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MEDEAS

MODELING THE RENEWABLE ENERGY TRANSITION IN EUROPE

Project Nr: 691287

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

Annex – documentation of the changes of MEDEAS-World between the version D4.1 (June 2017) and the final version for Python (November 2017)

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Table of contents

GUIDING EUROPEAN POLICY TOWARD A LOW-CARBON ECONOMY. MODELLING SUSTAINABLE ENERGY SYSTEM DEVELOPMENT UNDER ENVIRONMENTAL AND SOCIOECONOMIC CONSTRAINTS	1
DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES	2
DOCUMENT INFO SHEET	3
TABLE OF CONTENTS	4
SCOPE OF DOCUMENT	6
LIST OF ABBREVIATIONS AND ACRONYMS	7
EXECUTIVE SUMMARY	8
INTRODUCTION	9
METHODOLOGY	10
1. WATER USE	10
CONTEXT	10
DATA	11
METHODOLOGY FOR ESTIMATING WATER USE IN MEDEAS	12
WATER POTENTIAL	14
2. UPDATE OF CLIMATE MODULE	14
REVIEW OF EXISTING “SIMPLE” CLIMATE MODELS	14
STRUCTURE OF THE CLIMATE MODULE IN MEDEAS-W	15
3. EXPAND OPTIONS FOR POLICY TARGETS	18
FINAL ENERGY INTENSITIES	18
MINERAL RECYCLING	18
GHG EMISSIONS	19
4. ADAPTATION OF THE MODELLING IN VENSIM FOR PYTHON	20
PRE-CALCULATION OF MATRIXES FROM INPUT-OUTPUT TABLES	20
INTRODUCE TAGS PER MODULE	20
5. OTHER: MINOR UPDATES, IMPROVEMENT OF MODEL DOCUMENTATION AND CORRECTION OF BUGS	21
MINOR UPDATES	21
IMPROVEMENT OF MODEL DOCUMENTATION	22
CORRECCION OF BUGS	22



RESULTS.....	22
CONCLUSIONS.....	22
REFERENCES.....	24
LIST OF TABLES.....	26
LIST OF FIGURES.....	27



Scope of document

This report documents the main differences between the MEDEAS-World version delivered in June 2017 (D4.1) and the final version for its translation to Python. These are:

- Full implementation of water use,
- Replacement of the climate module based on DICE by a submodel based on C-ROADS,
- Expand options for policy targets,
- Adaptation of the modelling in Vensim due to Python programming requirements,
- Minor updates, improvement of model documentation and correction of bugs.

List of abbreviations and acronyms

AR	Accessible Runnoff
GDP	Gross Domestic Product
GHG	Greenhouse Gas
RCP	Radiative Concentration Pathway
WIOD	World Input-Output Database
PV	Photovoltaic
CSP	Concentrated Solar Panel
EROI	Energy Return on Energy Invested



Executive summary

This report documents the main differences between the MEDEAS-World version delivered in June 2017 (D4.1) and the final version for its translation to Python. These features have been updated/developed in parallel to the development of the MEDEAS-EU version, which will incorporate most of them. These are:

- Full implementation of water use,
- Replacement of the climate module based on DICE by a submodel based on C-ROADS,
- Expand options for policy targets,
- Adaptation of the modelling in Vensim due to Python programming requirements,
- Minor updates, improvement of model documentation and correction of bugs.

These modifications slightly modify the results reported in the D4.1 although do not qualitatively alter the behavior of the model.

Introduction

UVa has continued improving the world level version of MEDEAS after the deliverable in June 2017 (D4.1) (MEDEAS, 2017), in order to update and increase the dimensions represented in the model, as well as correcting bugs, which are inescapable in a model of such a size and complexity.

The work has focused on 3 main topics:

- Full implementation of water use,
- Replacement of the climate module based on DICE by a submodel based on C-ROADS,
- Expand options for policy targets,
- Adaptation of the modelling in Vensim,
- Minor updates, improvement of model documentation and correction of bugs.

