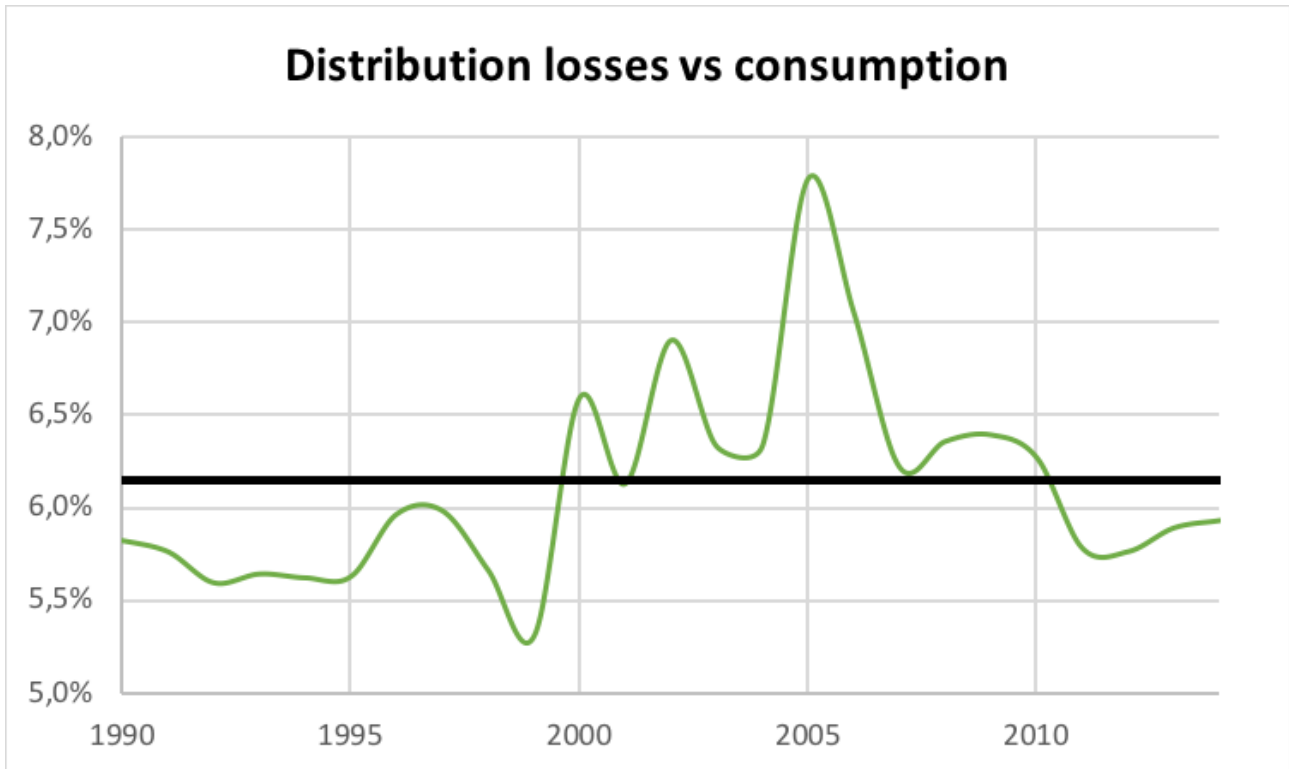


Figure 43: Distribution losses vs. consumption at global level for commercial heat (1990-2014) (IEA, 2018).

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.

### 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.).

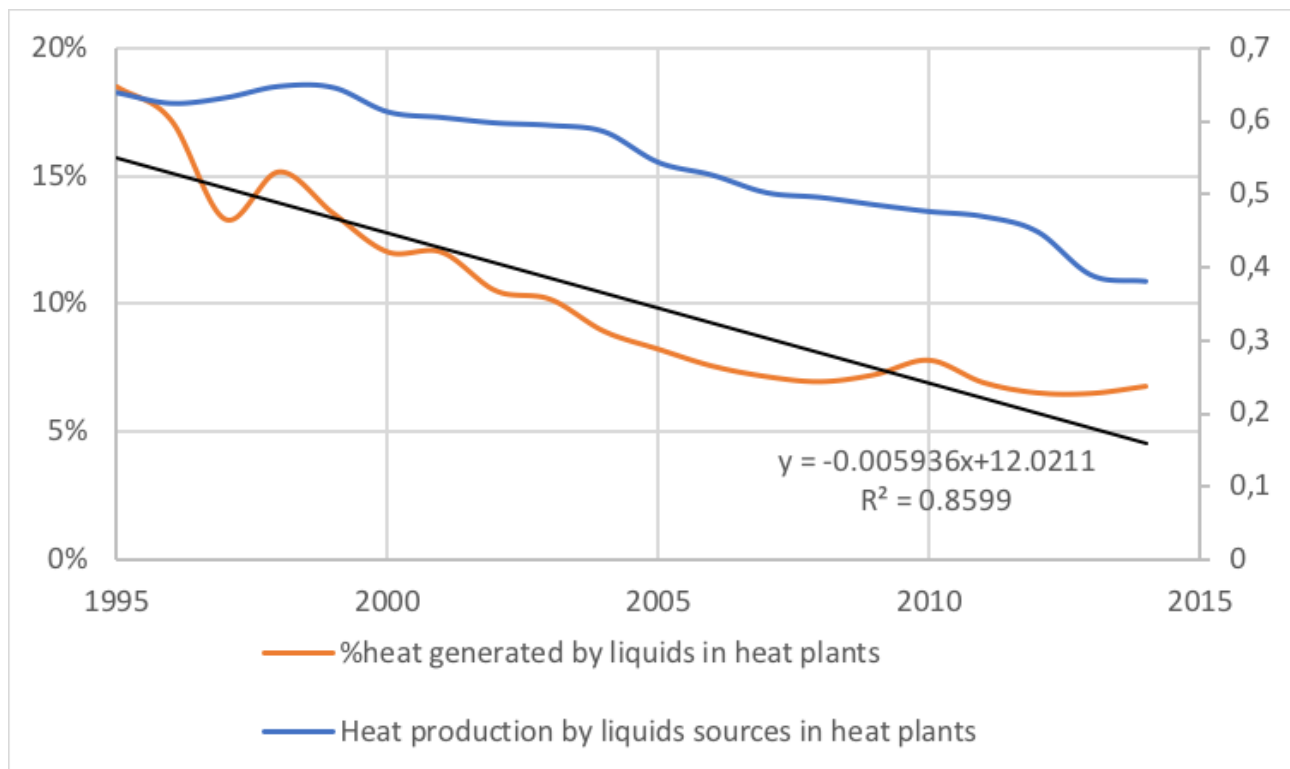


Figure 44: Heat production from oil sources (TWh) and as percentage of the total heat production (own analysis from (World Bank database, 2018)).

## 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%



### 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 happens 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 around 46.5% of the heat demand not covered by renewable sources is covered by CHP plants (Figure 45):

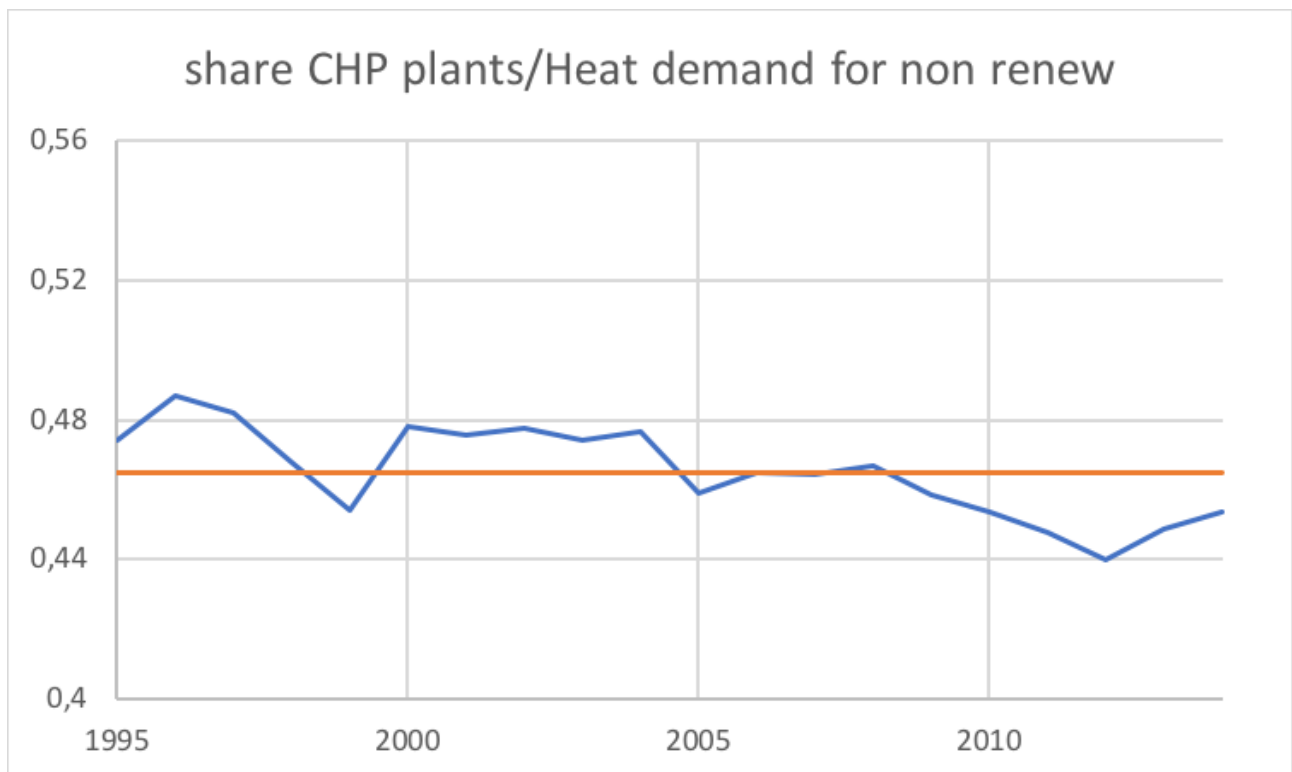


Figure 45: share of Heat demand without RES sources covered by CHP plants

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 decreasing trend in order to reach zero 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).

	<b>GAS</b>	<b>COAL</b>	<b>OIL</b>
<b>Efficiency elec CHP plants</b>	0.33	0.31	0.33
<b>Efficiency heat CHP plants</b>	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.

## 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

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.

### 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.

### 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:

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

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.

Therefore we might define the following constants:

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

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

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

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

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 ( $t_0$ , 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:

$$IH_{liq} = A_1 \cdot \%H_{liq4w} + A_2 \cdot \%H_{liq2w} = \frac{\text{liquids 4w} + 2w \text{ households}(t_0)}{\text{demand households}(t_0)}$$

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

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.

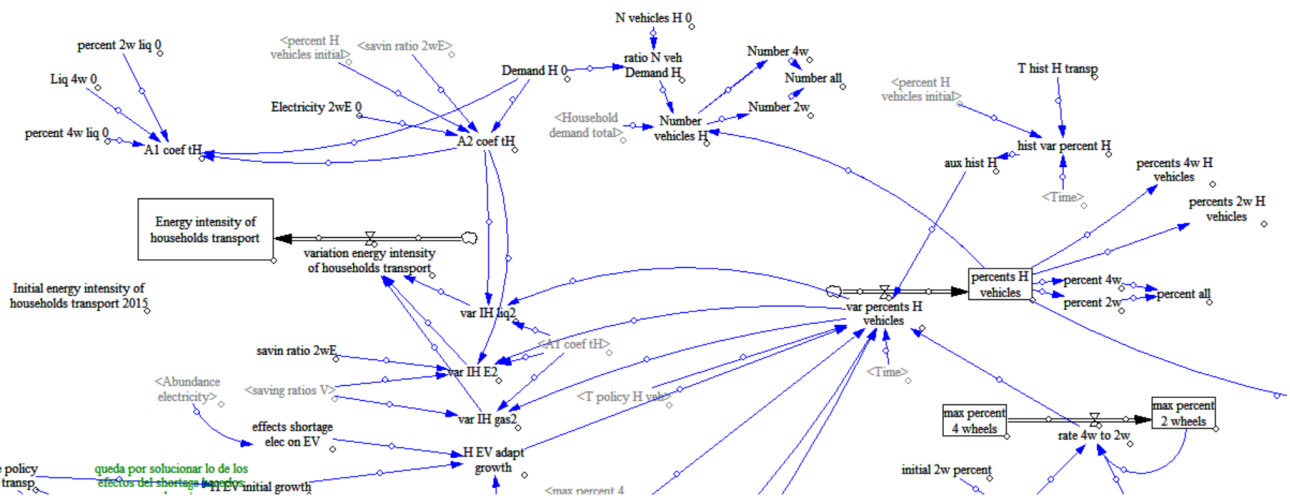


Figure 46: Stock and flow diagram of the household transport subsystem.

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

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

And assuming this ratio is constant through the simulation, therefore

$$= \text{Household Demand}(t) \cdot \text{ratio } N \text{ veh demand } H \cdot \text{percent vehicle type } i(t)$$



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:

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

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.

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:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Transport.

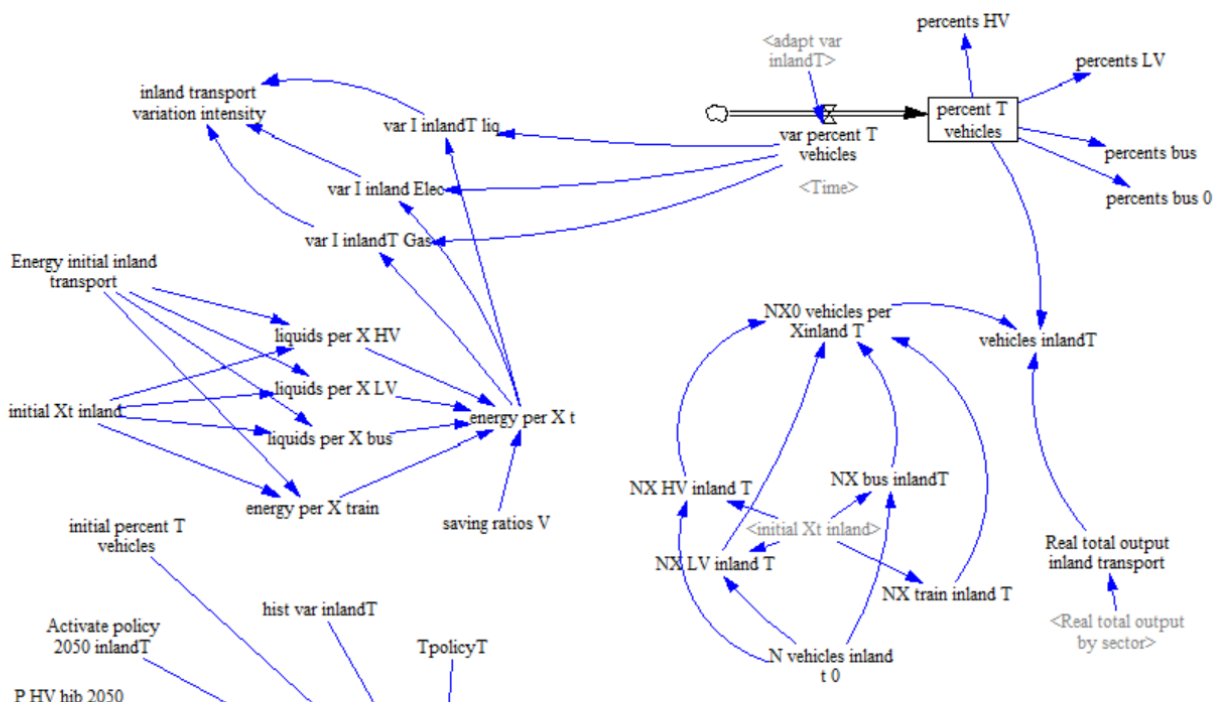


Figure 47: Stock and flow diagram of the household transport subsystem.

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.

### 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.

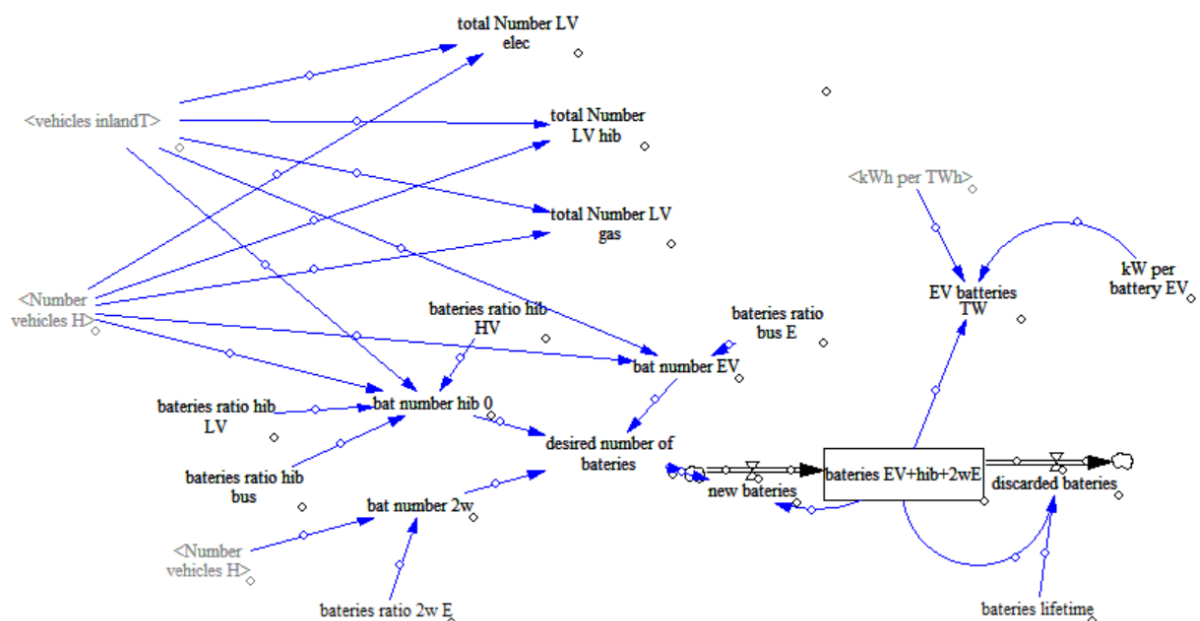


Figure 48: Diagram of the batteries submodule.

## 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).

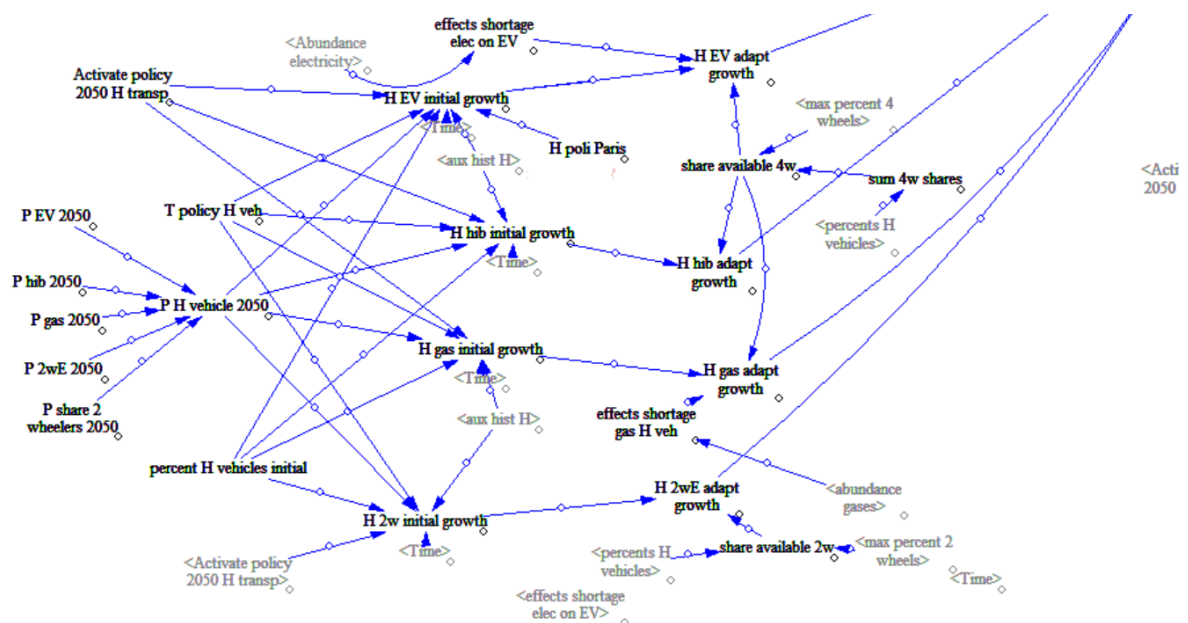


Figure 49: Diagram of the policies of Households Transport subsystem

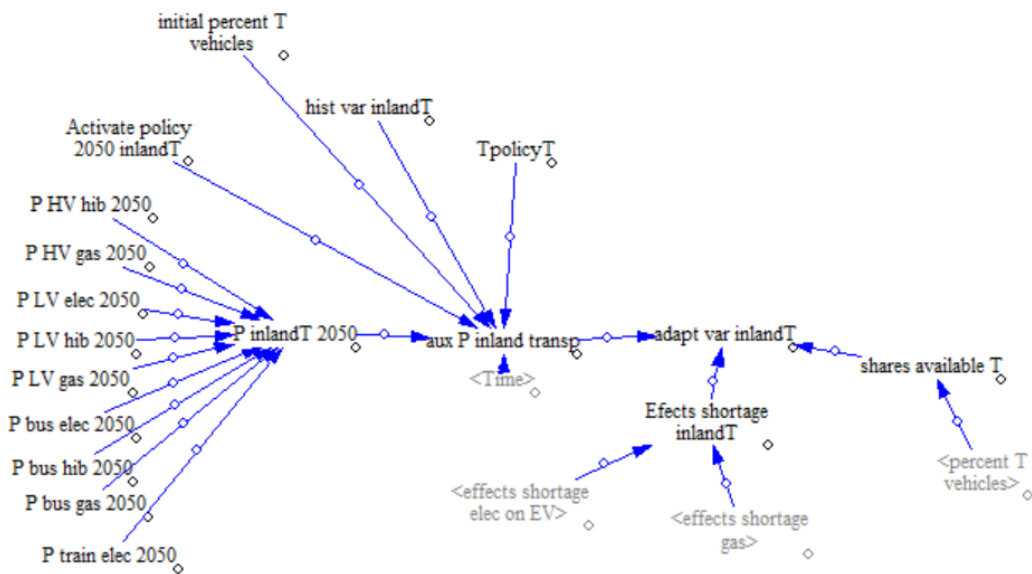


Figure 50: Diagram of the policies of Inland Transport subsystem

## 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

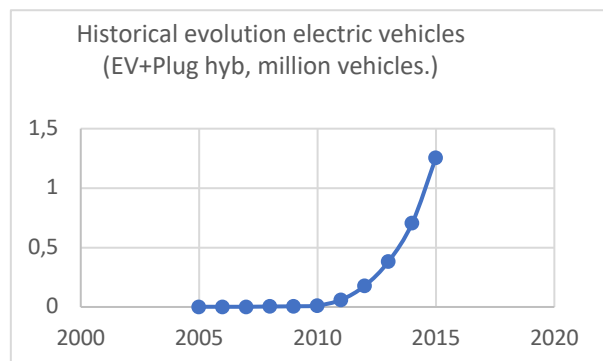
In spite of the promising forecasts done in previous decade, the global electric car stock in 2015 is still very low compared to the global amount of vehicles (see figure 5.6 for historical values). In their 2009 report (IEA 2009), the International Energy Agency proposed a “Blue EV Success” scenario which foresees 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 by 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, setting 100 million as the target of Paris agreements, which represents a strong growth from present values (see

Figure 51). This value could be established 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 negligible in the statistics which makes forecast very uncertain. A delay in the application of the policies of electric buses would probably be a realistic approach since these vehicles will need time in order to grow as an alternative.