The rationale for including these improvements has been as follows:

Water use representation has been completed in order to fulfill the requirement in the Grant Agreement.

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. In this sense, it was decided to replace it with an adaptation of a more complete model. After a review of different options an adaptation of C-ROADS was decided to be included.

The need to expand the representation of policy options in the model was one of the limitations pointed out in D4.1. Therefore, this was a key area of improvement. Three main options have been included: the possibility to project different levels of final energy intensities by scenario, the options to set targets of material recycling for each mineral individually, and the option to select which level of GHG emissions (other than those endogenously generated by MEDEAS, i.e. CO₂ and some CH₄) in relation to the RCP pathways.

The code in Vensim had to be modified in order to adapt to issues of Python programming with matrix operation and to facilitate the interpretation of modules.

Finally, as in any process of model development, minor updates have been implemented, model documentation has been improved and some bugs have been fixed. However, the overall introduced changes do not affect the main dynamics of the MEDEAS-World model presented in the D4.1. This final version corresponds with the v130 of model development.

Methodology

Follows a description of the main features included in the MEDEAS-World version between the version D4.1 (June 2017) and the final version for Python translation in November 2017. These features have been updated/developed in parallel to the development of the MEDEAS-EU version, which will incorporate most of them.

1. 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.

Context

Freshwater (water which is not salty) represents around 2.5% of the total volume of water on Earth. Out of this percentage, two thirds are locked in glaciers and ice caps. Just ~0.77% of all water (around 10,665,000 km³) is held in aquifers, soil pores, lakes, swamps, rivers, plant life and the atmosphere (Postel et al., 1996). Water resources are renewable (except for some groundwaters) but there are significant differences in availability around the world as well as wide variations in seasonal and annual precipitation (UN, 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 desalinated seawater (UN, 2009).

(AR, this is runoff that is realistically available for human use)

Agriculture uses by far most of the accessible runoff. This sector has a water demand of 2,880 km³ each year and about 65% of total demand is consumed. Industrial use of water is estimated to be around 975 km³ but in contrast to the agricultural sector, industry only consumes a small share of

this water, around 9%. Most of it is released back to the environment, however, it is usually polluted (Postel et al., 1996).

In this way, it is notice that the consumption of water will influence significantly in the environment development and, in particular, it will affect potential climate change policies. Recent estimates suggest that climate change will account for about 20% of the increase in global water scarcity (UN, 2003).

Most IAMs do not usually focus on modelling water demand and supply because they have assumed that adaptation to climate change will not be affected by water scarcity. However, there are some exceptions like the Global Change Assessment Model (GCAM) which incorporates a water-balance 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).

Data

Data are from from the environmental accounts from WIOD database (Genty et al., 2012) (Release 2013, <http://www.wiod.org/database/eas13> see also (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 1 represents the global consumption of water by type for the 1995-2009 period:



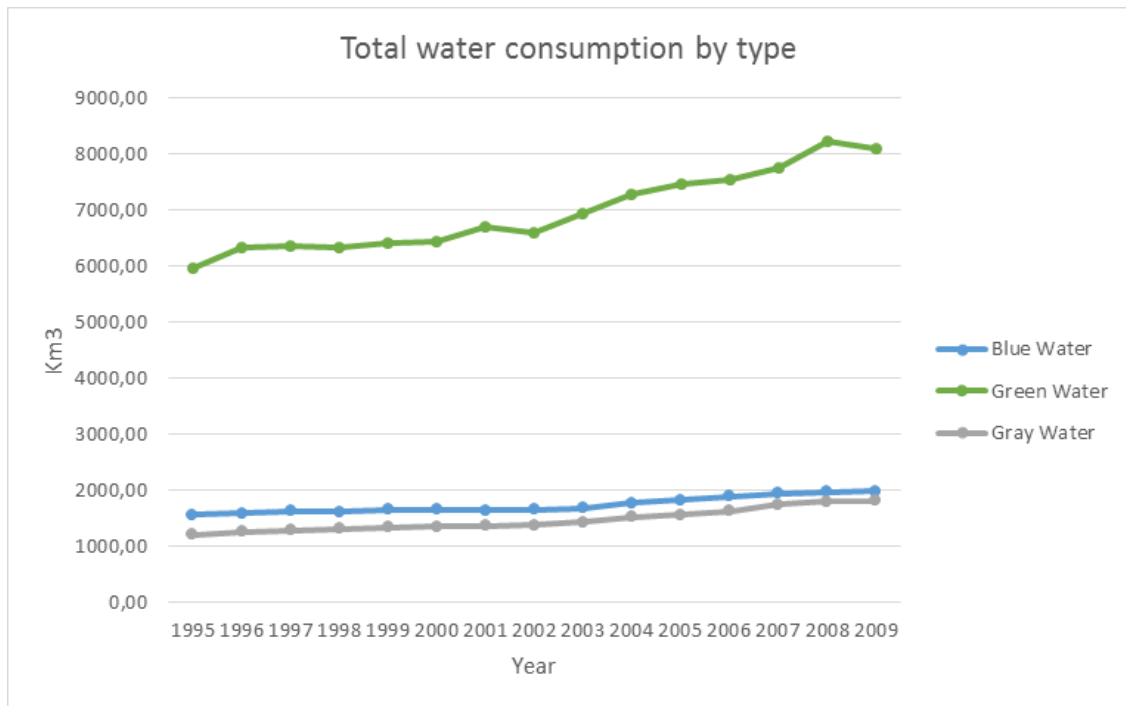


Figure 1: Global water consumption (1995-2009) by type from WIOD database.

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 2 shows the Forrester diagram of the estimation of water use in MEDEAS