(Own elaboration based on data from (IEA, 2016))

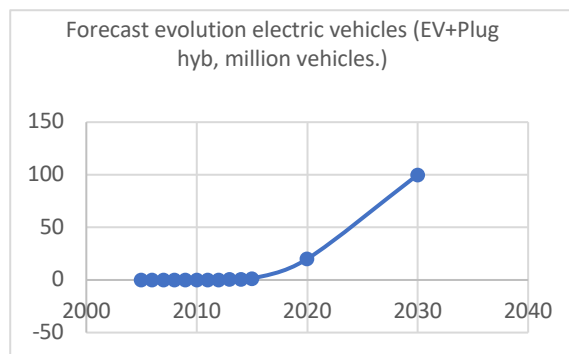


Figure 51: Historical evolution of EV+PHEV vehicles.



### 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 were 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.

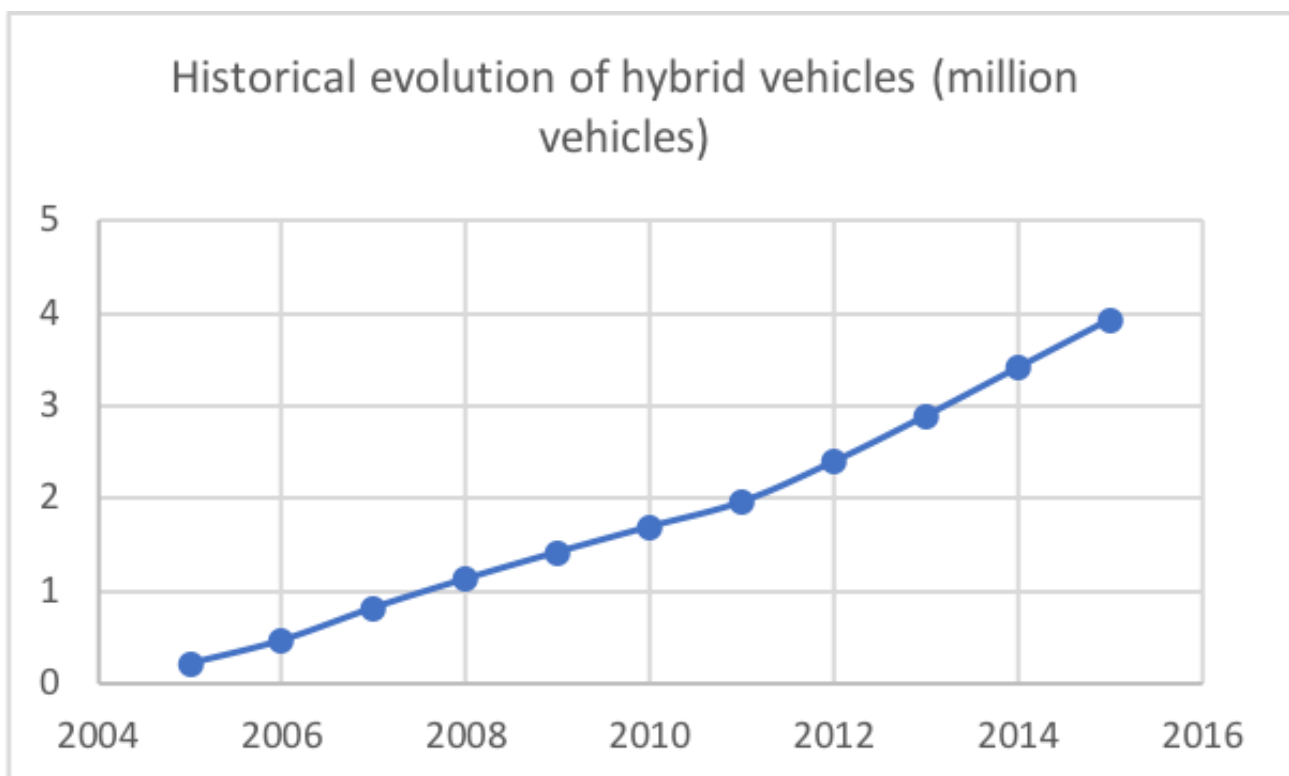


Figure 52: Historical evolution of hybrid vehicles worldwide (own elaboration based on data from (IEA, 2016))

### 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)<sup>21</sup> 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.

---

<sup>21</sup> At atmospheric pressure and temperature, natural gas has an energy content of around 40 MJ/m<sup>3</sup> 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).

## 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 (and 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 than 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 linear growth policy seems realistic for BAU MEDEAS scenarios.

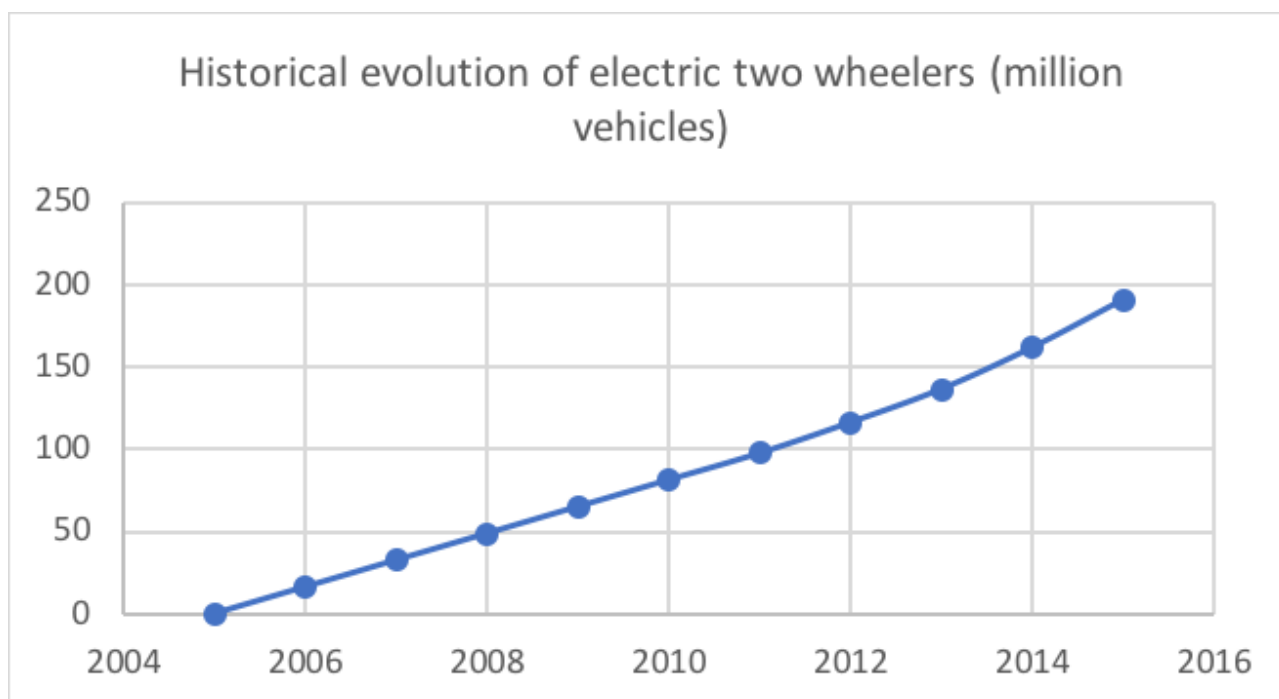


Figure 53: Evolution of the stock of electrical two wheelers worldwide. Own calculations based on data from (IEA, 2016).

### 2.3.7.3. Saving ratios

In order to establish 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 given 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 Southern 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 KWh passenger/Km for electricity and 3,035 KWh 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

Table 23.

Table 23: Saving ratios estimated for different vehicles and fuels compared to liquid-based equivalent vehicles.

	<b>electric</b>	<b>hybrid</b>	<b>gas</b>
<b>Light four wheelers</b>	0,33	0,6	1
<b>Heavy vehicles and buses</b>	0,5	0,6	1
<b>Two wheelers</b>	0,21		
<b>trains</b>	0,6		

## 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 estimated 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 established 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 weight needed for 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.

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

## 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



## 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

(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.

## 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.

- 2MW onshore wind turbines: currently the average wind onshore turbine capacity is ~1.2 MW.
- 3.6MW offshore wind turbines:
- $\text{LiMn}_2\text{O}_4$  electric vehicle batteries: although they are less efficient than other alternatives (e.g.  $\text{LiCoO}_2$ ), 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)	<p>Main reference: (De Castro and Capellán-Pérez, 2018). Realistic <math>C_p</math> of 0.25 and a lifetime of 25 years.</p> <p>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 <math>C_p</math>) would decrease by ~14% (García-Olivares, 2016), which would lead to a lower EROI ~80% lower (<math>\text{EROI}_{\text{CSP(Al)}} = \text{EROI}_{\text{CSP(Ag)}} * 0,86/1,08</math>).</p> <p>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/m<sup>2</sup>) of CSP are ~2x comparing to PV, this approximation is thus conservative.</p> <p>+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.</p>
Solar PV (Fixed-tilt silicon PV)	<p>Main reference: (Prieto and Hall, 2013); completed with (MEDEAS, 2016a) Annex 9 and other sources.</p> <p>Material data have been extracted and re-calculated from Prieto and Hall (2013) excluding data indirectly estimated from economic parameters (which could eventually be</p>

	<p>considered in a calculation of <math>EROI_{ext}</math>).</p> <p>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.</p> <p>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).</p> <p>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)).</p> <p>For the data of “silicon wafer”, we take as reference Alsema and Wild-Scholten (2006), who report a thickness of 300 <math>\mu\text{m}</math> (0.7kg/m<sup>2</sup> accounting for the density of silicon), 6,400 m<sup>2</sup>/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 <math>\mu\text{m}</math> (0.5kg/m<sup>2</sup> 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).</p>
Wind onshore (2MW turbines)	<p>Main reference: (GAMESA, 2013), completed with MEDEAS (MEDEAS, 2016a) and other sources.</p> <p>Although wind onshore turbines of higher capacity currently exist at commercial level (up to 8MW), the average current installed capacity is just <math>\sim 1.2</math> 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).</p>

		<p>Material requirements of Cu, Ni, Dy and Nd have been collated from MEDEAS (MEDEAS, 2016a). In the case of Dy 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).</p> <p>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.</p> <p>For the O&amp;M, we have followed the replacements of the components of the turbines following (Haapala and Prempreeda, 2014; Ribrant and Bertling, 2007).</p>
Wind offshore	3,6MW (LondonArray)	<p>Main reference: (LondonArray, 2016). Complemented with (SMart Wind, 2013) project data and with wind (conservative) onshore specifications when data not available for wind offshore.</p> <p>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.</p> <p>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).</p> <p>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.</p>

<p>Electric vehicle batteries (LiMn2O4 batteries)</p>	<p>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).</p> <p>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.</p> <p>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.</p> <p>No O&amp;M considered, no wear.</p> <p>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 <math>C_p</math> is 0.0055 (<math>80\text{KW} \cdot 10\text{years} \cdot 31.5\text{E6sec/year}</math>). 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 <math>C_p</math> of 0.0055 (<math>80\text{KW} \cdot 0.0055 = 439\text{W}</math>).</p> <p>In relation to their use as electric storage devices, in principle they could be used the rest of the time when the EV is not being used (i.e. <math>1 - 0.0055</math>), which could be a significant potential. However, their extensive use would wear the batteries, effectively reducing its lifetime. For example, increasing their <math>C_p</math> 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 <math>C_p</math> than for driving, i.e. that each battery would be able to function 10 years without wear (4,000 cycles).</p>
---	--

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 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	<p>The additional high power grids (and associated transformers) to integrate the variable generation of electricity from renewables is estimated.</p> <p>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 &gt;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.</p> <p>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 &gt;100MVA and a similar number of &gt;60 y &lt;100MVA. This represents around 5 transformers per power plant or 30 transformers of each type per installed GW (0.03 transformers/MW). Since there are 725,000 km of high power grids, the</p>



	<p>ratio is 24 km/transformer (i.e. 0.042 transformers/km grid).</p> <p>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 <math>C_p</math> 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).</p> <p>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).</p>
Inter-regional grids (HVDCs)	<p>We roughly estimate the material requirements of new HVDCs lines to integrate the variable electricity generation from renewables.</p> <p>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.</p> <p>Losses depend on the length of each HVDC line, however we take the average of ~7.5%.</p> <p>Applying this methodology, we observe that the material requirements of HVDCs are generally below 10% of those related to high power overgrids.</p>

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.

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

	Material intensity of technologies					kg/new MW of each RES var elec techn material overgrid high power	kg/new MW of each RES var elec techn Inter-regional grids (HVDC)
	kg/new MW	kg/new MW	kg/new MW	kg/new MW	kg/new MW		
	CSP	PV	wind onshore	wind offshore	Li batteries		
<b>Construction phase</b>							
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
Silicon 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
Synthetic 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
<b>Total construction phase</b>							
grid correction factor (A34+A41)	0.075	0.06	0.06	0.06	0.1		
<b>Operation and maintenance (yearly)</b>	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			
silicon 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			

### 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 ( $RR_i$ ), 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).

## 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).

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.

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, NaNO<sub>2</sub> and KNO<sub>3</sub>), 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<sub>st</sub>, see section 0). After this, just three minerals emerge from the set as potentially problematic: copper, sodium nitrates (NaNO<sub>3</sub>) and potassium nitrates (KNO<sub>3</sub>). 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%.<sup>22</sup>

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).

---

<sup>22</sup> 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 aluminium. 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 EROI<sub>st</sub>. Due to the allocation rule implemented in MEDEAS this would reduce the deployment of CSP.

#### 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

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. 1<sup>st</sup> run: we obtain a scenario where there is copper scarcity; 2<sup>nd</sup> run: in this simulation we replace copper by aluminium obtaining systems with a lower energy efficiency (more Joule effect), more CED, etc.



### 2.4.3. Modelling of recycling policies in MEDEAS

Recycling policies 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).

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

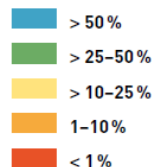


Figure 54 (UNEP, 2011): EOL-RR for sixty metals.

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 batteries, 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 product 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 appropriate infrastructure 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 appropriate policies, recycling rates could even worsen if the share of complex products continues to increase over the total (UNEP, 2013a, 2011).

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

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

- Table 30), the mean of the minimum and maximum is used.
- Given the lack of data for the recycling 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:

## Materials recycling

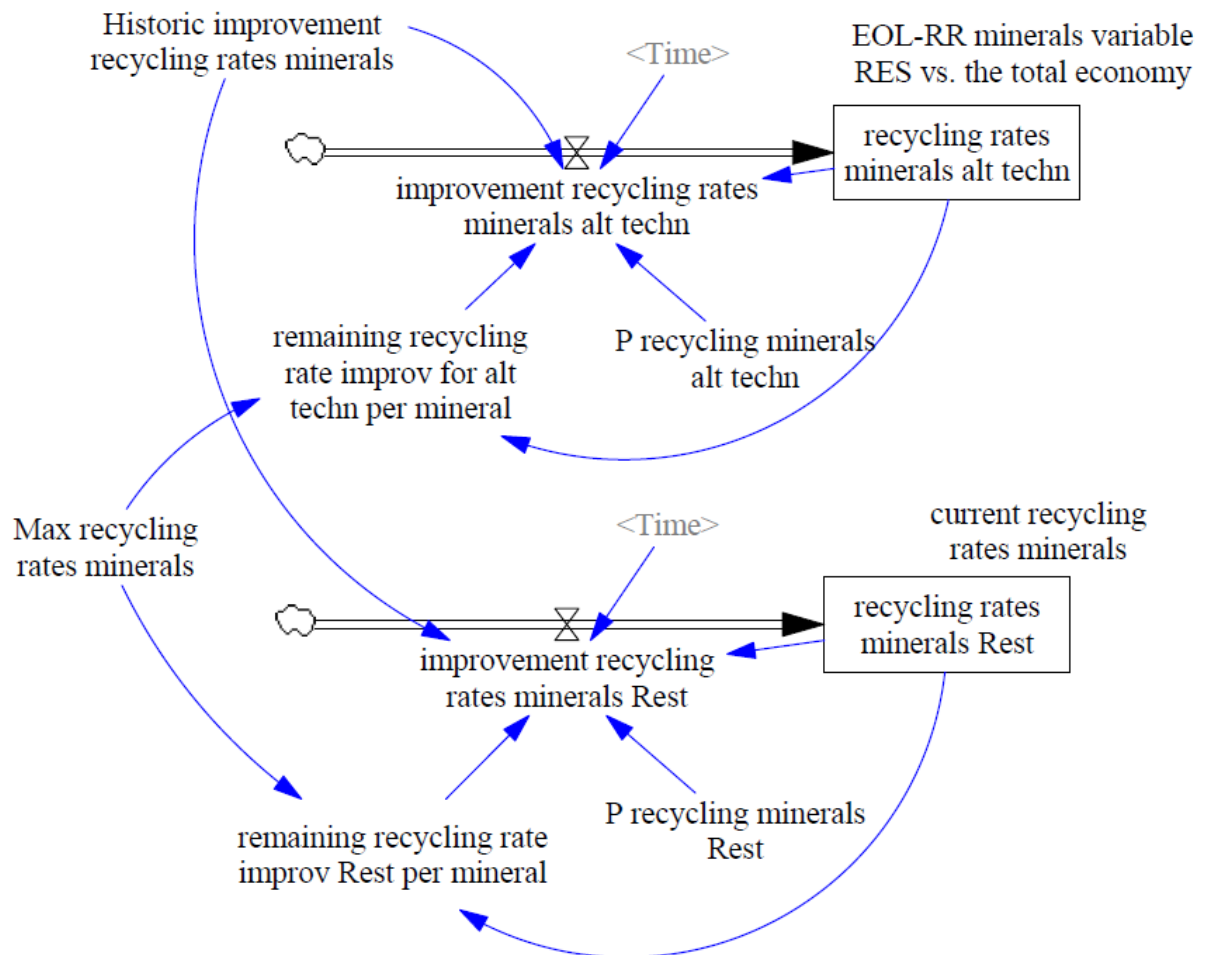


Figure 55 : Loop diagram of the mineral recycling policy in MEDEAS.

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.

## 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).

### 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:

$$EROI_i = \frac{\text{Annual elec output}_i \cdot \text{lifetime}_i}{(CED_i^{\text{New cap}} + CED_i^{\text{Decom wear cap}} + CED_i^{\text{GCF}} + CED_i^{\text{O\&M}} \cdot \text{lifetime}_i) \cdot g + \text{Annual elec output}_i \cdot \text{lifetime}_i \cdot SC_i}$$

$$= \frac{\text{Annual elec output}_i \cdot \text{lifetime}_i}{(CED_i^{\text{New cap}} \cdot (1 + \text{Decomm} + \text{GCF}_i) + CED_i^{\text{O\&M}} \cdot \text{lifetime}_i) \cdot g + \text{Annual elec output}_i \cdot \text{lifetime}_i \cdot SC_i}$$

$$\text{Annual elec output}_i = Cp_i \cdot \text{Installed new cap}_i \cdot 8760 \frac{h}{yr}$$

$i$ : electricity generation technology.

Annual elec output: Annual electricity output.

$Cp$ : capacity factor.

Installed new cap: installed new capacity.

Lifetime: lifetime of the installed infrastructure.

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

$CED^{\text{Decom wear cap}}$ : 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.  $\text{Decomm}=0.1$ .

$CED^{\text{GCF}}$ : 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.

$CED^{\text{O\&M}}$ : 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.



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

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

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<sup>23</sup>), 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:

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

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

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

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:

---

<sup>23</sup> 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).

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

(the term Installed new cap<sub>i</sub>(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<sub>i</sub>(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:

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

- RES variables:

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

CED<sup>overgrids</sup>: cumulative energy demand of overgrids high power and inter-regional grids (HVDCs).

## 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):

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

$$\text{Annual elec output}_i(t) = Cp_i(t) \cdot \text{Installed new cap}_i(t) \cdot 8760 \frac{h}{yr}$$

$Cp(t)$  depends on the level of overcapacity.

$CED_i^{\text{New cap}}(t)$  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).

$CED_i^{\text{decom wear cap}}$ : 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:

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

$g(t)$  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:

- 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):

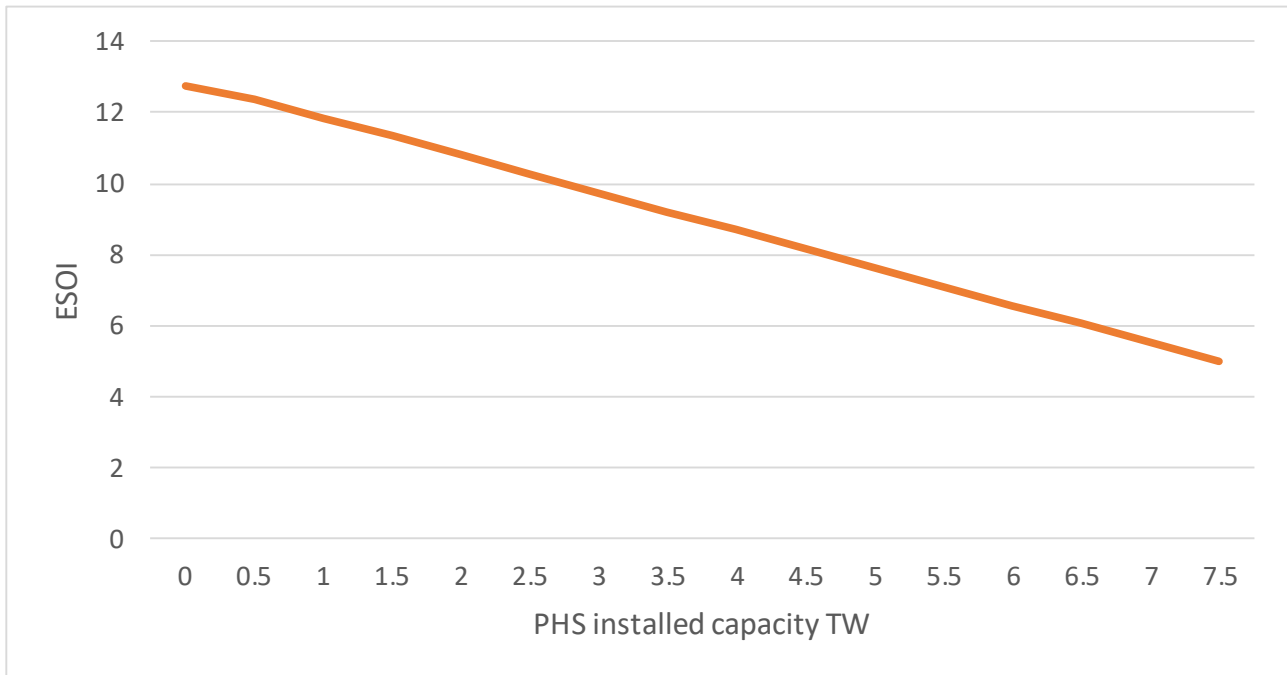


Figure 56: ESOI of PHS as a function of the installed capacity.

- 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

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):

$$EROI_{st}^{grid} = \frac{1 - \phi_i + \phi_i \eta_c}{\frac{1}{EROI_{st}} + \frac{\phi_i \eta_c}{ESOI_c}}$$

Where  $\phi$  represents the fraction of electricity stored,  $\eta_c$  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.

#### **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

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  $j$ :

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

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).

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



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  $NaNO_3$  (>75%).

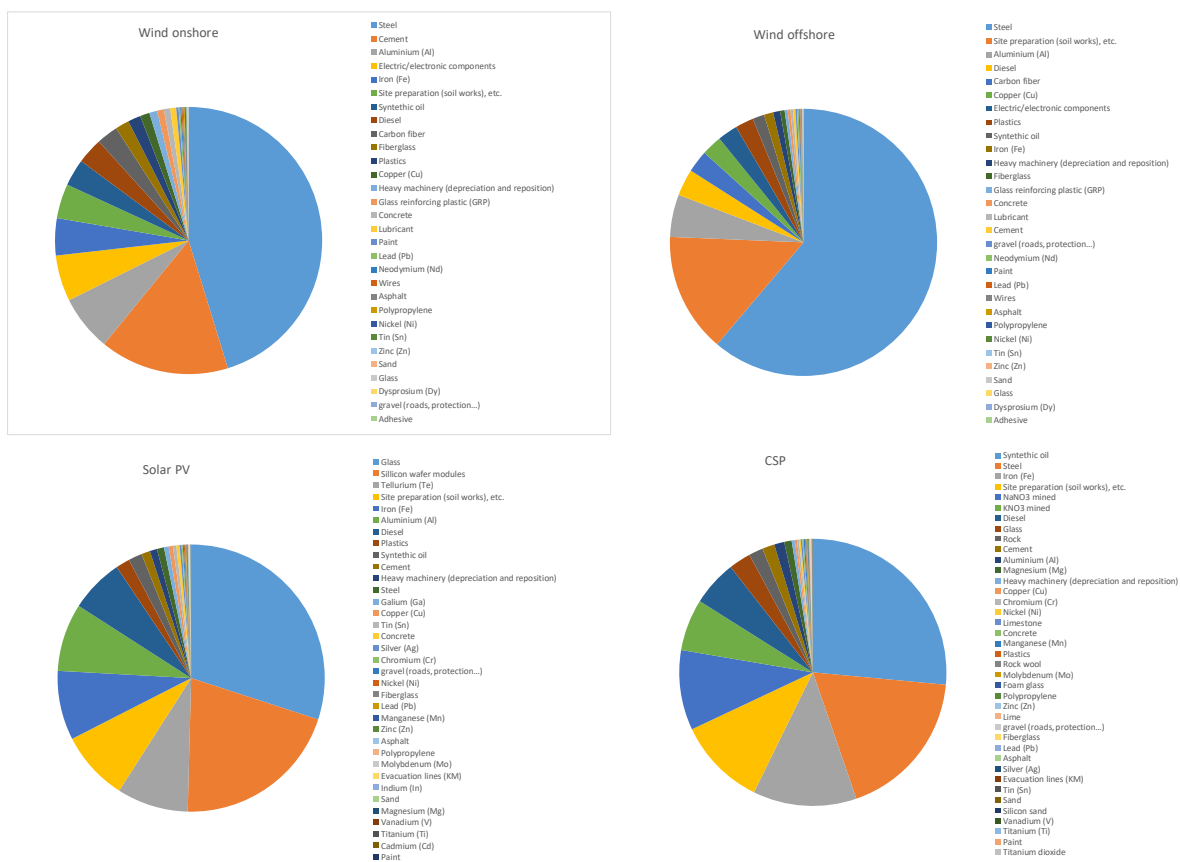


Figure 57 : CED for new installed capacity and operation and maintenance activities (O&M) per material and RES technology. If a material is not used then it is not showed in the legend. In the case of RES variables, it also includes also the material requirements for overgrids high power and inter-regional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

#### 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  $g \approx 0.35$  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  $\sim \frac{1}{4}$  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 ( $\sim 30\%$  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 computers and not space heating), then we might conclude that the quality-corrected EROI is 7.35 [x3 estimated]. But this is a double edged argument. It assumes that PV systems replace already existing electricity generated by fossil or nuclear fuels. The world consumes 59 EJ in electrical form, but a total of 509 EJ 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 require 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  $\sim 11.5$  TW of mean annual electric power would be produced to replace the  $\sim 17$  TW of the present system.

- **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  $g(\text{year}=2015)=0.66$  from MEDEAS. See section 0 for the recycling rates considered for estimating the EROI of dispatchable RES. Values of EROI<sub>pou</sub> can be estimated as EROI<sub>st</sub>-1. \* EROI<sub>st</sub> including additional grids and storage is scenario dependent is not reported here.

Technology	EROI <sub>st</sub> over lifetime (static definition)	Reference
<i>Dispatchable RES</i>		
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)
<i>Variable RES*</i>		
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)
<i>Electricity storage (ESOI)</i>		
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

reference given the relative similarities between both technologies. The review of the literature reveals that oceanic plants are usually characterized by a  $C_p$  between similar levels than wind offshore to 50% lower (IRENA, 2014a, 2014b). As for the other electricity generation technologies, the expected  $C_p$  (projects) tends to be higher than the  $C_p$  from real plants (e.g. for the wave power plant of Mutriku in Spain, a  $C_p$  expected of 0.23 (Torre-Enciso et al., 2009) and a real  $C_p < 0.1$ ). Moreover, oceanic technologies are more material intensive in the construction phase (roughly  $>1000\text{Tn/MW}^{24}$ ), 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  $C_p$  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  $C_p$  of 0.23 and a lifetime of 25 years, the EROI just accounting for concrete would be 2 :1. Hence, considering more realistic values ( $C_p=0.1$ ) and the full material requirements of the complete infrastructure would likely drive the EROI to below 1 :1.

<sup>24</sup> [http://www.tidalenergy.eu/sea\\_gen\\_turbine.html](http://www.tidalenergy.eu/sea_gen_turbine.html)

## 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:<sup>25</sup>

- 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  $C_p$  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

<sup>25</sup> See also (Hall, 2017a).

», 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 « intelligent/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:

$$EROI_{tot}^{elec}(t) = \frac{\sum_i \text{Output electricity over lifetime}_i(t)}{(\sum_i \text{Total CED}_i \text{ over lifetime}_i(t)) \cdot g(t)}$$

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  $EROI_{tot}^{elec}$  of this technology is not considered. The allocation of technologies is thus performed as a function of the  $EROI_{tot}^{elec}$  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.

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  $EROI_{tot}^{elec}$  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 $EROI_{tot}^{elec}$	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  $EROI_{tot}^{elec}$  (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.

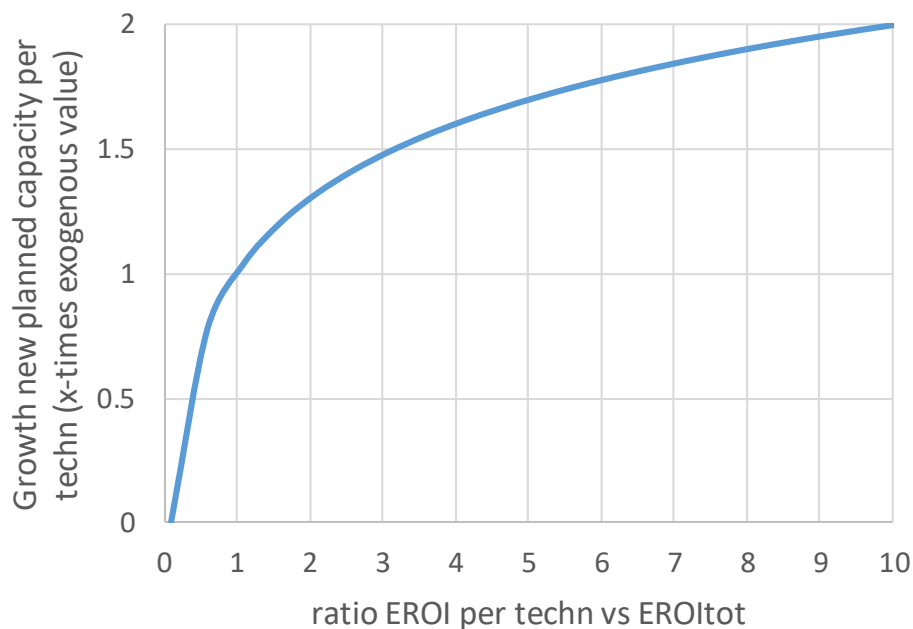


Figure 58: Growth in new planned capacities per technology as a function of the ratio of its EROI and the  $EROI_{elec,tot}$ .

## 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).

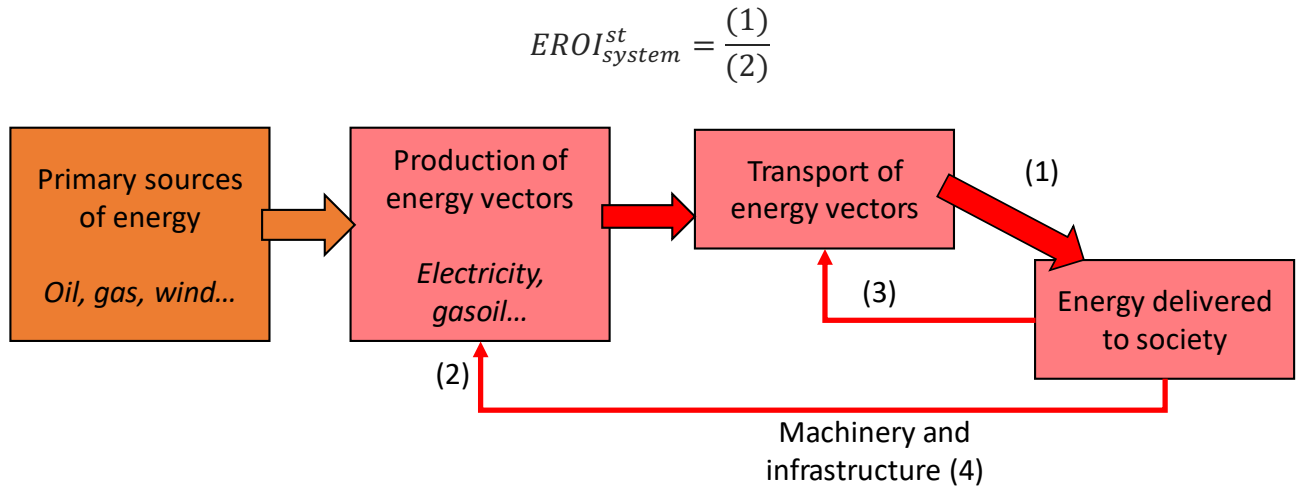


Figure 59: Representation of the energetic metabolism of our society. Red arrows refer to energy flows that are usable by human societies. The orange arrow is a flux of materials with potential energy which can be transformed. An exosomatic intermediary is always required so the useful exosomatic energy 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:



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

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

TFEI<sub>RES elec</sub>: total final energy investments for renewable technologies of electricity generation

TFEI<sub>storage elec</sub>: 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.

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

Given the lower EROI<sub>st</sub> 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 EROI 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 EROI of some energy sources and an overall estimate of all the energy used is made. This EROI is a consequence of the energy mix and the evolution of the EROI 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 EROI.

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):

- EROI<sub>st</sub> (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,
- EROI<sub>pou</sub> (point of use) includes the energy losses derived from the EROI<sub>st</sub>, 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 EROI<sub>st</sub>) plants (as well as the associated energy system).
- EROI<sub>ext</sub> (extended): EROI<sub>pou</sub> 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 EROI<sub>ext</sub> 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 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 EROI<sub>pou</sub> 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 EROI<sub>st</sub> metric instead of EROI<sub>pou</sub> or EROI<sub>ext</sub>.

### **Estimation of the EROI feedback factor**

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 be 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 :

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

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

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

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

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:

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

## 2.5. GHG emissions and climate submodule

### 2.5.1. Endogenous calculation of GHG emissions

The model computes the CO<sub>2</sub> and CH<sub>4</sub> emissions associated with the extraction and burning of fossil fuels (see Table 33). While CO<sub>2</sub> emissions are produced during the combustion of fossil fuels, CH<sub>4</sub> 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<sub>2</sub> and CH<sub>4</sub> 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. 1tCO<sub>2</sub>/toe = 23,8gCO<sub>2</sub>/MJ). \*In the absence of data, it was assumed the same emission coefficient of CH<sub>4</sub> than the respective conventional fuel from (Howarth, 2015) for CTL, GTL and unconventional oil.

Resource		Reference	Emission coefficient	
			CO <sub>2</sub> [gCO <sub>2</sub> /MJ]	CH <sub>4</sub> [gCH <sub>4</sub> /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*

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<sub>2</sub>/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.

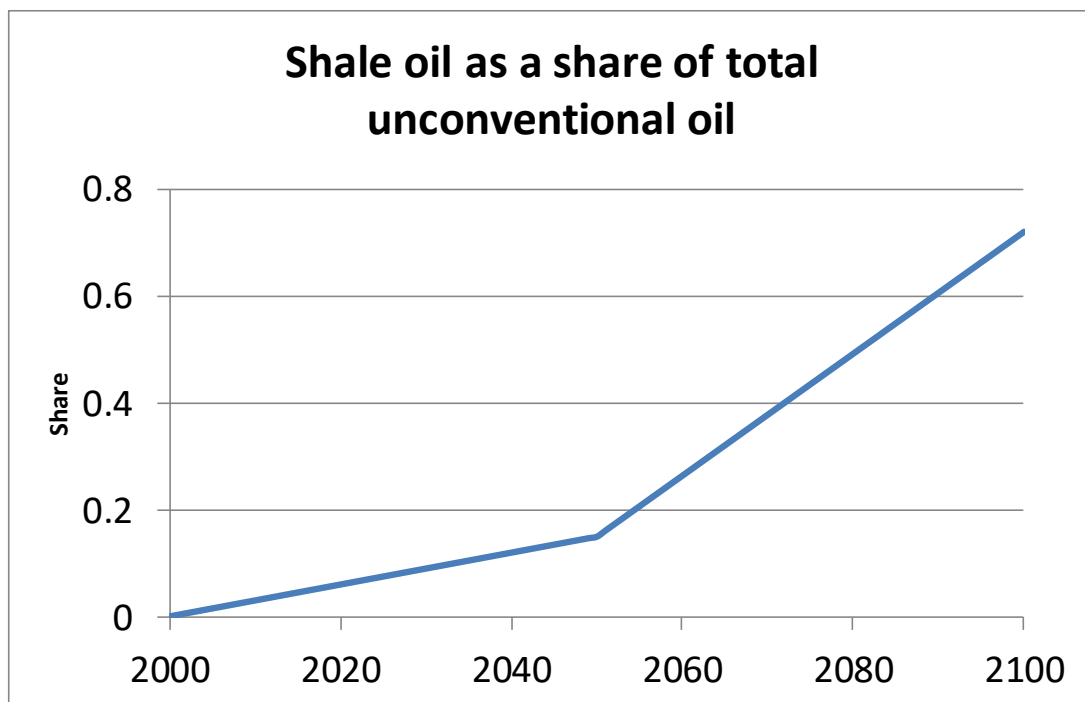


Figure 60: Shale oil as a share of total unconventional oil as estimated by (Mohr and Evans, 2010) (low case).

For projecting future emissions of the rest of GHG included in the model (CH<sub>4</sub>, N<sub>2</sub>O, PFCs, SF<sub>6</sub> and HFCs), the user can exogenously select a RCP pathway.

## 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 laptop 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 disadvantages 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 important to keep in mind that the followed modeling philosophy in 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 :

- 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.



### 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 CO<sub>2</sub> emissions endogenously generated by the model enter the carbon cycle representation, which estimates the level of CO<sub>2</sub> concentration in the atmosphere, the other GHG cycles which together contribute to the anthropogenic climate change. The cycle of each GHG is modelled separately, including the interaction between cycles such as between the CH<sub>4</sub> and the N<sub>2</sub>O, 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.

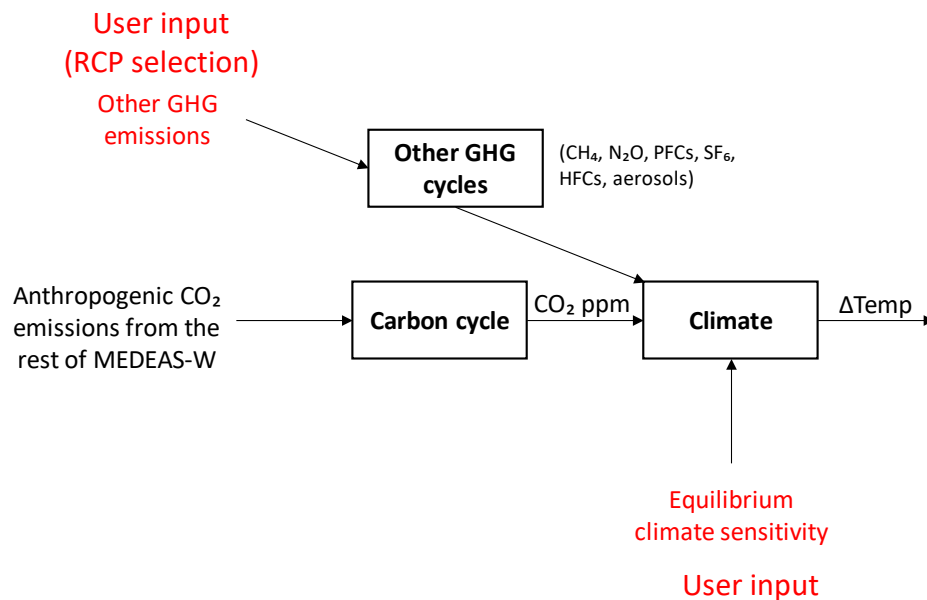


Figure 61 : Structure of the climate module in MEDEAS-World.

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.

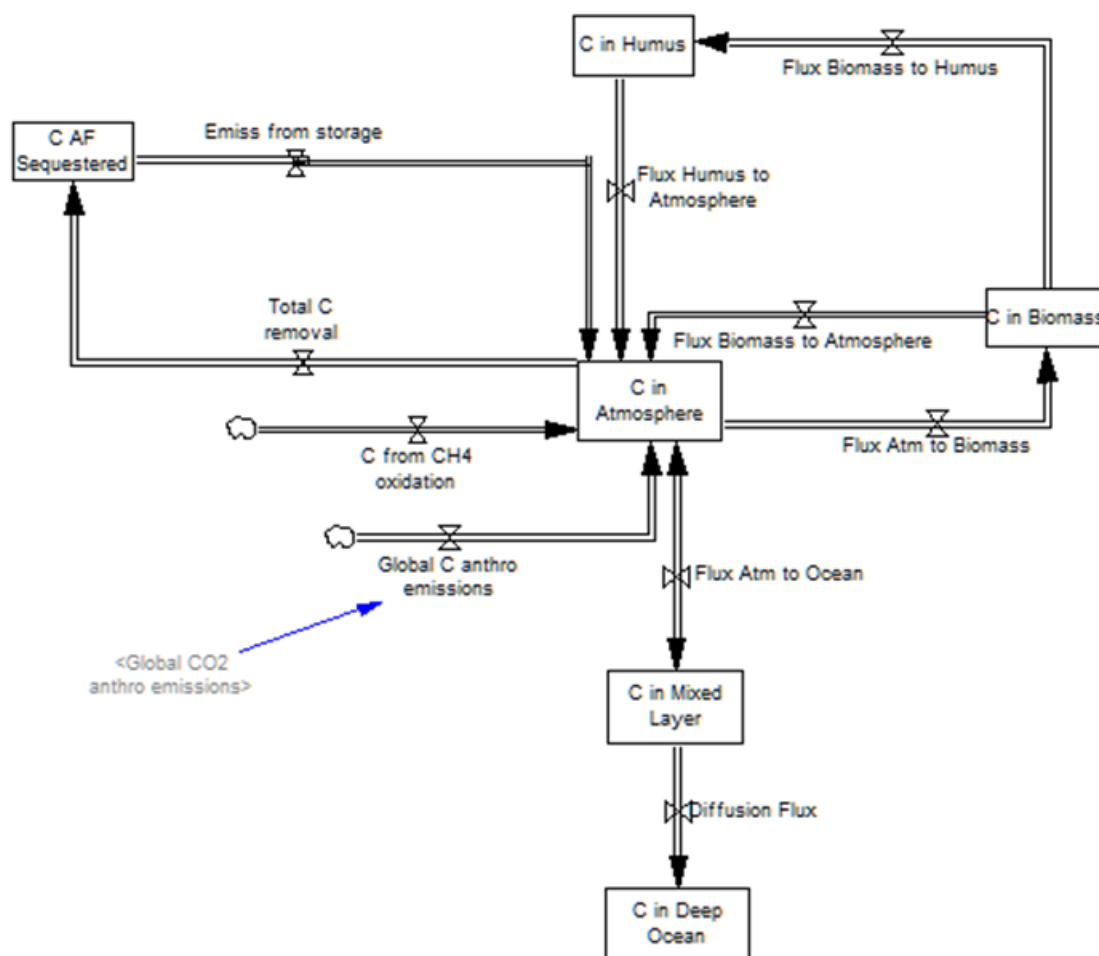


Figure 62 : Carbon cycle representation in MEDEAS-W.

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<sub>4</sub>, N<sub>2</sub>O, PFCs, SF<sub>6</sub> 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 of the climate cycle as the equilibrium climate sensitivity, which is set to the standard value of 2.9 °C by default. This part of the climate module has not significantly changed from the previous MEDEAS-W model version.

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<sub>2</sub> 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).

### 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”.<sup>26</sup> 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

---

<sup>26</sup> 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.”

damage (if any) 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):

- 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<sub>2</sub>e 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<sub>2</sub> 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<sup>2</sup> 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.

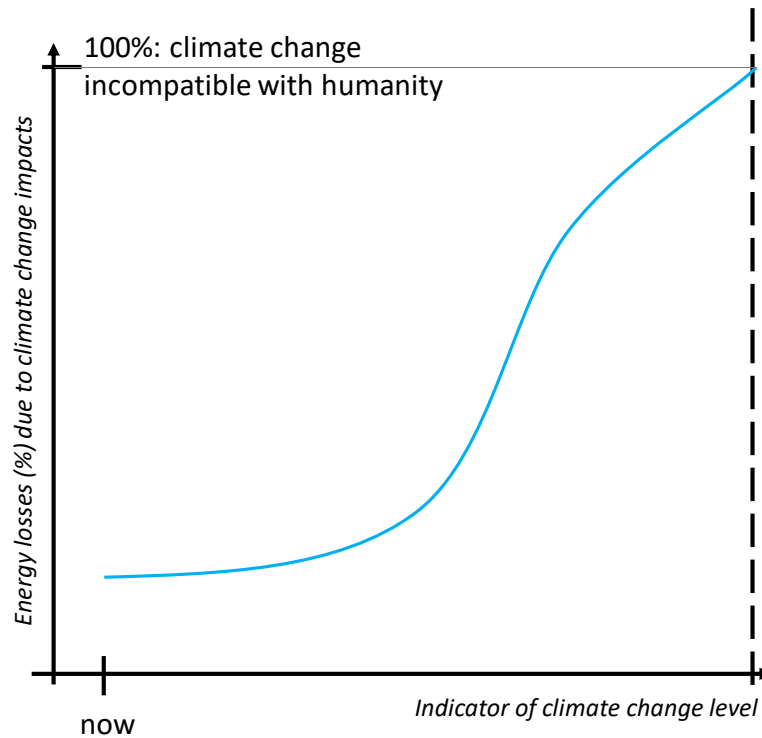


Figure 63: Qualitative representation of the energy loss function (ELF) applied in the MEDEAS framework.

In the standard version of MEDEAS an ELF with a logistic shape that uses CO<sub>2</sub> 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.