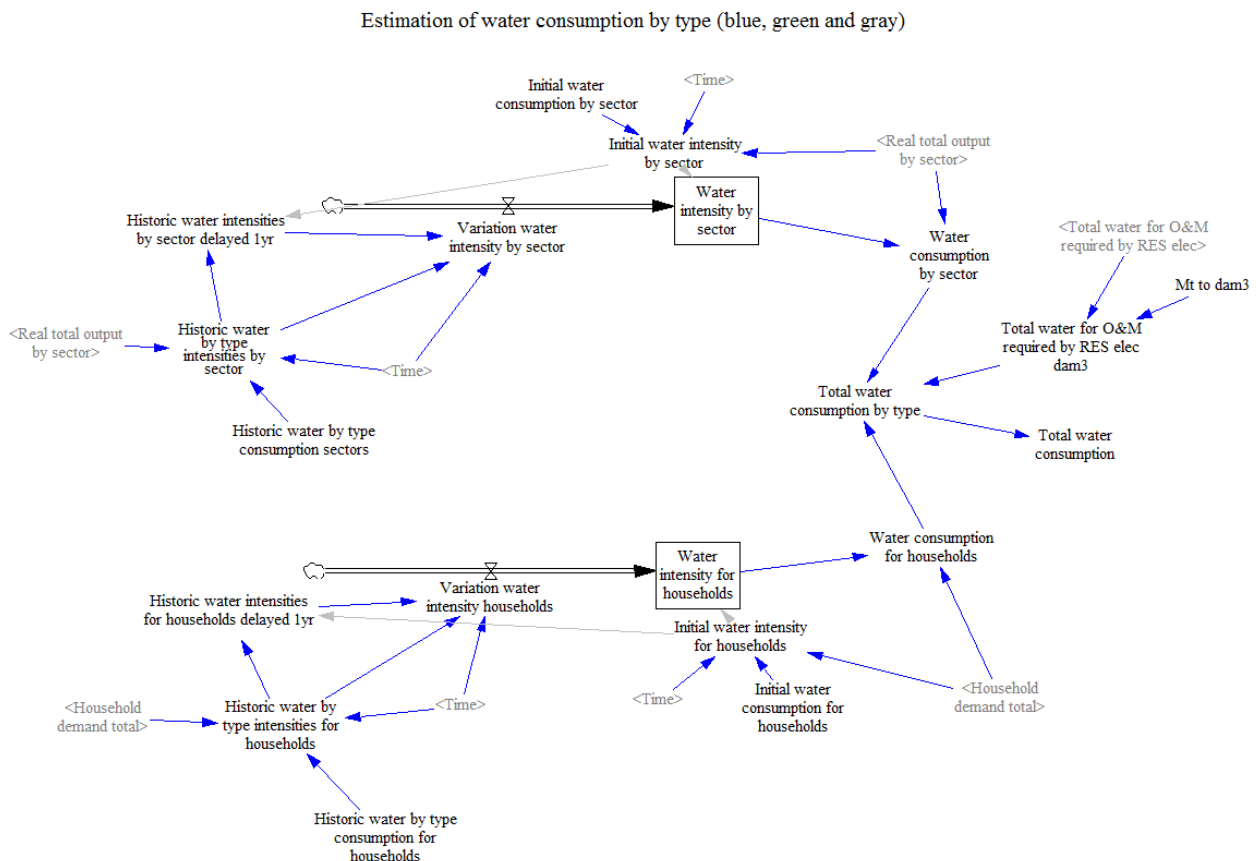


Figure 2: Forrester diagram of the estimation of water use in MEDEAS.

Water potential

Most (99%) offstream water uses – irrigation, domestic, industry and energy – are met by withdrawals¹ from renewable sources, either surface water or groundwater. Less than 1% (currently estimated at 30 km³ a year) comes from non-renewable (fossil) aquifers. The global renewable water resources have been estimated at 43,659 km³ (UN, 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 km³.

2. Update of climate module

Review of existing “simple” climate models

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, 1997, 2002). In this sense, it was decided to replace it with 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., 2012), DICE-1992 (Nordhaus, 1992), DICE-2013R (Nordhaus and Sztorc, 2013), ESCIMO (Randers et al., 2016), FREE (Fiddaman, 1997, 2002) 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.

Finally, 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

¹ Water withdrawal is the gross amount of water extracted from any source in the natural environment for human purposes (Box 7.2 (UN, 2009)).



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 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.

Structure of the climate module in MEDEAS-W

Figure 3 shows the main elements of the climate module modelled in MEDEAS-W: the anthropogenic CO₂ emissions endogenously generated by the model enter the carbon cycle representation, which estimates the level of CO₂ concentration in the atmosphere, the other GHG cycles which together contribute to the anthropogenic climate change. The cycle of each GHG is modelled separately, including the interaction between cycles such as between the CH₄ and the N₂O, 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.

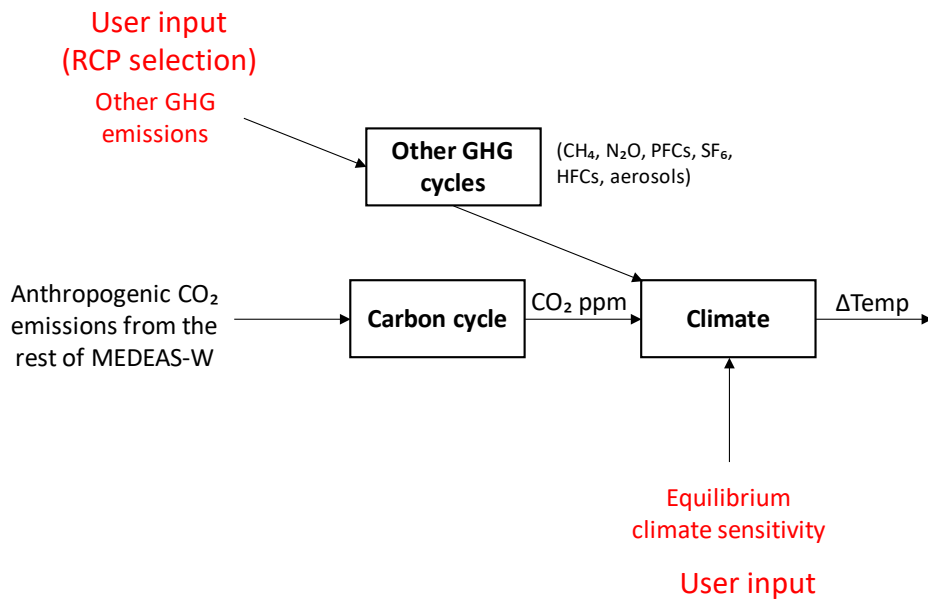


Figure 3 : Structure of the climate module in MEDEAS-World.