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):

$$FEC(t)_i^* = FEC(t)_i \cdot (1 - EL(t))$$

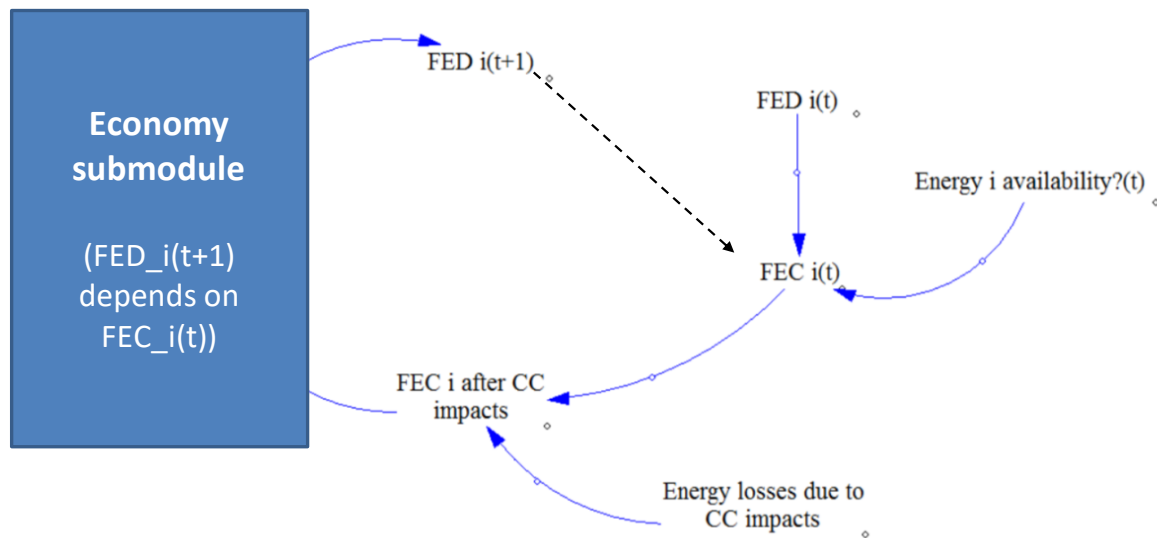


Figure 64: Implementation in MEDEAS framework of the energy losses due to climate change impacts.



## 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.

## 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 than 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).

## 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.

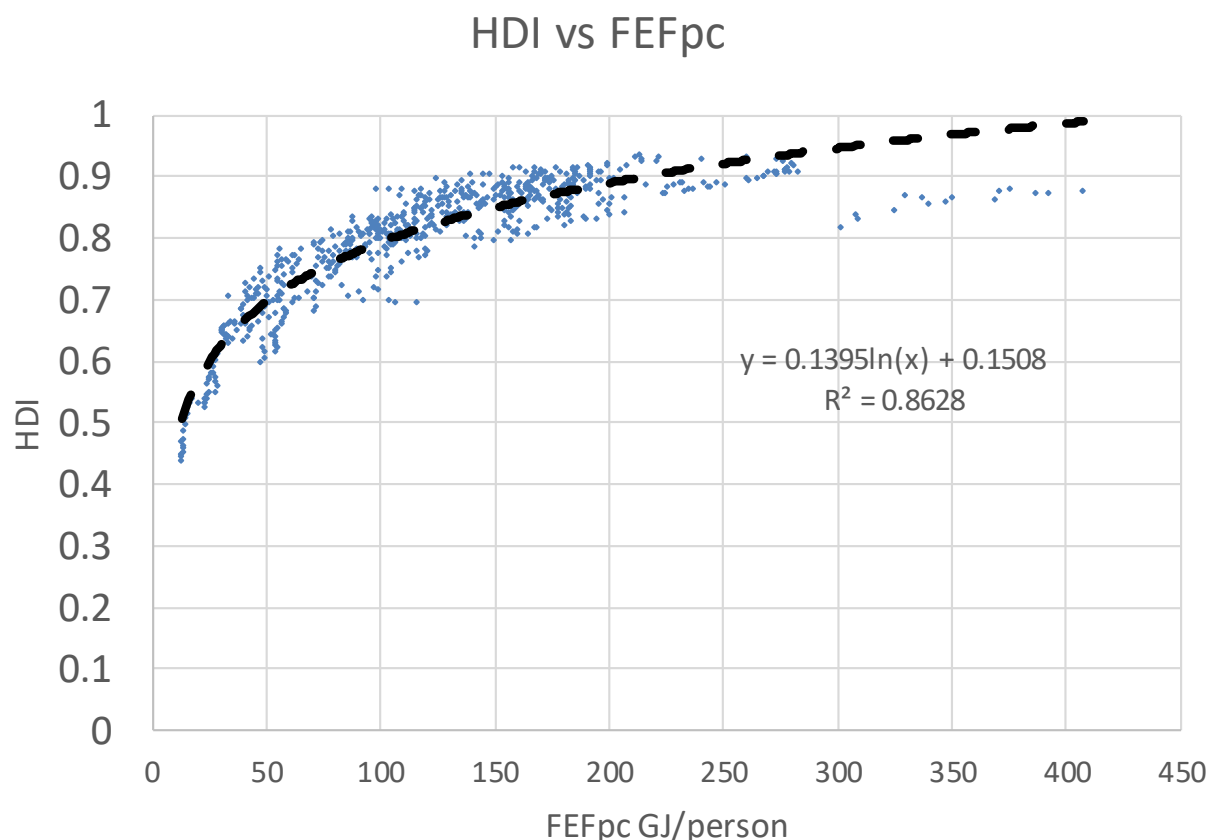


Figure 65: HDI vs Final Energy Footprint per capita (FEFpc) for 40 countries (1995-2009). Source: own work from data from (Iñaki Arto et al., 2016). Regressions published in the paper refer to primary energy, however from the point of view of the quality of life and in the context of scenarios of penetration 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).

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

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 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 km<sup>3</sup>) 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 km<sup>3</sup> each year and about 65% of total demand is consumed. Industrial use of water is estimated to be around 975 km<sup>3</sup> 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 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).



### 2.7.3.2. Data

Data are 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:

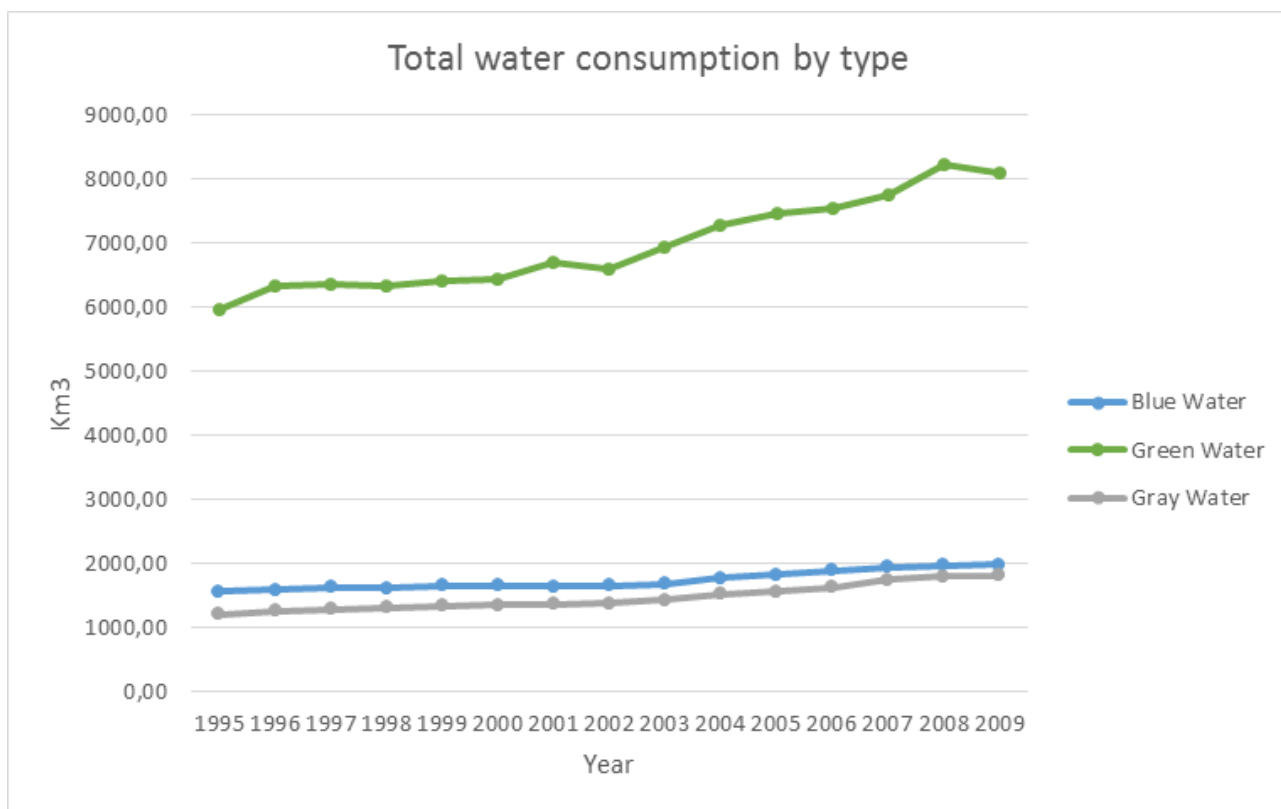


Figure 66: Global water consumption (1995-2009) by type from WIOD database.

### 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

### Estimation of water consumption by type (blue, green and gray)

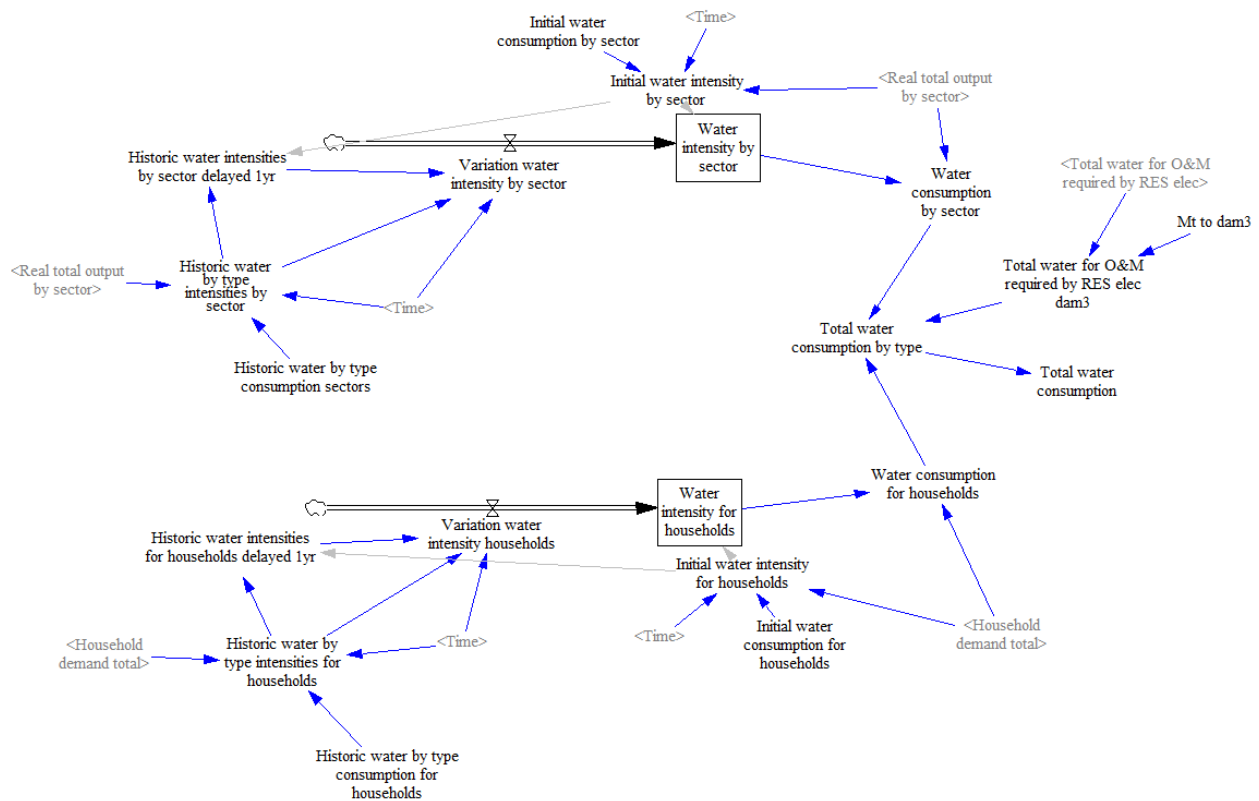


Figure 67: Stock and flow diagram of the estimation of water use in MEDEAS.

### 2.7.3.4. Water potential

Most (99%) offstream water uses – irrigation, domestic, industry and energy – are met by withdrawals<sup>27</sup> from renewable sources, either surface water or groundwater. Less than 1% (currently estimated at 30 km<sup>3</sup> 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 km<sup>3</sup> (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  $3,829/54\% = 7,091 \text{ km}^3$ . 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<sup>3</sup>.

---

<sup>27</sup> Water withdrawal is the gross amount of water extracted from any source in the natural environment for human purposes (Box 7.2 (UNESCO, 2009)).

### 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 “adaptive scenarios”.

	Policy targets/hypotheses
Socioeconomic inputs	GDPpc* Population*
Replacement of existing technologies by alternative low carbon technologies	Electricity* (8 renewables, nuclear <sup>28</sup> ) 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

<sup>28</sup> 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)

Other GHG (not endogenously modelled)	Selection of RCP scenario
---------------------------------------	---------------------------

Table 34 : Main policy targets included 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).

## 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<sub>2</sub> 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 2°C (or 2.6 W/m<sup>2</sup>, 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 CO<sub>2</sub> 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:



- 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<sup>29</sup>), 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 ( $g$ ):

$$\chi^i = \prod_j \chi_j^i$$

$$\chi_j^i = 1 - \frac{1}{EROI_j^i}$$

$$EROI^i = \frac{1}{\frac{1 - \chi^i}{g}}$$

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):

<sup>29</sup> 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).

$$\chi^{coal+CCS} = \frac{\left(\frac{1}{1-46}\right) \cdot (1 - 0.0057 \cdot 1.5) \cdot (1 - 0.0262 \cdot 1.5) \cdot (1 - 0.01 \cdot 1.5) \cdot (1 - 0.06)}{1.25}$$

$$EROI_{st}^{coal+CCS} = \frac{1}{1 - \chi^{coal+CCS} \cdot g}$$

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
EROI <sub>st</sub> 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 infrastructure	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
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 EROI<sub>pou</sub> 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 EROI<sub>pou</sub> < 1. In the light of these results, the technology BECCS 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.

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 or 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).<sup>30</sup> 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

<sup>30</sup> 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.

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 <2°C 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/m<sup>2</sup> (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)), 6,9TnCO<sub>2</sub>/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 CO<sub>2</sub> (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.

Additionally, IAMs and LCAs usually assume bioenergy carbon neutrality, i.e. that the CO<sub>2</sub> released from their combustion matches the CO<sub>2</sub> 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 CO<sub>2</sub> emissions... [far] from the 100% assumption made by LCA and other GHG accounting methods that assume 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 precautionary 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<sup>-1</sup>/year in warm and dry climates, and to 100–1 000 kgC ha<sup>-1</sup>/year in humid and cool climates. Although more research in this field is needed, and the actual values of these potential are questioned by some researchers (Baker et al., 2007; Powlson et al., 2011; Sommer and Bossio, 2014), RMP's are technologies interesting by 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 GtCO<sub>2</sub> of negative emissions based in ecosystem restoration and reforestation (0GtCO<sub>2</sub> for BECCS). However, these options also face land limitations: annual negative emissions of 1.1–3.3 Gt Ceq yr<sup>-1</sup> 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 (Karthä and Dooley, 2016).

## 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 hydrogen 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 1 liter of hydrogen at atmospheric conditions equals to 13KJ –thermal-, 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<sub>2</sub>, 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,<sup>31</sup> 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 hydrogen.

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).

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

---

<sup>31</sup> (Bernal-Aguistin and Dufo-López, 2008) also report an efficiency of the whole chain RES electricity-hydrogene-electricity of around 30%.

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. Hacetoglu 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  $\ll 1$ .

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).



### 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 difficult 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 between 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 research. 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 Russia, 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.

## 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).

## 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, EROI<sub>pou</sub> and EROI<sub>ext</sub> of the whole system.

### Interaction of Energy and Economy

- 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.

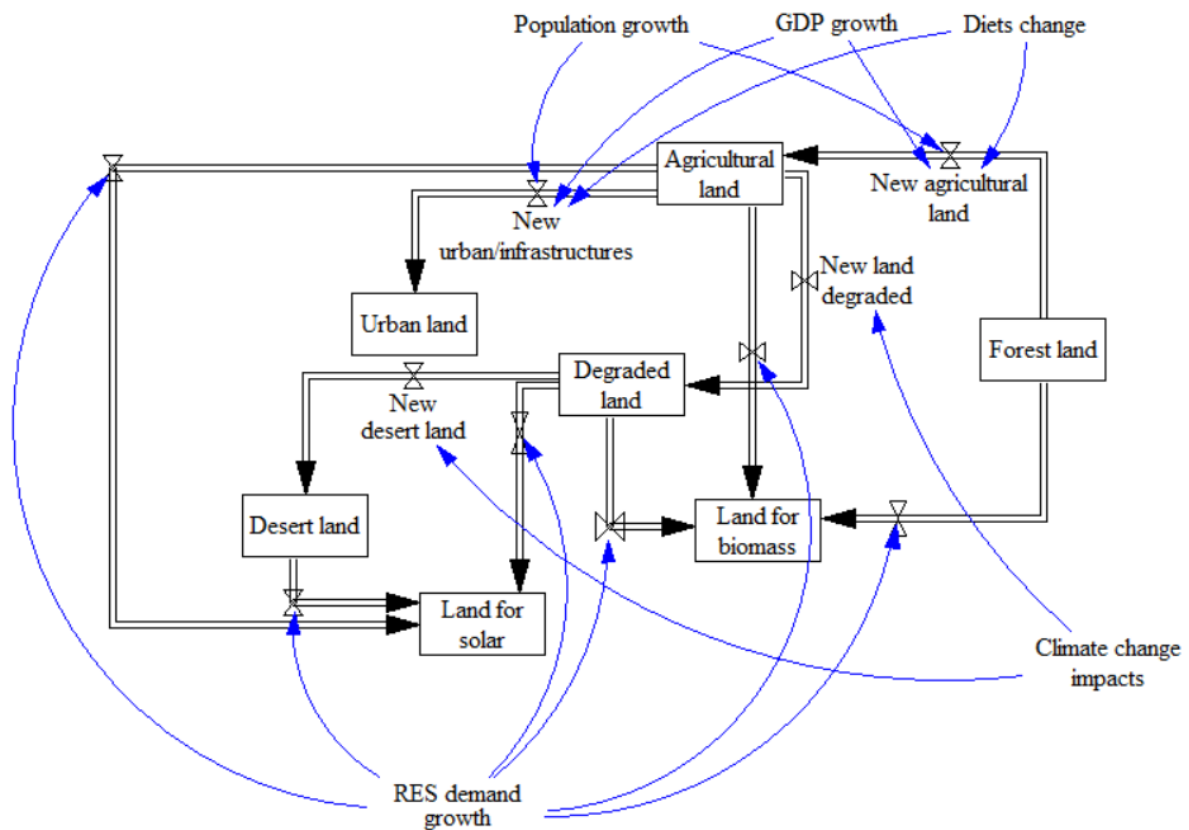


Figure 68: Modelling approach of the land-use module in MEDEAS framework. However this structure has not been finally included in the current version of the model.

## 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

- 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.

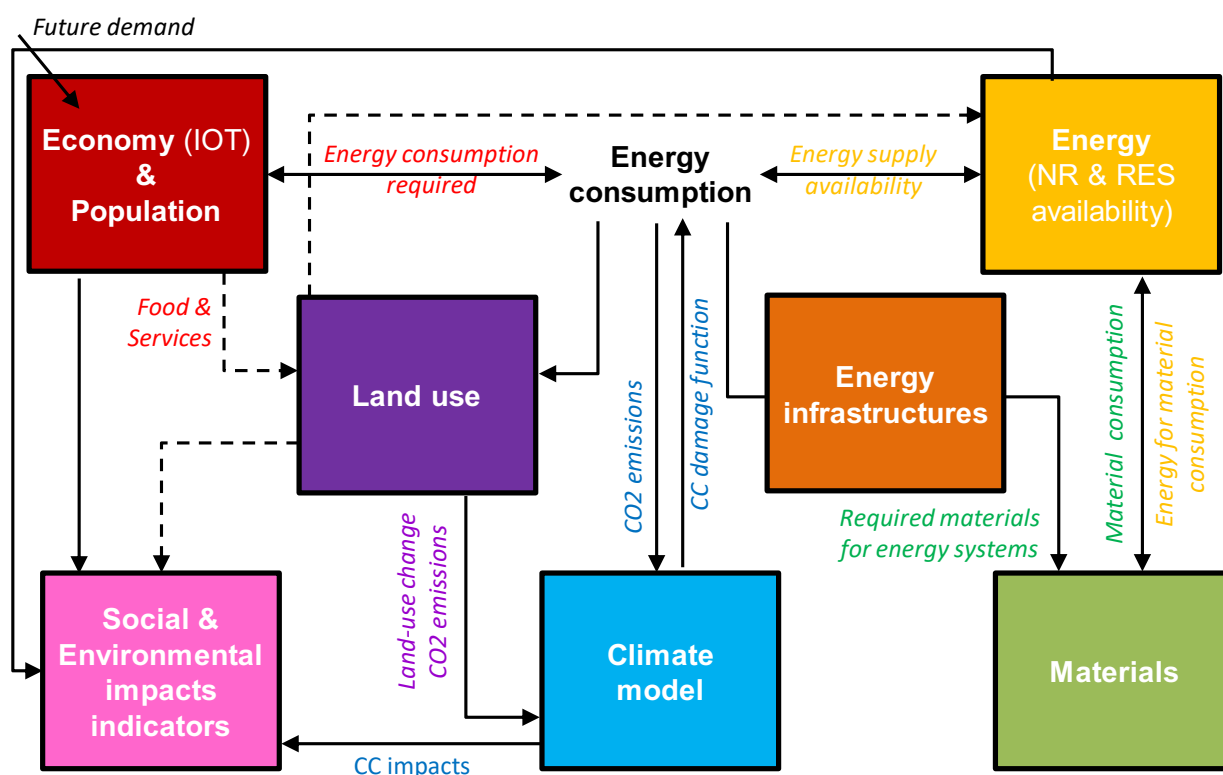


Figure 69: Overview of MEDEAS-World by modules. Straight lines represent relationships currently modelled, while dashed lines represent future potential developments.

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;

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).

## 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 (Daiglou et al., 2014; García-Olivares, 2015).
- Possibility to keep fossil fuel resources in the ground (McGlade and Ekins, 2015).



## 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

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.

## Acknowledgements

The authors gratefully acknowledge Iñaki Arto for assisting with the interpretation and use of the WIOD database and Robert W. Howarth for sharing his data in relation to methane emissions of fossil fuels.