Figure 4 shows a simplified representation of the carbon cycle, which represents the dynamics between the carbon in the biosphere (humus and biomass) and the ocean.

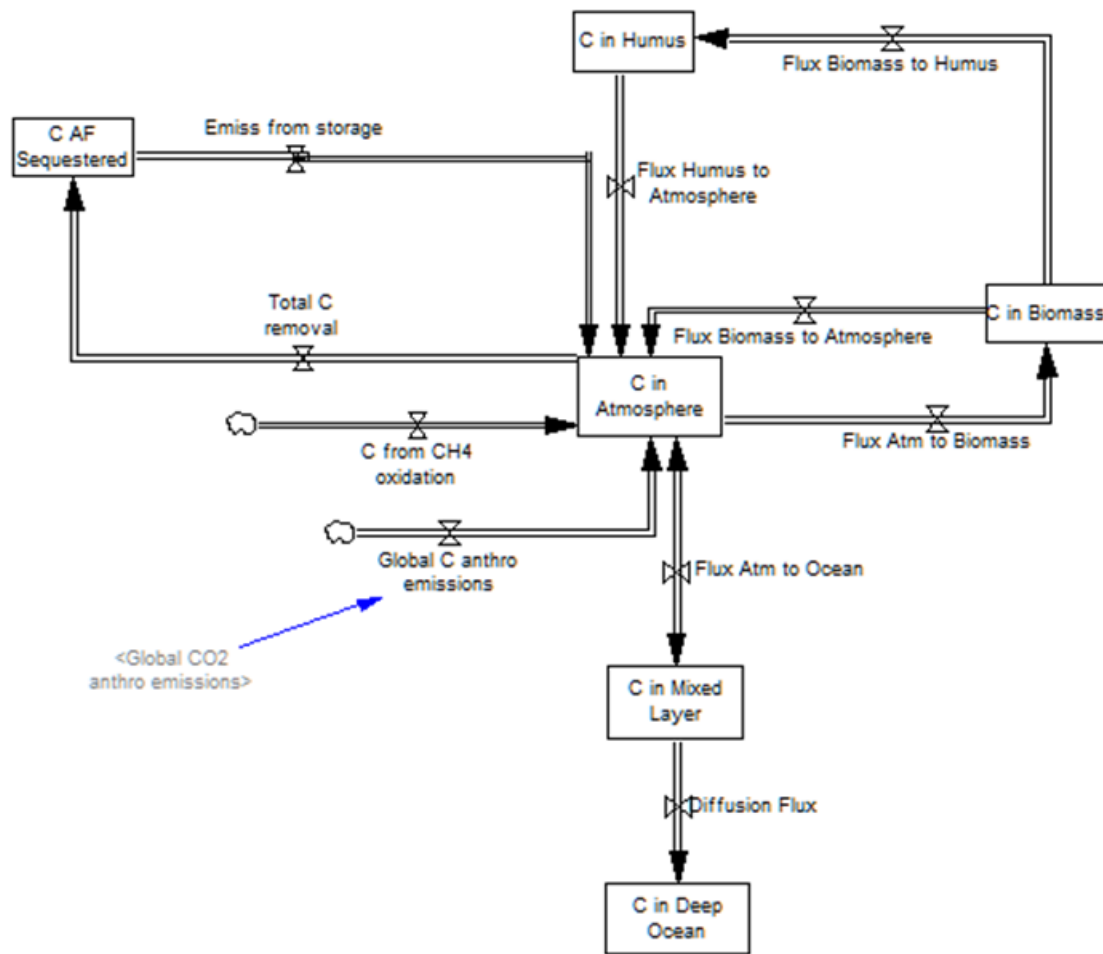


Figure 4 : Carbon cycle representation in MEDEAS-W.