## References

- Abbasi, T., Abbasi, S.A., 2012. Is the Use of Renewable Energy Sources an Answer to the Problems of Global Warming and Pollution? *Crit. Rev. Environ. Sci. Technol.* 42, 99–154. <https://doi.org/10.1080/10643389.2010.498754>
- Abbasi, T., Abbasi, S.A., 2011. ‘Renewable’ hydrogen: Prospects and challenges. *Renew. Sustain. Energy Rev.* 15, 3034–3040. <https://doi.org/10.1016/j.rser.2011.02.026>
- Alcamo, J., Leemans, R., Kreileman, E., 1998. Global change scenarios of the 21st century: results from the IMAGE 2.1 model. Pergamon, Tarrytown, N.Y.
- Aleklett, K., Höök, M., Jakobsson, K., Lardelli, M., Snowden, S., Söderbergh, B., 2010. The Peak of the Oil Age – Analyzing the world oil production Reference Scenario in World Energy Outlook 2008. *Energy Policy* 38, 1398–1414. <https://doi.org/10.1016/j.enpol.2009.11.021>
- Ali, S.H., Giurco, D., Arndt, N., Nickless, E., Brown, G., Demetriades, A., Durrheim, R., Enriquez, M.A., Kinnaird, J., Littleboy, A., others, 2017. Mineral supply for sustainable development requires resource governance. *Nature* 543, 367–372.
- ALIVE, 2016. D6.5: Report on LCA results for utilization phase model (No. Deliverable 6.5).
- Alsema, E.A., de Wild-Scholten, M.J., 2006. Environmental impacts of crystalline silicon photovoltaic module production, in: *Materials Research Society Symposium Proceedings*. Warrendale, Pa.; Materials Research Society; 1999, p. 73.
- Anderson, K., 2015. Duality in climate science. *Nat. Geosci.* advance online publication. <https://doi.org/10.1038/ngeo2559>
- Anderson, K., Peters, G., 2016. The trouble with negative emissions. *Science* 354, 182–183. <https://doi.org/10.1126/science.aah4567>
- Anseeuw, W., Boche, M., Breu, T., Giger, M., Lay, J., Messerli, P., Nolte, K., 2012. Transnational Land Deals for Agriculture in the Global South.
- Armaroli, N., Balzani, V., 2011. Towards an electricity-powered world. *Energy Environ. Sci.* 4, 3193–3222. <https://doi.org/10.1039/C1EE01249E>
- Arto, I., Andreoni, V., Rueda-Cantuche, J.M., 2016. Global use of water resources: A multiregional analysis of water use, water footprint and water trade balance. *Water Resour. Econ.* 15, 1–14. <https://doi.org/10.1016/j.wre.2016.04.002>
- Arto, Iñaki, Capellán-Pérez, I., Lago, R., Bueno, G., Bermejo, R., 2016. The energy requirements of a developed world. *Energy Sustain. Dev.* 33, 1–13. <https://doi.org/10.1016/j.esd.2016.04.001>
- Arvesen, A., Hertwich, E.G., 2012. Assessing the life cycle environmental impacts of wind power: A review of present knowledge and research needs. *Renew. Sustain. Energy Rev.* 16, 5994–6006. <https://doi.org/10.1016/j.rser.2012.06.023>
- ASPO, 2009. ASPO Newsletter n. 100.
- Baker, J.M., Ochsner, T.E., Venterea, R.T., Griffis, T.J., 2007. Tillage and soil carbon sequestration—What do we really know? *Agric. Ecosyst. Environ.* 118, 1–5. <https://doi.org/10.1016/j.agee.2006.05.014>

- Balmford, A., Green, R.E., Scharlemann, J.P.W., 2005. Sparing land for nature: exploring the potential impact of changes in agricultural yield on the area needed for crop production. *Glob. Change Biol.* 11, 1594–1605. <https://doi.org/10.1111/j.1365-2486.2005.001035.x>
- Bardi, U., 2017. *The Seneca Effect: Why Growth is Slow but Collapse is Rapid*. Springer.
- Bardi, U., 2014. *Extracted: How the Quest for Mineral Wealth Is Plundering the Planet*. Chelsea Green Publishing, White River Junction, Vermont.
- Bardi, U., Pagani, M., 2007. Peak minerals. *Oil Drum* 15.
- Barnhart, C.J., Dale, M., Brandt, A.R., Benson, S.M., 2013. The energetic implications of curtailing versus storing solar- and wind-generated electricity. *Energy Environ. Sci.* 6, 2804–2810. <https://doi.org/10.1039/C3EE41973H>
- Bermejo, R., 2014. *Handbook for a Sustainable Economy*. Springer.
- Bernal-Agustín, J.L., Dufo-López, R., 2008. Hourly energy management for grid-connected wind–hydrogen systems. *Int. J. Hydrog. Energy* 33, 6401–6413. <https://doi.org/10.1016/j.ijhydene.2008.08.026>
- Boccard, N., 2009. Capacity factor of wind power realized values vs. estimates. *Energy Policy* 37, 2679–2688. <https://doi.org/10.1016/j.enpol.2009.02.046>
- Bouwman, A., Kram, T., Goldewijk, K.K., 2006. Integrated modelling of global environmental change: an overview of IMAGE 2.4. Netherlands Environmental Assessment Agency, Bilthoven.
- Boyer, D., 2014. Energopower: An Introduction. *Anthropol. Q.* 87, 309–333. <https://doi.org/10.1353/anq.2014.0020>
- BP, 2017. BP Statistical Review of World Energy June 2017, Statistical Review of World Energy. British Petroleum.
- BP, 2016. BP Statistical Review of World Energy June 2016, Statistical Review of World Energy. British Petroleum.
- BP, 2015. BP Statistical Review of World Energy June 2015, Statistical Review of World Energy. British Petroleum.
- BP, 2013. BP Statistical Review of World Energy June 2013, Statistical Review of World Energy. British Petroleum.
- Brandt, A.R., 2017. How Does Energy Resource Depletion Affect Prosperity? Mathematics of a Minimum Energy Return on Investment (EROI). *Biophys. Econ. Resour. Qual.* 2, 2. <https://doi.org/10.1007/s41247-017-0019-y>
- Brandt, A.R., Farrell, A.E., 2007. Scraping the bottom of the barrel: greenhouse gas emission consequences of a transition to low-quality and synthetic petroleum resources. *Clim. Change* 84, 241–263. <https://doi.org/10.1007/s10584-007-9275-y>
- Briens, F., 2015. Investigating Pathways to Post-Growth Economies Through Prospective Macroeconomic Modeling: Vision and Scenarios for France. Presented at the Presentation at the 11th Biennial Conference of the European Society for Ecological Economics, Leeds.
- Brower, M., Barton, M., Lledó, L., Dubois, J., 2013. A study of wind speed variability using global reanalysis data. AWS Truepower.
- Cai, Y., Lenton, T.M., Lontzek, T.S., 2016. Risk of multiple interacting tipping points should encourage rapid CO2 emission reduction. *Nat. Clim. Change* 6, 520–525. <https://doi.org/10.1038/nclimate2964>

- Calvo, G., 2016. Exergy assessment of mineral extraction, trade and depletion. University of Zaragoza, Centro de Investigación de Recursos y Consumos Energéticos (CIRCE).
- Calvo, G., Mudd, G., Valero, Alicia, Valero, Antonio, 2016. Decreasing Ore Grades in Global Metallic Mining: A Theoretical Issue or a Global Reality? *Resources* 5, 36. <https://doi.org/10.3390/resources5040036>
- Calvo, G., Valero, Alicia, Valero, Antonio, 2017. Assessing maximum production peak and resource availability of non-fuel mineral resources: Analyzing the influence of extractable global resources. *Resour. Conserv. Recycl.* 125, 208–217. <https://doi.org/10.1016/j.resconrec.2017.06.009>
- Campbell, J.E., Lobell, D.B., Genova, R.C., Field, C.B., 2008. The Global Potential of Bioenergy on Abandoned Agriculture Lands. *Environ. Sci. Technol.* 42, 5791–5794. <https://doi.org/10.1021/es800052w>
- Capellán-Pérez, I., 2016a. Development and Application of Environmental Integrated Assessment Modelling towards Sustainability. University of the Basque Country, Bilbao, Spain.
- Capellán-Pérez, I., 2016b. Development and Application of Environmental Integrated Assessment Modelling towards Sustainability. University of the Basque Country, Bilbao, Spain.
- Capellán-Pérez, I., Arto, I., M. Polanco-Martínez, J., González-Eguino, M., B. Neumann, M., 2016a. Likelihood of climate change pathways under uncertainty on fossil fuel resource availability. *Energy Environ. Sci.* 9, 2482–2496. <https://doi.org/10.1039/C6EE01008C>
- Capellán-Pérez, I., Arto, I., Polanco-Martínez, J.M., González-Eguino, M., Neumann, M.B., 2016b. Likelihood of climate change pathways under uncertainty on fossil fuel resource availability. *Energy Environ. Sci.* 9, 2482–2496. <https://doi.org/10.1039/C6EE01008C>
- Capellán-Pérez, I., de Castro, C., 2017. Integration of global environmental change threat to human societies in energy-economy-environment models. Presented at the 12th Conference of the European Society for Ecological Economics, Budapest (Hungary).
- Capellán-Pérez, I., de Castro, C., Arto, I., 2017a. Assessing vulnerabilities and limits in the transition to renewable energies: Land requirements under 100% solar energy scenarios. *Renew. Sustain. Energy Rev.* 77, 760–782. <https://doi.org/10.1016/j.rser.2017.03.137>
- Capellán-Pérez, I., de Castro, C., Mediavilla, M., Miguel, L.J., de Blas Sanz, I., Carpintero, Ó., Frechoso, F., Nieto, J., 2017b. World Limits Model (WoLiM) 1.5- Model Documentation. Technical Report. Energy, Economy and System Dynamics Group of the University of Valladolid, Spain.
- Capellán-Pérez, I., Mediavilla, M., Castro, C. de, Carpintero, Ó., Miguel, L.J., 2015. More growth? An unfeasible option to overcome critical energy constraints and climate change. *Sustain. Sci.* 10, 397–411. <https://doi.org/10.1007/s11625-015-0299-3>
- Capellán-Pérez, I., Mediavilla, M., de Castro, C., Carpintero, Ó., Miguel, L.J., 2014. Fossil fuel depletion and socio-economic scenarios: An integrated approach. *Energy* 77, 641–666. <https://doi.org/10.1016/j.energy.2014.09.063>
- Carbajales-Dale, M., Barnhart, C.J., Brandt, A.R., Benson, S.M., 2014. A better currency for investing in a sustainable future. *Nat. Clim. Change* 4, 524–527. <https://doi.org/10.1038/nclimate2285>
- Carbajales-Dale, M., Raugei, M., Fthenakis, V., Barnhart, C., 2015. Energy return on investment (EROI) of solar PV: an attempt at reconciliation [point of view]. *Proc. IEEE* 103, 995–999.
- Christensen, P.P., 1989. Historical roots for ecological economics — Biophysical versus allocative approaches. *Ecol. Econ.* 1, 17–36. [https://doi.org/10.1016/0921-8009\(89\)90022-0](https://doi.org/10.1016/0921-8009(89)90022-0)

- Cochran, T.B., Feiveson, H.A., Patterson, W., Pshakin, G., Ramana, M., Schneider, M., Suzuki, T., von Hippel, F., 2010. Fast breeder reactor programs: history and status. *Int. Panel Fissile Mater.*
- Cordier, M., Uehara, T., Weih, J., Hamaide, B., 2017. An Input-output Economic Model Integrated Within a System Dynamics Ecological Model: Feedback Loop Methodology Applied to Fish Nursery Restoration. *Ecol. Econ.* 140, 46–57. <https://doi.org/10.1016/j.ecolecon.2017.04.005>
- Cormos, C.-C., 2012. Integrated assessment of IGCC power generation technology with carbon capture and storage (CCS). *Energy*, 8th World Energy System Conference, WESC 2010 42, 434–445. <https://doi.org/10.1016/j.energy.2012.03.025>
- Corsten, M., Ramírez, A., Shen, L., Koornneef, J., Faaij, A., 2013. Environmental impact assessment of CCS chains – Lessons learned and limitations from LCA literature. *Int. J. Greenh. Gas Control* 13, 59–71. <https://doi.org/10.1016/j.ijggc.2012.12.003>
- Costanza, R., Kubiszewski, I., Giovannini, E., Lovins, H., McGlade, J., Pickett, K.E., Ragnarsdóttir, K.V., Roberts, D., De Vogli, R., Wilkinson, R., 2014. Development: Time to leave GDP behind. *Nature* 505, 283–285. <https://doi.org/10.1038/505283a>
- Cottrell, F., 1955. *Energy and society: the relation between energy, social changes, and economic development*. McGraw-Hill.
- Cramer, W., Kicklighter, D.W., Bondeau, A., Iii, B.M., Churkina, G., Nemry, B., Ruimy, A., Schloss, A.L., Intercomparison, T.P.O.T.P.N.M., 1999. Comparing global models of terrestrial net primary productivity (NPP): overview and key results. *Glob. Change Biol.* 5, 1–15. <https://doi.org/10.1046/j.1365-2486.1999.00009.x>
- Creutzig, F., Ravindranath, N.H., Berndes, G., Bolwig, S., Bright, R., Cherubini, F., Chum, H., Corbera, E., Delucchi, M., Faaij, A., Fargione, J., Haberl, H., Heath, G., Lucon, O., Plevin, R., Popp, A., Robledo-Abad, C., Rose, S., Smith, P., Stromman, A., Suh, S., Masera, O., 2014. Bioenergy and climate change mitigation: an assessment. *GCB Bioenergy* n/a-n/a. <https://doi.org/10.1111/gcbb.12205>
- Crimmins, A., Balbus, J., Gamble, J., Beard, C., Bell, J., Dodgen, D., Eisen, R., Fann, N., Hawkins, M., Herring, S., Jantarasami, D., Mills, D., Saha, S., Sarofim, M., Trtanj, J., Ziska, L., 2016. The impacts of climate change on human health in the United States: a scientific assessment. U.S. Global Change Research Program, Washington DC (USA).
- Cuéllar-Franca, R.M., Azapagic, A., 2015. Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts. *J. CO2 Util.* 9, 82–102. <https://doi.org/10.1016/j.jcou.2014.12.001>
- Cumming, G.S., Alcamo, J., Sala, O., Swart, R., Bennett, E.M., Zurek, M., 2005. Are Existing Global Scenarios Consistent with Ecological Feedbacks? *Ecosystems* 8, 143–152. <https://doi.org/10.1007/s10021-004-0075-1>
- Dafermos, Y., Papatheodorou, C., 2015. Linking functional with personal income distribution: a stock-flow consistent approach. *Int. Rev. Appl. Econ.* 29, 787–815. <https://doi.org/10.1080/02692171.2015.1054365>
- Daily, G., 1997. *Nature's services: societal dependence on natural ecosystems*. Island Press.
- Daioglou, V., Faaij, A.P.C., Saygin, D., Patel, M.K., Wicke, B., Vuuren, D.P. van, 2014. Energy demand and emissions of the non-energy sector. *Energy Environ. Sci.* 7, 482–498. <https://doi.org/10.1039/C3EE42667J>



- Dale, M., 2012. Meta-analysis of non-renewable energy resource estimates. *Energy Policy* 43, 102–122. <https://doi.org/10.1016/j.enpol.2011.12.039>
- Dale, M., Krumdieck, S., Bodger, P., 2012a. Global energy modelling — A biophysical approach (GEMBA) part 1: An overview of biophysical economics. *Ecol. Econ.* 73, 152–157. <https://doi.org/10.1016/j.ecolecon.2011.10.014>
- Dale, M., Krumdieck, S., Bodger, P., 2012b. Global energy modelling — A biophysical approach (GEMBA) Part 2: Methodology. *Ecol. Econ.* 73, 158–167. <https://doi.org/10.1016/j.ecolecon.2011.10.028>
- Dale, M., Krumdieck, S., Bodger, P., 2011. A Dynamic Function for Energy Return on Investment. *Sustainability* 3, 1972–1985. <https://doi.org/10.3390/su3101972>
- Danielsen, F., Beukema, H., Burgess, N.D., Parish, F., Brühl, C.A., Donald, P.F., Murdiyarso, D., Phalan, B., Reijnders, L., Struebig, M., Fitzherbert, E.B., 2009. Biofuel Plantations on Forested Lands: Double Jeopardy for Biodiversity and Climate. *Conserv. Biol.* 23, 348–358. <https://doi.org/10.1111/j.1523-1739.2008.01096.x>
- Daudey, E., García-Peñalosa, C., 2007. The personal and the factor distributions of income in a cross-section of countries. *J. Dev. Stud.* 43, 812–829. <https://doi.org/10.1080/00220380701384406>
- de Castro, C., 2012. Global Solar Electric Power Potential: Technical and Ecological Limits (Working Paper.). Research Group in Energy, Economy and System Dynamics of the University of Valladolid, Valladolid, Spain.
- de Castro, C., 2009. Escenarios de Energía-Economía mundiales con modelos de dinámica de sistemas. University of Valladolid, Valladolid, Spain.
- De Castro, C., Capellán-Pérez, I., 2018. Concentrated Solar Power: actual performance and foreseeable future in high penetration scenarios of renewable energies. *Work. Pap. Univ. Valladolid.*
- de Castro, C., Carpintero, Ó., Frechoso, F., Mediavilla, M., de Miguel, L.J., 2014. A top-down approach to assess physical and ecological limits of biofuels. *Energy* 64, 506–512. <https://doi.org/10.1016/j.energy.2013.10.049>
- de Castro, C., Carpintero, Ó., Frechoso, F., Mediavilla, M., Miguel, L.J., 2013a. A top-down approach to assess physical and ecological limits of biofuels. *Accept. Publ. Energy.*
- de Castro, C., Mediavilla, M., Miguel, L.J., Frechoso, F., 2013b. Global solar electric potential: A review of their technical and sustainable limits. *Renew. Sustain. Energy Rev.* 28, 824–835. <https://doi.org/10.1016/j.rser.2013.08.040>
- de Castro, C., Mediavilla, M., Miguel, L.J., Frechoso, F., 2011. Global wind power potential: Physical and technological limits. *Energy Policy* 39, 6677–6682. <https://doi.org/10.1016/j.enpol.2011.06.027>
- De Haan, M., 2001. A Structural Decomposition Analysis of Pollution in the Netherlands. *Econ. Syst. Res.* 13, 181–196. <http://dx.doi.org/10.1080/09537320120052452>
- DeCicco, J.M., Liu, D.Y., Heo, J., Krishnan, R., Kurthen, A., Wang, L., 2016. Carbon balance effects of U.S. biofuel production and use. *Clim. Change* 138, 667–680. <https://doi.org/10.1007/s10584-016-1764-4>
- Delarue, E., Morris, J., 2015. Renewables Intermittency: Operational Limits and Implications for Long-Term Energy System Models (Technical Report). MIT Joint Program on the Science and Policy of Global Change.



- Deng, Y.Y., Haigh, M., Pouwels, W., Ramaekers, L., Brandsma, R., Schimschar, S., Grözinger, J., de Jager, D., 2015. Quantifying a realistic, worldwide wind and solar electricity supply. *Glob. Environ. Change* 31, 239–252. <https://doi.org/10.1016/j.gloenvcha.2015.01.005>
- DGTT, 2016. Observatorio de costes del transporte de mercancías por carretera. Ministerio de Fomento. Gobierno de España.
- Diaz-Maurin, F., Kovacic, Z., 2015. The unresolved controversy over nuclear power: A new approach from complexity theory. *Glob. Environ. Change* 31, 207–216. <https://doi.org/10.1016/j.gloenvcha.2015.01.014>
- Diener, E., Suh, E., 1997. MEASURING QUALITY OF LIFE: ECONOMIC, SOCIAL, AND SUBJECTIVE INDICATORS. *Soc. Indic. Res.* 40, 189–216. <https://doi.org/10.1023/A:1006859511756>
- Dietz, S., Stern, N., 2015. Endogenous Growth, Convexity of Damage and Climate Risk: How Nordhaus' Framework Supports Deep Cuts in Carbon Emissions. *Econ. J.* 125, 574–620.
- Dietzenbacher, E., Los, B., Stehrer, R., Timmer, M., de Vries, G., 2013a. The Construction of World Input–Output Tables in the Wiod Project. *Econ. Syst. Res.* 25, 71–98. <https://doi.org/10.1080/09535314.2012.761180>
- Dietzenbacher, E., Los, B., Stehrer, R., Timmer, M., Vries, G. de, 2013b. The Construction of World Input–Output Tables in the Wiod Project. *Econ. Syst. Res.* 25, 71–98. <https://doi.org/10.1080/09535314.2012.761180>
- Dillen, S.Y., Djomo, S.N., Al Afas, N., Vanbeveren, S., Ceulemans, R., 2013. Biomass yield and energy balance of a short-rotation poplar coppice with multiple clones on degraded land during 16 years. *Biomass Bioenergy* 56, 157–165. <https://doi.org/10.1016/j.biombioe.2013.04.019>
- Doornbosch, R., 2007. Biofuels—is the cure worse than the disease?, Round Table on Sustainable Development. ed. Organisation for Economic Co-operation and Development.
- Dowlatabadi, H., 1998. Sensitivity of climate change mitigation estimates to assumptions about technical change. *Energy Econ.* 20, 473–493. [https://doi.org/10.1016/S0140-9883\(98\)00009-7](https://doi.org/10.1016/S0140-9883(98)00009-7)
- Dunn, J.B., Gaines, L., Sullivan, J., Wang, M.Q., 2012. Impact of Recycling on Cradle-to-Gate Energy Consumption and Greenhouse Gas Emissions of Automotive Lithium-Ion Batteries. *Environ. Sci. Technol.* 46, 12704–12710. <https://doi.org/10.1021/es302420z>
- EABEV, 2008. Energy Consumption, CO2 Emissions and other considerations related to Battery Electric Vehicles. <http://www.going-electric.org/>.
- EC, 2010. Critical raw materials for the UE. Report of the Ad-hoc Working Group on defining critical raw materials. European Commission.
- Ehteshami, S.M.M., Chan, S., 2014. The role of hydrogen and fuel cells to store renewable energy in the future energy network—potentials and challenges. *Energy Policy* 73, 103–109.
- EIA, 2009. Assumptions to the annual Energy Outlook 2009. With projections to 2030 (No. DOE/EIA-0554(2009)).
- EIA US, 2014. Annual Energy Outlook (AEO) 2014 with projections to 2040. Energy Information Administration.
- EIA US, 2008. Annual Energy Outlook (AEO) 2008 with Projections to 2030 (AEO No. Report DOE/EIA-0383). Energy Information Administration.

- Ellis, L., Smith, K., 2010. The Global Upward Trend in the Profit Share. *Appl. Econ. Q.* 56, 231–255. <https://doi.org/10.3790/aeq.56.3.231>
- Elsby, M.W.L., Hobijn, B., Şahin, A., 2014. The Decline of the U.S. Labor Share. *Brook. Pap. Econ. Act.* 2013, 1–63. <https://doi.org/10.1353/eca.2013.0016>
- Elshkaki, A., Graedel, T.E., 2013. Dynamic analysis of the global metals flows and stocks in electricity generation technologies. *J. Clean. Prod.* 59, 260–273. <https://doi.org/10.1016/j.jclepro.2013.07.003>
- EUROELECTRIC, 2013. Power Distribution in Europe. Facts & Figures (No. D/2013/12.105/46).
- EUROELECTRIC, 2000. Study on the importance of harnessing the hydropower resources of the world (No. 03000Ren9761). Union of the Electricity Industry, Brussels (Belgium).
- European Commission, 2010. REPORT FROM THE COMMISSION on indirect land-use change related to biofuels and bioliquids (No. COM(2010) 811 final).
- EVI IEA, 2013. Global EV Outlook. Understanding the Electric Vehicle Landscape to 2020. Electric Vehicles Initiative. International Energy Agency.
- EWG, 2013. Fossil and Nuclear Fuels – the Supply Outlook (No. 2013/03/18 LBST). Energy Watch Group.
- EWG, 2008. Crude Oil - The Supply Outlook. Energy Watch Group / Ludwig-Boelkow-Foundation.
- EWG, 2007. Coal: Resources and Future Production (No. EWG-Paper No. 1/07).
- EWG, 2006. Uranium Resources and Nuclear Energy (No. 1/2006), EWG-Series. Energy Watch Group.
- FAO, 2017. Soil Organic Carbon: the hidden potential. FAO.
- FAO, 2012. The state of food insecurity in the world 2012. FAO, WFP & IFAD, Rome.
- FAO, 2009. How to Feed the World in 2050.
- FAO, 2003. World agriculture: towards 2015/2030: an FAO perspective. Earthscan/James & James.
- FAOSTAT, 2015. Statistics Division of the FAO. Food and Agriculture Organization of the United Nations, Rome (Italy).
- Fargione, J., Hill, J., Tilman, D., Polasky, S., Hawthorne, P., 2008. Land Clearing and the Biofuel Carbon Debt. *Science* 319, 1235–1238. <https://doi.org/10.1126/science.1152747>
- Farley, J., Daly, H.E., 2003. *Ecological Economics: Principles and Applications*, 1 edition. ed. Island Press, Washington.
- Ferroni, F., Hopkirk, R.J., 2016. Energy Return on Energy Invested (ERoEI) for photovoltaic solar systems in regions of moderate insolation. *Energy Policy* 94, 336–344. <https://doi.org/10.1016/j.enpol.2016.03.034>
- Fiddaman, T., Siegel, L.S., Sawin, E., Jones, A.P., Sterman, J., 2017. C-ROADS simulator reference guide v78b (No. v74).
- Fiddaman, T., Siegel, L.S., Sawin, E., Jones, A.P., Sterman, J., 2016. C-ROADS simulator reference guide (No. v74).
- Fiddaman, T.S., 2002. Exploring policy options with a behavioral climate–economy model. *Syst. Dyn. Rev.* 18, 243–267. <https://doi.org/10.1002/sdr.241>
- Fiddaman, T.S., 1997. Feedback complexity in integrated climate-economy models. Massachusetts Institute of Technology.