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: CH₄, N₂O, PFCs, SF₆ 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., 2012).

3. Expand options for policy targets

The need to expand the representation of policy options in the model was one of the limitations pointed out in D4.1. Therefore, this was a key area of improvement. Three main options have been included: the possibility to project different levels of final energy intensities by scenario, the options to set targets of material recycling for each mineral individually, and the option to select which level of GHG emissions (other than those endogenously generated by MEDEAS, i.e. CO₂ and some CH₄) in relation to the RCP pathways (see section 2).

Final energy intensities

The current version of MEDEAS-W allows more flexibility in the simulation of policy targets relative to the evolution of final energy intensities:

- Disaggregation by sector and for households,
- Possibility to simulate worse, same and better improvement trends than historical trends,
- Possibility to simulate scenarios without technological improvement.

Mineral recycling

In the updated version, the user can introduce the target level of recycling by mineral for a given year. This has required the adaptation of the Vensim code as showed in the Figure 3 below.

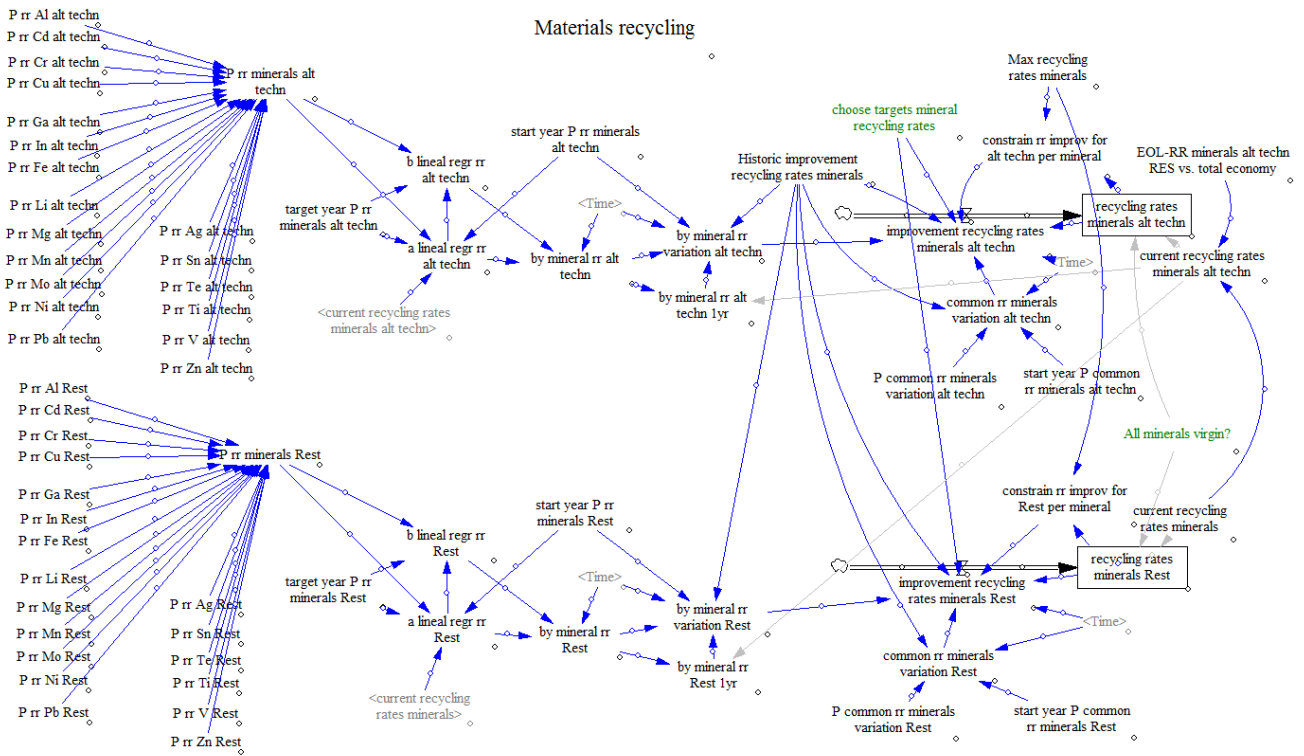


Figure 5 : Policy target recycling by mineral.