- Field, C.B., Campbell, J.E., Lobell, D.B., 2008. Biomass energy: the scale of the potential resource. *Trends Ecol. Evol.* 23, 65–72. <https://doi.org/10.1016/j.tree.2007.12.001>
- Fischedick, M., Esken, A., Pastowski, A., Schüwer, D., Supersberger, N., Nitsch, J., Viebahn, P., Bandi, A., Zuberbühler, U., Edenhofer, O., 2008. Ecological, Economic and Structural Comparison of Renewable Energy Technologies (RE) with Carbon Capture and Storage (CCS) — An Integrated Approach. Wuppertal Institute for Climate, Environment and Energy; German Aerospace Center; Centre for Solar Energy and Hydrogen Research; Potsdam Institute for Climate Impact Research.
- Fleurbaey, M., Blanchet, D., 2013. *Beyond GDP: Measuring welfare and assessing sustainability*. Oxford University Press.
- Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global Consequences of Land Use. *Science* 309, 570–574. <https://doi.org/10.1126/science.1111772>
- Fouquet, R., 2010. The slow search for solutions: Lessons from historical energy transitions by sector and service. *Energy Policy* 38, 6586–6596. <https://doi.org/10.1016/j.enpol.2010.06.029>
- François, B., Hingray, B., Raynaud, D., Borga, M., Creutin, J.D., 2016. Increasing climate-related-energy penetration by integrating run-of-the river hydropower to wind/solar mix. *Renew. Energy* 87, Part 1, 686–696. <https://doi.org/10.1016/j.renene.2015.10.064>
- FTF, 2011. *Future of Transport Fuels*. Report of the European Expert Group on Future Transport Fuels.
- Furtula, M.A., Danon, G.J., Bajić, V.V., Lukačev, D.N., 2017. Energy Consumption and Equivalent Emission of Co<sub>2</sub> at Wood Pellets Production in Serbia. *Therm. Sci.* 21, 1905–1915. <https://doi.org/10.2298/TSCI170220099F>
- Fuss, S., Canadell, J.G., Peters, G.P., Tavoni, M., Andrew, R.M., Ciais, P., Jackson, R.B., Jones, C.D., Kraxner, F., Nakicenovic, N., Le Quéré, C., Raupach, M.R., Sharifi, A., Smith, P., Yamagata, Y., 2014. Betting on negative emissions. *Nat. Clim. Change* 4, 850–853. <https://doi.org/10.1038/nclimate2392>
- Füssel, H.-M., 2010. Modeling impacts and adaptation in global IAMs. *Wiley Interdiscip. Rev. Clim. Change* 1, 288–303. <https://doi.org/10.1002/wcc.40>
- GAMESA, 2013. ECOWIND. Life cycle assessment of 1KWh generated by a GAMESA onshore windfarm G90 2.0 MW.
- García-Olivares, A., 2016. Energy for a sustainable post-carbon society. *Sci. Mar.* 80, 257–268. <https://doi.org/10.3989/scimar.04295.12A>
- García-Olivares, A., 2015. Substitutability of Electricity and Renewable Materials for Fossil Fuels in a Post-Carbon Economy. *Energies* 8, 13308–13343. <https://doi.org/10.3390/en81212371>
- García-Olivares, A., Ballabrera-Poy, J., García-Ladona, E., Turiel, A., 2012. A global renewable mix with proven technologies and common materials. *Energy Policy* 41, 561–574. <https://doi.org/10.1016/j.enpol.2011.11.018>
- GEEDS, 2016. MEDEAS model: Conceptual Overview (Deliverable 4.1 MEDEAS). GEEDS, University of Valladolid.
- Genty, A., 2012. Final database of environmental satellite accounts: technical report on their compilation. WIOD Deliverable 4.6, Documentation.

- Genty, A., Arto, I., Neuwahl, F., 2012. Final database of environmental satellite accounts: technical report on their compilation. WIOD Deliv. 46 Doc. Downloadable [HttpwwwwiodorgpublicationssourcedocsEnvironmentalSourcespdf](http://www.wiod.org/publicationssourcedocs/EnvironmentalSourcespdf).
- Gernaat, D.E.H.J., Bogaart, P.W., Vuuren, D.P. van, Biemans, H., Niessink, R., 2017. High-resolution assessment of global technical and economic hydropower potential. *Nat. Energy* 2, 821. <https://doi.org/10.1038/s41560-017-0006-y>
- GFN, 2015. National Footprint Accounts, <http://www.footprintnetwork.org/>. Global Footprint Network.
- Gimeno-Gutiérrez, M., Lacal-Arántegui, R., 2015. Assessment of the European potential for pumped hydropower energy storage based on two existing reservoirs. *Renew. Energy* 75, 856–868. <https://doi.org/10.1016/j.renene.2014.10.068>
- Giraud, G., Isaac, F.M., Bovari, E., Zatsepina, E., 2016. Coping with the Collapse: A Stock-Flow Consistent Monetary Macrodynamics of Global Warming.
- Gomiero, T., Paoletti, M.G., Pimentel, D., 2010. Biofuels: Efficiency, Ethics, and Limits to Human Appropriation of Ecosystem Services. *J. Agric. Environ. Ethics* 23, 403–434. <https://doi.org/10.1007/s10806-009-9218-x>
- González-Eguino, M., Neumann, M.B., 2016. Significant implications of permafrost thawing for climate change control. *Clim. Change* 136, 381–388. <https://doi.org/10.1007/s10584-016-1666-5>
- González-Eguino, M., Neumann, M.B., Arto, I., Capellán-Pérez, I., Faria, S.H., 2017. Mitigation implications of an ice-free summer in the Arctic Ocean. *Earths Future* 5, 59–66. <https://doi.org/10.1002/2016EF000429>
- Goudriaan, J., Ketner, P., 1984. A simulation study for the global carbon cycle, including man's impact on the biosphere. *Clim. Change* 6, 167–192. <https://doi.org/10.1007/BF00144611>
- Green, R., Milner, J., Dangour, A.D., Haines, A., Chalabi, Z., Markandya, A., Spadaro, J., Wilkinson, P., 2015. The potential to reduce greenhouse gas emissions in the UK through healthy and realistic dietary change. *Clim. Change* 129, 253–265. <https://doi.org/10.1007/s10584-015-1329-y>
- Greene, D.L., 1999. An assessment of energy and environmental issues related to increased use of Gas-to-Liquids fuels in Transportation.
- Greenpeace, GWEC, SolarPowerEurope, 2015. Energy [R] evolution-A sustainable world energy outlook 2015. Greenpeace, GWEC, SolarPowerEurope.
- Grubler, A., 2010. The costs of the French nuclear scale-up: A case of negative learning by doing. *Energy Policy* 38, 5174–5188. <https://doi.org/10.1016/j.enpol.2010.05.003>
- Grushevenko, E., Grushevenko, D., 2012. Unconventional Oil Potential Tends to Change the World Oil Market. *Energy Sci. Technol.* 4, 68–74. <https://doi.org/10.3968/j.est.1923847920120401.178>
- Guerra, E., Artavia, L., 2016. Energy Production and the Potential for Electric Motorcycles in Solo and Central Java, Indonesia [WWW Document]. Kleinman Cent. Energy Policy. URL <http://kleinmanenergy.upenn.edu/policy-digests/energy-production-and-potential-electric-motorcycles-solo-and-central-java-indonesia>
- Haapala, K.R., Prempreeda, P., 2014. Comparative life cycle assessment of 2.0 MW wind turbines. *Int. J. Sustain. Manuf.*
- Haberl, H., Erb, K.H., Krausmann, F., Gaube, V., Bondeau, A., Plutzer, C., Gingrich, S., Lucht, W., Fischer-Kowalski, M., 2007. Quantifying and mapping the human appropriation of net primary production

in earth's terrestrial ecosystems. *Proc. Natl. Acad. Sci.* 104, 12942–12947. <https://doi.org/10.1073/pnas.0704243104>

- Haberl, H., Erb, K.-H., Krausmann, F., Running, S., Searchinger, T.D., Smith, W.K., 2013. Bioenergy: how much can we expect for 2050? *Environ. Res. Lett.* 8, 031004. <https://doi.org/10.1088/1748-9326/8/3/031004>
- Haberl, H., Sprinz, D., Bonazountas, M., Cocco, P., Desaubies, Y., Henze, M., Hertel, O., Johnson, R.K., Kastrup, U., Laconte, P., Lange, E., Novak, P., Paavola, J., Reenberg, A., van den Hove, S., Vermeire, T., Wadhams, P., Searchinger, T., 2012. Correcting a fundamental error in greenhouse gas accounting related to bioenergy. *Energy Policy* 45, 18–23. <https://doi.org/10.1016/j.enpol.2012.02.051>
- Hacatoglu, K., Rosen, M.A., Dincer, I., 2012. Comparative life cycle assessment of hydrogen and other selected fuels. *Int. J. Hydrog. Energy*, Proceedings of the Symposium on Hydrogen Production and Applications at the 240th American Chemical Society National Meeting, August 22–26, 2010, Boston, Massachusetts, USA 37, 9933–9940. <https://doi.org/10.1016/j.ijhydene.2012.04.020>
- Hall, C.A.S., 2017a. Will EROI be the Primary Determinant of Our Economic Future? The View of the Natural Scientist versus the Economist. *Joule* 1, 635–638. <https://doi.org/10.1016/j.joule.2017.09.010>
- Hall, C.A.S., 2017b. Energy Return on Investment as Master Driver of Evolution 59–72. [https://doi.org/10.1007/978-3-319-47821-0\\_6](https://doi.org/10.1007/978-3-319-47821-0_6)
- Hall, C.A.S., Balogh, S., Murphy, D.J.R., 2009. What is the Minimum EROI that a Sustainable Society Must Have? *Energies* 2, 25–47. <https://doi.org/10.3390/en20100025>
- Hall, C.A.S., Klitgaard, K.A., 2012. *Energy and the Wealth of Nations: Understanding the Biophysical Economy*. Springer New York, New York, NY.
- Hall, C.A.S., Lambert, J.G., Balogh, S.B., 2014. EROI of different fuels and the implications for society. *Energy Policy* 64, 141–152. <https://doi.org/10.1016/j.enpol.2013.05.049>
- Hammond, G., Jones, C., 2011. *Inventory of Carbon & Energy (ICE) Version 2.0*. Sustainable Energy Research Team (SERT) Department of Mechanical Engineering University of Bath, UK.
- Hammond, G.P., Spargo, J., 2014. The prospects for coal-fired power plants with carbon capture and storage: A UK perspective. *Energy Convers. Manag.* 86, 476–489. <https://doi.org/10.1016/j.enconman.2014.05.030>
- Hansen, J., Kharecha, P., Sato, M., Masson-Delmotte, V., Ackerman, F., Beerling, D.J., Hearty, P.J., Hoegh-Guldberg, O., Hsu, S.-L., Parmesan, C., Rockstrom, J., Rohling, E.J., Sachs, J., Smith, P., Steffen, K., Van Susteren, L., von Schuckmann, K., Zachos, J.C., 2013. Assessing “Dangerous Climate Change”: Required Reduction of Carbon Emissions to Protect Young People, Future Generations and Nature. *PLoS ONE* 8, e81648. <https://doi.org/10.1371/journal.pone.0081648>
- Hansen, J., Sato, M., Hearty, P., Ruedy, R., Kelley, M., Masson-Delmotte, V., Russell, G., Tselioudis, G., Cao, J., Rignot, E., Velicogna, I., Tormey, B., Donovan, B., Kandiano, E., von Schuckmann, K., Kharecha, P., Legrande, A.N., Bauer, M., Lo, K.-W., 2016a. Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2 °C global warming could be dangerous. *Atmos Chem Phys* 16, 3761–3812. <https://doi.org/10.5194/acp-16-3761-2016>
- Hansen, J., Sato, M., Kharecha, P., von Schuckmann, K., Beerling, D.J., Cao, J., Marcott, S., Masson-Delmotte, V., Prather, M.J., Rohling, E.J., others, 2016b. Young People’s Burden: Requirement of Negative CO<sub>2</sub> Emissions. *ArXiv Prepr. ArXiv160905878*.



- Hardt, L., O'Neill, D.W., 2017. Ecological Macroeconomic Models: Assessing Current Developments. *Ecol. Econ.* 134, 198–211. <https://doi.org/10.1016/j.ecolecon.2016.12.027>
- Haszeldine, R.S., 2009. Carbon Capture and Storage: How Green Can Black Be? *Science* 325, 1647–1652. <https://doi.org/10.1126/science.1172246>
- Heard, B.P., Brook, B.W., Wigley, T.M.L., Bradshaw, C.J.A., 2017. Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems. *Renew. Sustain. Energy Rev.* 76, 1122–1133. <https://doi.org/10.1016/j.rser.2017.03.114>
- Hearps, P., Dargaville, R., McConnell, D., Sandiford, M., Forcey, T., Seligman, P., 2014. Opportunities for pumped hydro energy storage in Australia. *Melb. Energy Inst. Vic.* 3010.
- Hejazi, M., Edmonds, J., Clarke, L., Kyle, P., Davies, E., Chaturvedi, V., Wise, M., Patel, P., Eom, J., Calvin, K., Moss, R., Kim, S., 2014. Long-term global water projections using six socioeconomic scenarios in an integrated assessment modeling framework. *Technol. Forecast. Soc. Change* 81, 205–226. <https://doi.org/10.1016/j.techfore.2013.05.006>
- Hekkert, M.P., Hendriks, F.H.J.F., Faaij, A.P.C., Neelis, M.L., 2005. Natural gas as an alternative to crude oil in automotive fuel chains well-to-wheel analysis and transition strategy development. *Energy Policy* 33, 579–594. <https://doi.org/10.1016/j.enpol.2003.08.018>
- Hermann, W.A., 2006. Quantifying global exergy resources. *Energy* 31, 1349–1366. <https://doi.org/10.1016/j.energy.2005.09.006>
- Hertwich, E.G., Gibon, T., Bouman, E.A., Arvesen, A., Suh, S., Heath, G.A., Bergesen, J.D., Ramirez, A., Vega, M.I., Shi, L., 2015. Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. *Proc. Natl. Acad. Sci.* 112, 6277–6282. <https://doi.org/10.1073/pnas.1312753111>
- Heun, M.K., Carbajales-Dale, M., Haney, B.R., 2015. *Beyond GDP. National Accounting in the Age of Resource Depletion*, Springer. ed.
- Holttinen, H., Meibom, P., Orth, A., Lange, B., O'Malley, M., Tande, J.O., Estanqueiro, A., Gomez, E., Söder, L., Strbac, G., Smith, J.C., van Hulle, F., 2011. Impacts of large amounts of wind power on design and operation of power systems, results of IEA collaboration. *Wind Energy* 14, 179–192. <https://doi.org/10.1002/we.410>
- Höök, M., Aleklett, K., 2010. A review on coal-to-liquid fuels and its coal consumption. *Int. J. Energy Res.* 34, 848–864. <https://doi.org/10.1002/er.1596>
- Höök, M., Fantazzini, D., Angelantoni, A., Snowden, S., 2013. Hydrocarbon liquefaction: viability as a peak oil mitigation strategy.
- Höök, M., Li, J., Oba, N., Snowden, S., 2011. Descriptive and Predictive Growth Curves in Energy System Analysis. *Nat. Resour. Res.* 20, 103–116. <https://doi.org/10.1007/s11053-011-9139-z>
- Höök, M., Tang, X., 2013. Depletion of fossil fuels and anthropogenic climate change—A review. *Energy Policy, Special Section: Transition Pathways to a Low Carbon Economy* 52, 797–809. <https://doi.org/10.1016/j.enpol.2012.10.046>
- Höök, M., Zittel, W., Schindler, J., Aleklett, K., 2010. Global coal production outlooks based on a logistic model. *Fuel* 89, 3546–3558. <https://doi.org/10.1016/j.fuel.2010.06.013>
- Houghton, R.A., Byers, B., Nassikas, A.A., 2015. A role for tropical forests in stabilizing atmospheric CO<sub>2</sub>. *Nat. Clim. Change* 5, 1022–1023. <https://doi.org/10.1038/nclimate2869>

- Howarth, R.W., 2015. Methane emissions and climatic warming risk from hydraulic fracturing and shale gas development: implications for policy. *Energy Emiss. Control Technol.* 3, 45–54.
- Howarth, R.W., Santoro, R., Ingraffea, A., 2011. Methane and the greenhouse-gas footprint of natural gas from shale formations. *Clim. Change* 106, 679–690. <https://doi.org/10.1007/s10584-011-0061-5>
- Hsiang, S.M., Jina, A.S., 2014. The Causal Effect of Environmental Catastrophe on Long-Run Economic Growth: Evidence From 6,700 Cyclones (Working Paper No. 20352). National Bureau of Economic Research. <https://doi.org/10.3386/w20352>
- IEA, 2018. IEA World Energy Statistics and Balances, World Energy Statistics and Balances (database). IEA/OECD, Paris (France).
- IEA, 2016. Global EV Outlook 2016. Beyond one million electric cars. OECD/IEA, Paris.
- IEA, 2014. Heating without global warming—market developments and policy considerations for renewable heat. International Energy Agency, Paris.
- IEA, 2013. IEA Key Stats 2013. International Energy Agency.
- IEA, 2010. The contribution of natural gas vehicles to sustainable transport. OECD Publishing.
- IEA ETP, 2016. Energy Technology Perspectives 2016. Towards Sustainable Urban Energy Systems. International Energy Agency.
- IGU & UN ECE, 2012. NATURAL GAS FOR VEHICLES (NGV). International Gas Union and United Nations Economic Commission for Europe.
- Imhoff, M.L., Bounoua, L., 2006. Exploring global patterns of net primary production carbon supply and demand using satellite observations and statistical data. *J. Geophys. Res. Atmospheres* 111, D22S12. <https://doi.org/10.1029/2006JD007377>
- Imhoff, M.L., Bounoua, L., Ricketts, T., Loucks, C., Harriss, R., Lawrence, W.T., 2004. Global patterns in human consumption of net primary production. *Nature* 429, 870–873. <https://doi.org/10.1038/nature02619>
- IPCC, 2014a. Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2014. Fifth Assess. Rep. Intergov. Panel Clim. Change.
- IPCC, 2014b. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.
- IPCC, 2014c. Climate Change 2014: Mitigation of Climate Change. Fifth Assess. Rep. Intergov. Panel Clim. Change.
- IPCC, 2011. Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge University Press, United Kingdom and New York (USA).
- IPCC, 2007a. Mitigation of Climate Change - Contribution of Working Group III, Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
- IPCC, 2007b. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007. Fourth Assess. Rep. Intergov. Panel Clim. Change.
- IPCC, 2006. 2006 IPCC guidelines for national greenhouse gas inventories. Institute for Global Environmental Strategies (IGES), Hayama (Japan).
- IRENA, 2014a. Tidal energy (IRENA Ocean Energy Technology Brief No. 3).

- IRENA, 2014b. Wave energy (IRENA Ocean Energy Technology Brief No. 4).
- IRENA db, 2017. IRENA Resource (Database). International Renewable Energy Agency, <http://resourceirena.irena.org>.
- IRIZAR, 2015. i2e: 12 m urban bus with 100% electric trac\$on and climate control (PRODUCT/SERVICE). IRIZAR S. Coop.
- Jacobson, M.Z., Delucchi, M.A., 2011. Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials. *Energy Policy* 39, 1154–1169. <https://doi.org/10.1016/j.enpol.2010.11.040>
- James, D.E., Jansen, H.M.A., Opschoor, J.B., 1978. *Economic Approaches to Environmental Problems*. Elsevier North Holland, Amsterdam.
- Janda, K., Kristoufek, L., Zilberman, D., 2012. Biofuels: policies and impacts. A review. *Agric. Econ. - UZEI v. 58*(8) p. 372–386.
- Jarecki, M.K., Lal, R., 2003. Crop Management for Soil Carbon Sequestration. *Crit. Rev. Plant Sci.* 22, 471–502. <https://doi.org/10.1080/713608318>
- Jorge, R.S., Hawkins, T.R., Hertwich, E.G., 2012a. Life cycle assessment of electricity transmission and distribution—part 1: power lines and cables. *Int. J. Life Cycle Assess.* 17, 9–15. <https://doi.org/10.1007/s11367-011-0335-1>
- Jorge, R.S., Hawkins, T.R., Hertwich, E.G., 2012b. Life cycle assessment of electricity transmission and distribution—part 2: transformers and substation equipment. *Int. J. Life Cycle Assess.* 17, 184–191. <https://doi.org/10.1007/s11367-011-0336-0>
- Kainuma, M., 2003. *Climate policy assessment: Asia-Pacific integrated modeling*. Springer, Tokyo.
- Karabarbounis, L., Neiman, B., 2014. The Global Decline of the Labor Share. *Q. J. Econ.* 129, 61–103. <https://doi.org/10.1093/qje/qjt032>
- Kartha, S., Dooley, K., 2016. The risks of relying on tomorrow“ s „negative emissions“ to guide today“ s mitigation action. Working Paper 2016–08, Stockholm Environment Institute. Retrieved 4 October, 2016 from <https://www.sei-international.org/publications>.
- Kastner, T., Rivas, M.J.I., Koch, W., Nonhebel, S., 2012. Global changes in diets and the consequences for land requirements for food. *Proc. Natl. Acad. Sci.* 109, 6868–6872. <https://doi.org/10.1073/pnas.1117054109>
- Keith, D.W., DeCarolís, J.F., Denkenberger, D.C., Lenschow, D.H., Malyshev, S.L., Pacala, S., Rasch, P.J., 2004. The influence of large-scale wind power on global climate. *Proc. Natl. Acad. Sci. U. S. A.* 101, 16115–16120. <https://doi.org/10.1073/pnas.0406930101>
- Kemfert, C., 2005. Induced technological change in a multi-regional, multi-sectoral, integrated assessment model (WIAGEM): Impact assessment of climate policy strategies. *Ecol. Econ.* 54, 293–305. <https://doi.org/10.1016/j.ecolecon.2004.12.031>
- Kerschner, C., Capellán-Pérez, I., 2017. Peak-Oil and Ecological Economics, in: Spash, C.L. (Ed.), *Routledge Handbook of Ecological Economics: Nature and Society*. Abingdon, pp. 425–435.
- Kerschner, C., O'Neill, D.W., 2016. Economic Growth and Sustainability, in: Kopnina, H., Shoreman-Ouimet, E. (Eds.), *Sustainability. Key Issues, Key Issues in Environment and Sustainability*. Routledge, p. 392.



- Kessides, I.N., Wade, D.C., 2011. Deriving an Improved Dynamic EROI to Provide Better Information for Energy Planners. *Sustainability* 3, 2339–2357. <https://doi.org/10.3390/su3122339>
- King, C.W., 2016. Information Theory to Assess Relations Between Energy and Structure of the U.S. Economy Over Time. *Biophys. Econ. Resour. Qual.* 1, 10. <https://doi.org/10.1007/s41247-016-0011-y>
- Koroneos, C.J., Nanaki, E.A., 2012. Integrated solid waste management and energy production - a life cycle assessment approach: the case study of the city of Thessaloniki. *J. Clean. Prod.* 27, 141–150. <https://doi.org/10.1016/j.jclepro.2012.01.010>
- Kousky, C., 2014. Informing climate adaptation: A review of the economic costs of natural disasters. *Energy Econ.* 46, 576–592. <https://doi.org/10.1016/j.eneco.2013.09.029>
- Kubiszewski, I., Costanza, R., Franco, C., Lawn, P., Talberth, J., Jackson, T., Aylmer, C., 2013. Beyond GDP: Measuring and achieving global genuine progress. *Ecol. Econ.* 93, 57–68. <https://doi.org/10.1016/j.ecolecon.2013.04.019>
- Laherrère, J., 2010. Peak Oil y Seguridad Energética. Presented at the Segundo Simposio ASPO Argentina Buenos Aires, Buenos Aires (Argentina).
- Laherrère, J., 2006. Oil and gas, what future? Presented at the Groningen annual Energy Convention, Groningen, Netherlands.
- Lambert, J., Hall, C., Balogh, S., Poisson, A., Gupta, A., 2012. EROI of global energy resources: preliminary status and trends. *Rep. Prep. Coll. Environ. Sci. For. State Univ. N. Y. U. K. Dep. Int. Dev. Lond.*
- Lassaletta, L., Billen, G., Grizzetti, B., Garnier, J., Leach, A.M., Galloway, J.N., 2014. Food and feed trade as a driver in the global nitrogen cycle: 50-year trends. *Biogeochemistry* 1–17. <https://doi.org/10.1007/s10533-013-9923-4>
- Latunussa, C.E.L., Ardente, F., Blengini, G.A., Mancini, L., 2016. Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels. *Sol. Energy Mater. Sol. Cells, Life cycle, environmental, ecology and impact analysis of solar technology* 156, 101–111. <https://doi.org/10.1016/j.solmat.2016.03.020>
- Lavoie, M., 2014. *Postkeynesian Economics: New Foundations*. Edward Elgar, Chentelham.
- L.D. Roper, 2017. L.D. Roper webpage. <http://www.roperld.com/personal/RoperLDavid.htm> (Retrieved 27-4-2017).
- Lelieveld, J., Proestos, Y., Hadjinicolaou, P., Tanarhte, M., Tyrllis, E., Zittis, G., 2015. Strongly increasing heat extremes in the Middle East and North Africa (MENA) in the 21st century. *Clim. Change* 1–16.
- Lenton, T.M., Ciscar, J.-C., 2013. Integrating tipping points into climate impact assessments. *Clim. Change* 117, 585–597. <https://doi.org/10.1007/s10584-012-0572-8>
- Lenzen, M., 2010. Current State of Development of Electricity-Generating Technologies: A Literature Review. *Energies* 3, 462–591. <https://doi.org/10.3390/en3030462>
- Leontief, W., 1970. Environmental Repercussions and the Economic Structure: An Input-Output Approach. *Rev. Econ. Stat.* 52, 262–271. <https://doi.org/10.2307/1926294>
- Levene, J.I., Mann, M.K., Margolis, R.M., Milbrandt, A., 2007. An analysis of hydrogen production from renewable electricity sources. *Sol. Energy* 81, 773–780.

- Levin, S.A., Carpenter, S.R., Godfray, H.C.J., Kinzig, A.P., Loreau, M., Losos, J.B., Walker, B., Wilcove, D.S., 2009. The Princeton guide to ecology. Princeton University Press.
- Li, B., Li, J., Yuan, C., 2013. Life Cycle Assessment of Lithium Ion Batteries with Silicon Nanowire Anode for Electric Vehicles. Presented at the 2013 IEEE International Symposium on Sustainable Systems & Technology (ISSST 2013). <https://doi.org/DOI: 10.6084/m9.figshare.805147>
- Li, X., Zhong, S., Bian, X., Heilman, W.E., 2010. Climate and climate variability of the wind power resources in the Great Lakes region of the United States. *J. Geophys. Res. Atmospheres* 115, D18107. <https://doi.org/10.1029/2009JD013415>
- Liebreich, M., 2014. Imperial Business Insights. Bloomberg New Energy Finance, London.
- LondonArray, 2016. London Array. London Array, <http://www.londonarray.com/> (Retrieved 28-03-2016).
- Lund, J.W., Boyd, T.L., 2015. Direct Utilization of Geothermal Energy 2015 Worldwide Review, in: Proceedings World Geothermal Congress 2015. Presented at the World Geothermal Congress 2015, Melbourne, Australia, p. 31.
- Mackay, D.J.C., 2013. Solar energy in the context of energy use, energy transportation and energy storage. *Philos. Trans. R. Soc. Lond. Math. Phys. Eng. Sci.* 371, 20110431. <https://doi.org/10.1098/rsta.2011.0431>
- Maggio, G., Cacciola, G., 2012. When will oil, natural gas, and coal peak? *Fuel* 98, 111–123. <https://doi.org/10.1016/j.fuel.2012.03.021>
- Martinez-Alier, J., 2003. The Environmentalism of the poor: a study of ecological conflicts and valuation. Edward Elgar Publishing.
- Masui, T., Hanaoka, T., Hikita, S., Kainuma, M., 2006. Assessment of CO<sub>2</sub> Reductions and Economic Impacts Considering Energy-Saving Investments. *Energy J.* 27, 175–190.
- McGlade, C., Ekins, P., 2015. The geographical distribution of fossil fuels unused when limiting global warming to 2 °C. *Nature* 517, 187–190. <https://doi.org/10.1038/nature14016>
- Meadows, D.H., 1972. The Limits to Growth; A Report for the Club of Rome's Project on the Predicament of Mankind, 2 edition. ed. Universe Pub, New York.
- Meadows, D.H., Randers, J., Meadows, D.L., 2004. The limits to growth: the 30-year update. Chelsea Green Publishing Company, White River Junction, Vt.
- MEDEAS, 2017. Deliverable D3.4 (Deliverable MEDEAS project). INSTM, MU, UVa.
- MEDEAS, 2016a. Deliverable D2.1 (Deliverable MEDEAS project). CIRCE, MU, CRES & INSTM.
- MEDEAS, 2016b. Deliverable D2.2 (Deliverable MEDEAS project). CIRCE, BSERC, MU, UVa, IIASA, ICM-CSIC & AEA.
- Mediavilla, M., de Castro, C., Capellán, I., Javier Miguel, L., Arto, I., Frechoso, F., 2013. The transition towards renewable energies: Physical limits and temporal conditions. *Energy Policy* 52, 297–311. <https://doi.org/10.1016/j.enpol.2012.09.033>
- Meinshausen, M., Raper, S., Wigley, T., 2011a. Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration. *Atmos Chem Phys* 11, 1417–1456. <https://doi.org/10.5194/acp-11-1417-2011>
- Meinshausen, M., Wigley, T., Raper, S., 2011b. Emulating atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6–Part 2: Applications. *Atmospheric Chem. Phys.* 11, 1457–1471.

- Millenium Ecosystem Assessment, 2005. Ecosystems and Human Well-Being: Synthesis. United Nations Environment Programme, Washington, DC.
- Miller, L., Gans, F., Kleidon, A., 2011. Estimating maximum global land surface wind power extractability and associated climatic consequences. *Earth Syst Dynam* 2, 1–12.
- Miller, R.E., Blair, P.D., 2009. Input-Analysis. Foundations and Extensions. Cambridge University Press, Cambridge, UK.
- Mills, A., Wiser, R., Porter, K., 2012. The cost of transmission for wind energy in the United States: A review of transmission planning studies. *Renew. Sustain. Energy Rev.* 16, 1–19. <https://doi.org/10.1016/j.rser.2011.07.131>
- Mohr, S.H., 2012. Fossil fuel future production, world and Australia focus. Presented at the Australian Frontiers of Science 2012: Science for a green economy, Sydney, 2-4 December 2012.
- Mohr, S.H., Evans, G.M., 2011. Long term forecasting of natural gas production. *Energy Policy* 39, 5550–5560. <https://doi.org/10.1016/j.enpol.2011.04.066>
- Mohr, S.H., Evans, G.M., 2010. Long term prediction of unconventional oil production. *Energy Policy* 38, 265–276. <https://doi.org/10.1016/j.enpol.2009.09.015>
- Mohr, S.H., Evans, G.M., 2009. Forecasting coal production until 2100. *Fuel* 88, 2059–2067. <https://doi.org/10.1016/j.fuel.2009.01.032>
- Mohr, S.H., Mudd, G., Giurco, D., 2012. Lithium Resources and Production: Critical Assessment and Global Projections. *Minerals* 2, 65–84. <https://doi.org/10.3390/min2010065>
- Mohr, S.H., Wang, J., Ellem, G., Ward, J., Giurco, D., 2015. Projection of world fossil fuels by country. *Fuel* 141, 120–135. <https://doi.org/10.1016/j.fuel.2014.10.030>
- Mori, M., Jensterle, M., Mržljak, T., Drobnič, B., 2014. Life-cycle assessment of a hydrogen-based uninterruptible power supply system using renewable energy. *Int. J. Life Cycle Assess.* 19, 1810–1822. <https://doi.org/10.1007/s11367-014-0790-6>
- Morita, T., Jiang, K., Masui, T., Matsuoka, Y., Rana, A., 2003. Long-term Scenarios based on AIM Model, in: *Climate Policy Assessment*. Springer, Tokyo, pp. 17–36.
- Motesharrei, S., Rivas, J., Kalnay, E., 2014. Human and nature dynamics (HANDY): Modeling inequality and use of resources in the collapse or sustainability of societies. *Ecol. Econ.* 101, 90–102. <https://doi.org/10.1016/j.ecolecon.2014.02.014>
- Mudd, G.M., 2010. The Environmental sustainability of mining in Australia: key mega-trends and looming constraints. *Resour. Policy* 35, 98–115. <https://doi.org/10.1016/j.resourpol.2009.12.001>
- Murphy, T., 2011. Using physics and estimation to assess energy, growth, options [WWW Document]. Math. URL <https://dothemath.ucsd.edu/2011/08/mpg-for-electric-cars/>
- Murray, J.W., 2016. Limitations of Oil Production to the IPCC Scenarios: The New Realities of US and Global Oil Production. *Biophys. Econ. Resour. Qual.* 1, 13.
- Neher, F., Miola, A., 2015. The Role of Social Inequalities for the Vulnerability to Climate Related Extreme Weather Events. Joint Research Centre, Publications Office of the European Union, Luxembourg.
- Neumeyer, C., Goldston, R., 2016. Dynamic EROI Assessment of the IPCC 21st Century Electricity Production Scenario. *Sustainability* 8, 421. <https://doi.org/10.3390/su8050421>
- Nielsen, J.E., 2011. Simple method for Converting Installed Solar Collector Area to Annual Collector Output.

- Nilsson, S., Schopfhauser, W., 1995. The carbon-sequestration potential of a global afforestation program. *Clim. Change* 30, 267–293. <https://doi.org/10.1007/BF01091928>
- Nordhaus, W., Sator, P., 2013. DICE 2013R: Introduction and user's manual. Retrieved Novemb.
- Nordhaus, W.D., 1994. Managing the global commons: the economics of climate change. MIT press Cambridge, MA.
- Nordhaus, W. D., 1992. An Optimal Transition Path for Controlling Greenhouse Gases. *Science* 258, 1315–1319. <https://doi.org/10.1126/science.258.5086.1315>
- Nordhaus, William D., 1992. The “DICE” Model: Background and Structure of a Dynamic Integrated Climate-Economy Model of the Economics of Global Warming (Cowles Foundation Discussion Paper No. 1009). Cowles Foundation for Research in Economics, Yale University.
- Northey, S., Mohr, S., Mudd, G., Weng, Z., Giurco, D., 2014. Modelling future copper ore grade decline based on a detailed assessment of copper resources and mining. *Resour. Conserv. Recycl.* 83, 190–201.
- NREL, 2012. Renewable Electricity Futures Study (Entire Report) (4 vols. No. NREL/TP-6A20-52409). National Renewable Energy Laboratory, Golden, CO, USA.
- Oeschger, H., Siegenthaler, U., Schotterer, U., Gugelmann, A., 1975. A box diffusion model to study the carbon dioxide exchange in nature. *Tellus* 27, 168–192. <https://doi.org/10.1111/j.2153-3490.1975.tb01671.x>
- Parish, F., Sirin, A., Charman, D., Joosten, H., Minaeva, T., Silvius, M., Stringer, L., 2008. Assessment on peatlands, biodiversity and climate change. Global Environment Centre, Kuala Lumpur and Wetlands International Wageningen.
- Patzek, T.W., Croft, G.D., 2010. A global coal production forecast with multi-Hubbert cycle analysis. *Energy* 35, 3109–3122. <https://doi.org/10.1016/j.energy.2010.02.009>
- Pelkmans, L., De Keukeleere, D., Lenaers, G., 2001. Emissions and fuel consumption of natural gas powered city buses versus diesel buses in real-city traffic. WIT Press.
- Pihl, E., Kushnir, D., Sandén, B., Johnsson, F., 2012. Material constraints for concentrating solar thermal power. *Energy, Integration and Energy System Engineering, European Symposium on Computer-Aided Process Engineering* 2011 44, 944–954. <https://doi.org/10.1016/j.energy.2012.04.057>
- Pimentel, D., 2006. Soil Erosion: A Food and Environmental Threat. *Environ. Dev. Sustain.* 8, 119–137. <https://doi.org/10.1007/s10668-005-1262-8>
- Pindyck, R.S., 2015. The Use and Misuse of Models for Climate Policy (Working Paper No. 21097). National Bureau of Economic Research.
- Pindyck, R.S., 2013. Climate Change Policy: What Do the Models Tell Us? (Working Paper No. 19244). National Bureau of Economic Research.
- Pollit, H., 2014. Technical Manual, Version 6.0.
- Pollitt, H., Barker, A., Barton, J., Pirgmaier, E., Polzin, C., Lutter, S., Hinterberger, F., Stocker, A., 2010. A Scoping Study on the Macroeconomic View of Sustainability. Cambridge Econometrics and Sustainable Europe Research Institute.
- Postel, S.L., Daily, G.C., Ehrlich, P.R., 1996. Human appropriation of renewable fresh water. *Science* 271, 785–788. <https://doi.org/10.1126/science.271.5250.785>

- Powlson, D.S., Whitmore, A.P., Goulding, K.W.T., 2011. Soil carbon sequestration to mitigate climate change: a critical re-examination to identify the true and the false. *Eur. J. Soil Sci.* 62, 42–55. <https://doi.org/10.1111/j.1365-2389.2010.01342.x>
- Prieto, P.A., Hall, C.A.S., 2013. *Spain's Photovoltaic Revolution: The Energy Return on Investment*, 2013th ed. Springer.
- Ragnarsdóttir, K.V., Sverdrup, H., Koca, D., 2012. Assessing long term sustainability of global supply of natural resources and materials, in: *Sustainable Development-Energy, Engineering and Technologies-Manufacturing and Environment*. InTech.
- Ragnarsdóttir, K.V., Sverdrup, H., Koca, D., 2011. Challenging the planetary boundaries I: Basic principles of an integrated model for phosphorous supply dynamics and global population size. *Appl. Geochem.* 26, S303–S306.
- Randers, J., 2012. 2052: A global forecast for the next forty years. Chelsea Green Publishing Company.
- Randers, J., Golüke, U., Wenstøp, F., Wenstøp, S., 2016. A User-friendly Earth System Model of Low Complexity: The ESCIMO system dynamics model of global warming towards 2100. *Earth Syst. Dyn. Discuss.* 1–35. <https://doi.org/10.5194/esd-2016-13>
- Ranis, G., Stewart, F., Samman, E., 2006. Human Development: Beyond the Human Development Index. *J. Hum. Dev.* 7, 323–358. <https://doi.org/10.1080/14649880600815917>
- Raugei, M., Sgouridis, S., Murphy, D., Fthenakis, V., Frischknecht, R., Breyer, C., Bardi, U., Barnhart, C., Buckley, A., Carbajales-Dale, M., Csala, D., de Wild-Scholten, M., Heath, G., Jæger-Waldau, A., Jones, C., Keller, A., Leccisi, E., Mancarella, P., Pearsall, N., Siegel, A., Sinke, W., Stolz, P., 2017. Energy Return on Energy Invested (ERoEI) for photovoltaic solar systems in regions of moderate insolation: A comprehensive response. *Energy Policy* 102, 377–384. <https://doi.org/10.1016/j.enpol.2016.12.042>
- Reiner, D.M., 2016. Learning through a portfolio of carbon capture and storage demonstration projects. *Nat. Energy* 1, 15011. <https://doi.org/10.1038/nenergy.2015.11>
- REN21, 2017. *Renewables Global Futures Report. Great debates towards 100% renewable energy*. Paris: REN21 Secretariat.
- REN21, 2016. *Renewables 2016. Global Status Report*. REN 21, Paris.
- REN21, 2014. *Renewables 2014. Global Status Report*. REN 21.
- Rezai, A., Stagl, S., 2016. Ecological macroeconomics: introduction and review. *Ecol. Econ.* 121, 181–185.
- Ribrant, J., Bertling, L., 2007. Survey of failures in wind power systems with focus on Swedish wind power plants during 1997-2005, in: *2007 IEEE Power Engineering Society General Meeting. Presented at the 2007 IEEE Power Engineering Society General Meeting*, pp. 1–8. <https://doi.org/10.1109/PES.2007.386112>
- Ritchie, J., Dowlatabadi, H., 2017. The 1000 GtC coal question: Are cases of vastly expanded future coal combustion still plausible? *Energy Econ.* 65, 16–31. <https://doi.org/10.1016/j.eneco.2017.04.015>
- Rockström, J., Lannerstad, M., Falkenmark, M., 2007. Assessing the water challenge of a new green revolution in developing countries. *Proc. Natl. Acad. Sci.* 104, 6253–6260. <https://doi.org/10.1073/pnas.0605739104>
- Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., Wit, C.A. de, Hughes, T., Leeuw, S. van der, Rodhe, H.,

- Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A., 2009. A safe operating space for humanity. *Nature* 461, 472–475. <https://doi.org/10.1038/461472a>
- Sagar, A.D., Najam, A., 1998. The human development index: a critical review. *Ecol. Econ.* 25, 249–264. [https://doi.org/10.1016/S0921-8009\(97\)00168-7](https://doi.org/10.1016/S0921-8009(97)00168-7)
- Sanz, A., Vega, P., Mateos, M., 2014. Las cuentas ecológicas del transporte en España. Libros en Acción, Madrid.
- Schade, C., Pimentel, D., 2010. Population crash: prospects for famine in the twenty-first century. *Environ. Dev. Sustain.* 12, 245–262. <https://doi.org/10.1007/s10668-009-9192-5>
- Scheidel, A., Sorman, A.H., 2012. Energy transitions and the global land rush: Ultimate drivers and persistent consequences. *Glob. Environ. Change, Global transformations, social metabolism and the dynamics of socio-environmental conflicts* 22, 588–595. <https://doi.org/10.1016/j.gloenvcha.2011.12.005>
- Schenk, N.J., Moll, H.C., 2007. The use of physical indicators for industrial energy demand scenarios. *Ecol. Econ.* 63, 521–535. <https://doi.org/10.1016/j.ecolecon.2006.12.008>
- Schlachtberger, D.P., Becker, S., Schramm, S., Greiner, M., 2016. Backup flexibility classes in emerging large-scale renewable electricity systems. *Energy Convers. Manag., Sustainable development of energy, water and environment systems for future energy technologies and concepts* 125, 336–346. <https://doi.org/10.1016/j.enconman.2016.04.020>
- Schlesinger, W.H., 1991. Biogeochemistry, an Analysis of Global Change. Academic Press, New York (USA).
- Schneider, M., Froggatt, A., 2016. The World Nuclear Industry Status Report 2016. Mycle Schneider Consulting Project, Paris, London, Washington DC.
- Schneider, M., Froggatt, A., 2014. The World Nuclear Industry Status Report 2014. Mycle Schneider Consulting Project, Paris, London, Washington DC.
- Schneider, M., Froggatt, A., Hazemann, J., 2012. The World Nuclear Industry Status Report 2012.
- Schneider, S.H., Morton, L., 1981. The Primordial Bond Exploring Connections Between Man and Nature Through the Humanities and Sciences. Plenum Press N. Y.
- Schreiber, A., Zapp, P., Marx, J., 2012. Meta-Analysis of Life Cycle Assessment Studies on Electricity Generation with Carbon Capture and Storage. *J. Ind. Ecol.* 16, S155–S168. <https://doi.org/10.1111/j.1530-9290.2011.00435.x>
- Scott, V., Gilfillan, S., Markusson, N., Chalmers, H., Haszeldine, R.S., 2013. Last chance for carbon capture and storage. *Nat. Clim. Change* 3, 105–111. <https://doi.org/10.1038/nclimate1695>
- Scrieciu, S., Rezai, A., Mechler, R., 2013a. On the economic foundations of green growth discourses: the case of climate change mitigation and macroeconomic dynamics in economic modeling. *Wiley Interdiscip. Rev. Energy Environ.* 2, 251–268. <https://doi.org/10.1002/wene.57>
- Scrieciu, S., Rezai, A., Mechler, R., 2013b. On the economic foundations of green growth discourses: the case of climate change mitigation and macroeconomic dynamics in economic modeling. *Wiley Interdiscip. Rev. Energy Environ.* 2, 251–268. <https://doi.org/10.1002/wene.57>
- Searchinger, T., Heimlich, R., Houghton, R.A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D., Yu, T.-H., 2008. Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. *Science* 319, 1238–1240. <https://doi.org/10.1126/science.1151861>



- Sgouridis, S., Csala, D., Bardi, U., 2016. The sower's way: quantifying the narrowing net-energy pathways to a global energy transition. *Environ. Res. Lett.* 11, 094009. <https://doi.org/10.1088/1748-9326/11/9/094009>
- SHC, 2016. Solar Heat Worldwide. Markets and Contribution to the Energy Supply 2014. Solar Heating & Cooling Programme IEA.
- Shearer, C., Ghio, N., Myllyvirta, L., Yu, A., Nace, T., 2016. Boom and Bust 2016. Tracking the Global Coal Plant Pipeline. Study Comm. CoalSwarm Greenpeace Sierra Club.
- Skrebowski, C., 2010. The Oil Crunch: a wake-up call for the UK economy. UK Industry Taskforce on Peak Oil & Energy Security (ITPOES).
- SMart Wind, 2013. Hornsea offshore wind farm project one. Chapter 3: project description (No. 7.1.3.). Smart Wind Limited, London.
- Smil, V., 2015. Power Density: A Key to Understanding Energy Sources and Uses. The MIT Press, Cambridge, Massachusetts.
- Smil, V., 2010. Energy Transitions: History, Requirements, Prospects. Praeger, Santa Barbara, California, USA.
- Smil, V., 2008. Energy in nature and society: general energetics of complex systems. MIT Press, Cambridge, Massachusetts, USA.
- Smith, P., 2016. Soil carbon sequestration and biochar as negative emission technologies. *Glob. Change Biol.* 22, 1315–1324. <https://doi.org/10.1111/gcb.13178>
- Smith, P., Davis, S.J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R.B., Cowie, A., Kriegler, E., van Vuuren, D.P., Rogelj, J., Ciais, P., Milne, J., Canadell, J.G., McCollum, D., Peters, G., Andrew, R., Krey, V., Shrestha, G., Friedlingstein, P., Gasser, T., Grüber, A., Heidug, W.K., Jonas, M., Jones, C.D., Kraxner, F., Littleton, E., Lowe, J., Moreira, J.R., Nakicenovic, N., Obersteiner, M., Patwardhan, A., Rogner, M., Rubin, E., Sharifi, A., Torvanger, A., Yamagata, Y., Edmonds, J., Yongsung, C., 2016. Biophysical and economic limits to negative CO<sub>2</sub> emissions. *Nat. Clim. Change* 6, 42–50. <https://doi.org/10.1038/nclimate2870>
- Smith, P., Gregory, P.J., Vuuren, D. van, Obersteiner, M., Havlík, P., Rounsevell, M., Woods, J., Stehfest, E., Bellarby, J., 2010. Competition for land. *Philos. Trans. R. Soc. B Biol. Sci.* 365, 2941–2957. <https://doi.org/10.1098/rstb.2010.0127>
- Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., Smith, J., 2008. Greenhouse gas mitigation in agriculture. *Philos. Trans. R. Soc. B Biol. Sci.* 363, 789–813. <https://doi.org/10.1098/rstb.2007.2184>
- Söderbergh, B., Robelius, F., Aleklett, K., 2007. A crash programme scenario for the Canadian oil sands industry. *Energy Policy* 35, 1931–1947. <https://doi.org/10.1016/j.enpol.2006.06.007>
- Sommer, R., Bossio, D., 2014. Dynamics and climate change mitigation potential of soil organic carbon sequestration. *J. Environ. Manage.* 144, 83–87. <https://doi.org/10.1016/j.jenvman.2014.05.017>
- Spash, C.L., 2016. This Changes Nothing: The Paris Agreement to Ignore Reality. *Globalizations* 13, 928–933. <https://doi.org/10.1080/14747731.2016.1161119>
- Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., Vries, W. de, Wit, C.A. de, Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan,

- V., Reyers, B., Sörlin, S., 2015. Planetary boundaries: Guiding human development on a changing planet. *Science* 1259855. <https://doi.org/10.1126/science.1259855>
- Stehfest, E., van Vuuren, D., A. Bouwman, Kram, T., 2014. Integrated assessment of global environmental change with IMAGE 3.0: Model description and policy applications. Netherlands Environmental Assessment Agency (PBL).
- Sterman, J., Fiddaman, T., Franck, T., Jones, A., McCauley, S., Rice, P., Sawin, E., Siegel, L., 2012a. Climate interactive: the C-ROADS climate policy model. *Sys.Dyn.Rev.* 28, 295–305. <https://doi.org/10.1002/sdr.1474>
- Sterman, J., Fiddaman, T., Franck, T., Jones, A., McCauley, S., Rice, P., Sawin, E., Siegel, L., 2012b. Climate interactive: the C-ROADS climate policy model. *Syst. Dyn. Rev.* 28, 295–305. <https://doi.org/10.1002/sdr.1474>
- Stern, D.I., 1997. Limits to substitution and irreversibility in production and consumption: A neoclassical interpretation of ecological economics. *Ecol. Econ.* 21, 197–215. [https://doi.org/10.1016/S0921-8009\(96\)00103-6](https://doi.org/10.1016/S0921-8009(96)00103-6)
- Stern, N., 2013. The Structure of Economic Modeling of the Potential Impacts of Climate Change: Grafting Gross Underestimation of Risk onto Already Narrow Science Models. *J. Econ. Lit.* 51, 838–859. <https://doi.org/10.1257/jel.51.3.838>
- Sverdrup, H.U., Ragnarsdottir, K.V., Koca, D., 2017. Integrated Modelling of the Global Cobalt Extraction, Supply, Price and Depletion of Extractable Resources Using the WORLD6 Model. *Biophys. Econ. Resour. Qual.* 2, 4.
- Sverdrup, H.U., Ragnarsdottir, K.V., Koca, D., 2014. On modelling the global copper mining rates, market supply, copper price and the end of copper reserves. *Resour. Conserv. Recycl.* 87, 158–174.
- Tainter, J., 1990. *The Collapse of Complex Societies*. Cambridge University Press.
- Taylor, L., Rezai, A., Foley, D.K., 2016. An integrated approach to climate change, income distribution, employment and economic growth. *Ecol. Econ.* 121, 196–205.
- Teske, S., Pregger, T., Simon, S., Naegler, T., Graus, W., Lins, C., 2011. Energy [R]evolution 2010—a sustainable world energy outlook. *Energy Effic.* 4, 409–433. <https://doi.org/10.1007/s12053-010-9098-y>
- Timmer, M., Dietzenbacher, E., Los, B., Stehrer, R., de Vries, G., 2015. An Illustrated User Guide to the World Input–Output Database: the Case of Global Automotive Production. *Rev. Int. Econ.* 23, 575–605.
- Timmer, M., Erumban, A.A., Gouma, R., Los, B., Temurshoev, U., de Vries, G.J., Arto, I., Genty, V.A.A., Neuwahl, F., Francois, J., others, 2012. The world input-output database (WIOD): contents, sources and methods. Institute for International and Development Economics.
- Torre-Enciso, Y., Ortubia, I., de Aguilera, L.L., Marqués, J., 2009. Mutriku wave power plant: from the thinking out to the reality, in: *Proceedings of the 8th European Wave and Tidal Energy Conference*, Uppsala, Sweden. pp. 319–329.
- Toyota, 2017. Toyota 2017 [WWW Document]. Toyota. URL <https://www.toyota.com/prius/features/mpg/1221/1223/1224/1225>
- Trainer, F., 2007. *Renewable energy cannot sustain a consumer society*. Springer Science & Business Media.



- Trainer, T., 2017. The overlooked significance of the EROI for renewable energy supply systems. <http://www.thesimplerway.info/REsystem%20EROI.html>.
- Trainer, T., 2013. Can Europe run on renewable energy? A negative case. *Energy Policy* 63, 845–850. <https://doi.org/10.1016/j.enpol.2013.09.027>
- Trainer, T., 2012. A critique of Jacobson and Delucchi's proposals for a world renewable energy supply. *Energy Policy* 44, 476–481. <https://doi.org/10.1016/j.enpol.2011.09.037>
- Uehara, T., Nagase, Y., Wakeland, W., 2013. Integrating Economics and System Dynamics Approaches for Modeling an Ecological-Economic System. *Syst. Sci. Fac. Publ. Present*.
- UN, 2015. Report of the Inter-Agency and Expert Group on Sustainable Development Goal Indicators. United Nations. Economic and Social Council. Statistical Commission.
- UN, 2003. The United Nations World Water Development Report 1—Water for people, water for life. United Nations Educational Scientific and Cultural Organization, Paris.
- UN, 1990. Human development report. U. N. Dev. Programme.
- UNEP, 2013a. Metal recycling: Opportunities, limits, infrastructure. International Resource Panel. United Nations Environment Programme.
- UNEP, 2013b. Environmental risks and Challenges of anthropogenic metals flows and cycles. International Resource Panel. United Nations Environment Programme.
- UNEP, 2011. Recycling rates of metals. A status report. International Resource Panel. United Nations Environment Programme.
- UNEP, 2009. Towards sustainable production and use of resources: Assessing biofuels. United Nations Environment Programme, Paris.
- UNESCO, 2009. The United Nations World Water Development Report 3—Water in a Changing World. United Nations Educational Scientific and Cultural Organization, Paris.
- UNFCCC, 2015. Paris Declaration on Electro-Mobility and Climate Change & Call to Action.
- US DOE, 2014. Top 9 Things You Didn't Know About America's Power Grid. US Department of Energy (DOE), <https://energy.gov/> (Retrieved 23-5-2017).
- US DOE, 2012. Large power transformers and the US electric grid. US Department of Energy (DOE).
- US EIA db, 2015. International Energy Statistics (Database). US Energy Information Administration, <http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm>.
- USGS, 2017. Mineral Commodity Summaries. United States Geological Survey, <https://minerals.usgs.gov/minerals/pubs/mcs/>.
- van de Ven, D.-J., González-Eguino, M., Arto, I., 2017. The potential of behavioural change for climate change mitigation: a case study for the European Union. *Mitig. Adapt. Strateg. Glob. Change* 1–34. <https://doi.org/10.1007/s11027-017-9763-y>
- Van den Bergh, J., 2007. Abolishing GDP (SSRN Scholarly Paper No. ID 962343). Social Science Research Network, Rochester, NY.
- van den Bergh, J.C.J.M., 2009. The GDP paradox. *J. Econ. Psychol.* 30, 117–135. <https://doi.org/10.1016/j.joep.2008.12.001>

- Van Leeuwen, J., Smith, P., 2008. Nuclear power—the energy balance. <https://www.stormsmith.nl>, Netherlands.
- van Leeuwen, J.W.S., 1985. Nuclear uncertainties: Energy loans for fission power. *Energy Policy* 13, 253–266. [https://doi.org/10.1016/0301-4215\(85\)90158-2](https://doi.org/10.1016/0301-4215(85)90158-2)
- van Sluisveld, M.A.E., Martínez, S.H., Daioglou, V., van Vuuren, D.P., 2016. Exploring the implications of lifestyle change in 2°C mitigation scenarios using the IMAGE integrated assessment model. *Technol. Forecast. Soc. Change* 102, 309–319. <https://doi.org/10.1016/j.techfore.2015.08.013>
- van Vuuren, D.P., Edmonds, J.A., Kainuma, M., Riahi, K., Weyant, J., 2011. A special issue on the RCPs. *Clim. Change* 109, 1–4. <https://doi.org/10.1007/s10584-011-0157-y>
- Vaughan, N.E., Gough, C., 2016. Expert assessment concludes negative emissions scenarios may not deliver. *Environ. Res. Lett.* 11, 095003. <https://doi.org/10.1088/1748-9326/11/9/095003>
- Verhoef, E., Dijkema, G.P., Reuter, M.A., 2004. Process knowledge, system dynamics, and metal ecology. *J. Ind. Ecol.* 8, 23–43.
- Viebahn, P., Nitsch, J., Fishedick, M., Esken, A., Schüwer, D., Supersberger, N., Zuberbühler, U., Edenhofer, O., 2007. Comparison of carbon capture and storage with renewable energy technologies regarding structural, economic, and ecological aspects in Germany. *Int. J. Greenh. Gas Control* 1, 121–133. [https://doi.org/10.1016/S1750-5836\(07\)00024-2](https://doi.org/10.1016/S1750-5836(07)00024-2)
- Vitousek, P.M., Ehrlich, P.R., Ehrlich, A.H., Matson, P.A., 1986. Human appropriation of the products of photosynthesis. *BioScience* 36, 368–373.
- Wagner, F., 2014. Considerations for an EU-wide use of renewable energies for electricity generation. *Eur. Phys. J. Plus* 129, 1–14. <https://doi.org/10.1140/epjp/i2014-14219-7>
- Wagner, Friedrich, 2014. Electricity by intermittent sources: An analysis based on the German situation 2012. *Eur. Phys. J. Plus* 129, 20. <https://doi.org/10.1140/epjp/i2014-14020-8>
- Wang, J., Feng, L., Tang, X., Bentley, Y., Höök, M., 2017. The implications of fossil fuel supply constraints on climate change projections: A supply-side analysis. *Futures* 86, 58–72. <https://doi.org/10.1016/j.futures.2016.04.007>
- Watkiss, P., Benzie, M., Klein, R.J.T., 2015. The complementarity and comparability of climate change adaptation and mitigation. *Wiley Interdiscip. Rev. Clim. Change* 6, 541–557. <https://doi.org/10.1002/wcc.368>
- WBGU, 2009. Future Bioenergy and Sustainable Land Use. German Advisory Council on Global Change (WBGU).
- Weißbach, D., Ruprecht, G., Huke, A., Czerski, K., Gottlieb, S., Hussein, A., 2013. Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants. *Energy* 52, 210–221. <https://doi.org/10.1016/j.energy.2013.01.029>
- Weitemeyer, S., Kleinhans, D., Vogt, T., Agert, C., 2015. Integration of Renewable Energy Sources in future power systems: The role of storage. *Renew. Energy* 75, 14–20. <https://doi.org/10.1016/j.renene.2014.09.028>
- Weitzman, M.L., 2012. GHG Targets as Insurance Against Catastrophic Climate Damages. *J. Public Econ. Theory* 14, 221–244. <https://doi.org/10.1111/j.1467-9779.2011.01539.x>
- WEO, 2014. World Energy Outlook 2014. OECD / IEA, Paris.

- WEO, 2012. World Energy Outlook 2012. OECD / IEA, Paris.
- WEO, 2010. World Energy Outlook 2010. OECD / IEA, Paris.
- WEO, 2008. World Energy Outlook 2008. OECD / IEA, Paris.
- White, L.A., 1943. Energy and the Evolution of Culture. *Am. Anthropol.*, New Series 45, 335–356.
- WHO, W.H., 2014. Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s. World Health Organization.
- Wikipedia, 2017a. List of electric bus makers and models [WWW Document]. Wikipedia. URL [https://en.wikipedia.org/wiki/List\\_of\\_electric\\_bus\\_makers\\_and\\_models](https://en.wikipedia.org/wiki/List_of_electric_bus_makers_and_models) (accessed 6.29.17).
- Wikipedia, 2017b. Batteries electric and hybrid vehicles [WWW Document]. Wikipedia. URL [https://en.wikipedia.org/wiki/Electric\\_vehicle\\_battery](https://en.wikipedia.org/wiki/Electric_vehicle_battery) (accessed 6.29.17).
- Wilhelm, W.W., Johnson, J.M.F., Karlen, D.L., Lightle, D.T., 2007. Corn Stover to Sustain Soil Organic Carbon Further Constrains Biomass Supply. *Agron. J.* 99, 1665. <https://doi.org/10.2134/agronj2007.0150>
- Williams, R.H., Larson, E.D., Liu, G., Kreutz, T.G., 2009. Fischer–Tropsch fuels from coal and biomass: Strategic advantages of once-through (“polygeneration”) configurations. *Energy Procedia, Greenhouse Gas Control Technologies 9 Proceedings of the 9th International Conference on Greenhouse Gas Control Technologies (GHGT-9)*, 16–20 November 2008, Washington DC, USA 1, 4379–4386. <https://doi.org/10.1016/j.egypro.2009.02.252>
- WMD, 2016. World-Mining-Data (No. 31). International Organizing Committee for the World Mining Congresses; Austrian federal Ministry of Science, Research and Economy, Vienna.
- Wood, D.A., Nwaoha, C., Towler, B.F., 2012. Gas-to-liquids (GTL): A review of an industry offering several routes for monetizing natural gas. *J. Nat. Gas Sci. Eng.* 9, 196–208. <https://doi.org/10.1016/j.jngse.2012.07.001>
- World Bank database, 2018. World Bank database. <http://data.worldbank.org/>.
- Zenzey, E., 2013. Energy as a Master Resource, in: *State of the World 2013: Is Sustainability Still Possible?* Worldwatch Institute, Washington: Island Press, pp. 73–83.
- Zittel, W., 2012. Feasible Futures for the Common Good. Energy Transition. Paths in a Period of Increasing Resource Scarcities. Ludwig-Bölkow-Systemtechnik GmbH, Munich (Germany).

## List of Tables

Table 1. Industrial sectors from WIOD used in MEDEAS world. Source: own elaboration from WIOD (Dietzenbacher et al., 2013a) .....	48
Table 2. Panel data regression for Households consumption. Source: own elaboration.....	54
Table 3. Panel data regression of Gross fixed capital formation. Source: own elaboration.....	55
Table 4. Income share scenarios .....	58
Table 5. Sectoral final energy sensitiveness by sources (EJ/million 1995 US\$). Source: own elaboration.....	66
Table 6: Equivalence between MEDEAS final energy categories and the WIOD and IEA categories. Losses and non-energy use of materials are not considered. ....	78
Table 7. Parameters for the modelling of energy distribution losses.....	84
Table 8. Parameters for the modelling of energy transformation losses. ....	84
Table 9. Parameters for the modelling of gain gas in transformation processes losses.....	85
Table 10 : Sources of energy supply in MEDEAS. Natural gas refers to both conventional and unconventional. Oil refers to both conventional and unconventional.....	88
Table 11: Equivalence between volume and energy applied by different agencies and authors. *Equivalence used by de Castro (2009).....	102
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 (10 <sup>12</sup> barrels); RAR: reasonably assured resources; IR: Inferred resources; NEA: Nuclear Energy Association. ....	107
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. ....	120
Table 14: Techno-sustainable potential of non-electric renewable sources excluding bioenergy. ....	124
Table 15: Data of electric renewable in the model. “TWe” represents the gross annual power electric production: TWh/8760. ....	126
Table 16: Techno-ecological potential of RES for heat and electricity. ....	129
Table 17: Integration cost adapted from (Holttinen et al., 2011).....	140
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. ....	141
Table 19: Assumptions for the efficiency of fossil and nuclear power plants.....	144
Table 20: Historical installed capacity growth of RES technologies for electricity generation (annual averaged growth over the period). ....	145
Table 21: Historical installed capacity growth of RES technologies for heat generation (annual averaged growth over the period), commercial and non-commercial uses aggregated.....	156
Table 22. CHP plants efficiencies for heat for the 2014: Own elaboration from (IEA, 2018). ....	158
Table 23: Saving ratios estimated for different vehicles and fuels compared to liquid-based equivalent vehicles. ....	178
Table 24: Ratios of battery size relative to light purely electric vehicles. ....	179
Table 25: Results of regressions of final fuel non-energy use demand as a function of GDP.....	180
Table 26: Material requirements per RES variable electricity generation technologies considered in MEDEAS. ....	184
Table 27 : Material requirements for electric grids related to the RES variable electricity generation technologies.....	188

Table 28: Material requirements (kg) per new MW installed. Source : own compilation.....	190
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)).....	193
Table 30 : Energy consumption per unit of material consumption for virgin and recycled materials. ....	212
Table 31 ; EROI over lifetime for each of the RES technologies for electricity generation considered in MEDEAS. We take $g(\text{year}=2015)=0.66$ from MEDEAS. See section 0 for the recycling rates considered for estimating the EROI of dispatchable RES. Values of EROI <sub>pou</sub> can be estimated as EROI <sub>st</sub> -1. * EROI <sub>st</sub> including additional grids and storage is scenario dependent is not reported here.....	215
Table 32: Assumptions to build the allocation rule of renewable technologies for producing electricity in MEDEAS. ....	219
Table 33: CO <sub>2</sub> and CH <sub>4</sub> 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. 1tCO <sub>2</sub> /toe = 23,8gCO <sub>2</sub> /MJ). *In the absence of data, it was assumed the same emission coefficient of CH <sub>4</sub> than the respective conventional fuel from (Howarth, 2015) for CTL, GTL and unconventional oil.....	225
Table 34 : Main policy targets included in the MEDEAS framework. « * » indicates « desired » policy targets, i.e. ....	251
Table 35: EROI estimation of coal and bioenergy power plants with and without CCS. ....	254

## List of Figures

Figure 1: Overview of MEDEAS-World by modules and the modelled linkages between them.....	35
Figure 2: Overview of MEDEAS-World by modules and the modelled linkages between them.....	41
Figure 3. Macro-economic modelling in IAMs. Source: (Scrieciu et al., 2013b) .....	46
Figure 4. Schematic overview of MEDEAS Economy module. Own elaboration.....	49
Figure 5. Causal loop map of MEDEAS Economy module. Source: own elaboration. ....	50
Figure 6. Schematic national and interregional Input-Output Tables.....	59
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. ....	60
Figure 8. Energy-Economy feedback in MEDEAS. Source: own elaboration.....	63
Figure 9: Historical evolution of electricity intensity by sector for the period 1995-2009. Source: WIOD and own work. ....	70
Figure 10: “a” parameter by sector and type of energy.....	72
Figure 11: Simplified structure of the energy intensities model. ....	74
Figure 12: Simplified structure of the energy intensities model with a limit in energy intensity. ....	74
Figure 13: Simplified structure of the energy intensities model with efficiency energy acceleration. ....	75
Figure 14: Simplified structure of the energy intensities model with the change in energy source.	76
Figure 15: TCF by fuels 2009. Source: WIOD database. ....	81
Figure 16: Historic FED by fuel after adjusting WIOD data from IEA balances. Heat refers solely to commercial heat.....	81
Figure 17: TPES 2009. Source: (IEA, 2018).....	82
Figure 18: Losses in 2009. Source: (IEA, 2018).....	83

Figure 19: FED by fuel after heat correction.....	87
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.....	91
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). ....	93
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.....	93
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 (Alekklett 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. (Alekklett 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.....	97
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). ....	98
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).....	100



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).	101
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)).	104
Figure 28: Stock and flow map diagram of coal extraction.	105
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).	106
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).	109
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).	110
Figure 32: Stock and flow map of the model of the bioenergy in land subject to competition in MEDEAS.	119
Figure 33: Stock and flow diagram of the extraction of (primary energy) from thermal commercial RES.	122
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.	133
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%).	135
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.	136

Figure 37: Distribution losses vs. consumption at global level (1980-2012) (US EIA db, 2015).....	142
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). ....	143
Figure 39: Infrastructure of RES technologies for the generation of electricity (vectorial programming). ....	146
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. ....	148
Figure 41 (own analysis from (World Bank database, 2018)): Electricity production from oil sources (TWh) and as percentage of the total electricity production. ....	149
Figure 42: Stock and flow diagram of electric generation from nuclear power.....	150
Figure 43: Distribution losses vs. consumption at global level for commercial heat (1990-2014) (IEA, 2018).....	154
Figure 44: Heat production from oil sources (TWh) and as percentage of the total heat production (own analysis from (World Bank database, 2018)). ....	155
Figure 45: share of Heat demand without RES sources covered by CHP plants .....	157
Figure 46: Stock and flow diagram of the household transport subsystem. ....	164
Figure 47: Stock and flow diagram of the household transport subsystem. ....	167
Figure 48: Diagram of the batteries submodule. ....	168
Figure 49: Diagram of the policies of Households Transport subsystem.....	169
Figure 50: Diagram of the policies of Inland Transport subsystem .....	170
Figure 51: Historical evolution of EV+PHEV vehicles. (Own elaboration based on data from (IEA, 2016)).....	172

Figure 52: Historical evolution of hybrid vehicles worldwide (own elaboration based on data from (IEA, 2016)).....	173
Figure 53: Evolution of the stock of electrical two wheelers worldwide. Own calculations based on data from (IEA, 2016).....	175
Figure 54 (UNEP, 2011): EOL-RR for sixty metals.....	198
Figure 55 : Loop diagram of the mineral recycling policy in MEDEAS. ....	202
Figure 56: ESOI of PHS as a function of the installed capacity. ....	208
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. ....	213
Figure 58 : Growth in new planned capacities per technology as a function of the ratio of its EROI and the EROI <sub>electot</sub> .....	219
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. ....	220
Figure 60: Shale oil as a share of total unconventional oil as estimated by (Mohr and Evans, 2010) (low case). ....	226
Figure 61 : Structure of the climate module in MEDEAS-World.....	229
Figure 62 : Carbon cycle representation in MEDEAS-W.....	230
Figure 63: Qualitative representation of the energy loss function (ELF) applied in the MEDEAS framework.....	235
Figure 64: Implementation in MEDEAS framework of the energy losses due to climate change impacts.....	236

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.....	240
Figure 66: Global water consumption (1995-2009) by type from WIOD database.....	246
Figure 67: Stock and flow diagram of the estimation of water use in MEDEAS.....	248
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. ....	265
Figure 69: Overview of MEDEAS-World by modules. Straight lines represent relationships currently modelled, while dashed lines represent future potential developments.....	266