GHG emissions

In relation with the update of the climate module of MEDEAS, the user is now able to select which RCP level he wants to use as reference for those GHG not endogenously calculated in the model (i.e. CO₂ emissions and some CH₄):

- RCP2.6
- RCP4.5
- RCP6.0
- RCP8.5

This improvement allows for more flexibility and realism in the assumptions when performing simulations. For more information on the RCP see (van Vuuren et al., 2011).

4. Adaptation of the modelling in Vensim for Python

Two main changes had to be introduced in the Vensim code to adapt to Python programming requirements:

- Pre-calculate some matrixes from Input-Output tables and read the data from an external file,
- Introduce tags for each Vensim view in order to identify each view to a MEDEAS module.

Pre-calculation of matrixes from Input-Output tables

Matrix operations were an issue during the translation of the code to Python. To avoid this issue, the Leontieff Matrix (L) is directly loaded from an external file instead of being endogenously obtained from the A Matrix. The same applied for the IA matrix.

Introduce tags per module

Different tags were included per Vensim view in order to identify each view to a MEDEAS module. These have been organized as follows:

Tag module		Name module	Level -1	Level -2
P		Population		
I		Final energy intensities		
E		Energy		
	EE		Electricity demand and supply	
	EER			Renewables
	EH		Heat demand and supply	
	EHR			Renewables
	EA		Energy availability	
EAR				Renewables
EAN				Non-renewables
e		Economy		

D	Demand ^a		
C	Climate		
S	Social & Environmental Indicators		
L	Land		
T	Transportation		
M	Materials		
N	EROI		

Table 1 : Module tags for Python code. ^aDemand include two types of demand: (1) monetary (1995\$) for sectors and households, and (2) energy demands.

5. Other: minor updates, improvement of model documentation and correction of bugs

Minor updates

Two minor updates have been included in order to improve the representation of some features in the model.

First, more sources of energy investments have been modelled in the updated version of the model, including estimates of those related with electricity production from renewable dispatchable sources (hydroelectric, geothermal, biomass and oceanic), as well as for electricity storage technologies (pumped hydro storage (PHS) and electric vehicle batteries). These energy investments corresponds with the denominator of the expressions of the EROI static (over the lifetime, see section 2.4.4 in D4.1 (MEDEAS, 2017)) for renewable dispatchable electricity technologies and the ESOI for electricity storage technologies. Thus, summing-up, MEDEAS-W includes the energy investments for all renewable technologies for the generation of electricity and the associated technologies for storing electricity.

Second, a view with the explicit representation of the capacity of PHS has been included following the same structure than for renewable technologies for the generation of electricity (see Figure 35 in D4.1 (MEDEAS, 2017)). This allows to more realistically represent the dynamics between the penetration of variable technologies and the storage requirements, as well as estimate the associated energy investments.

Improvement of model documentation

Model documentation, in reports and as comments in the code have been improved, expanding explanations and references. The latter is especially important to have a fully understandable Python version code (comments from the Vensim code programme are automatically included in the Python model version).

Correccion of bugs

As it is normal in any process of model development, different bugs have been found and corrected in the last months. Most of them were minor and do not affect significantly the results of the simulations. A couple of them were significant and affected the feedback of the EROI to the system (which was overestimated), and the projection of GDP levels following exogenous assumptions (which underestimated the energy demand). However, after analysis, it was concluded that the correction of these bugs do not alter the qualitatively behavior of the model reported in D4.1.

Results

No results are reported in this Annex.

Conclusions

This report documents the main differences between the MEDEAS-World version delivered in June 2017 (D4.1) and the final version for its translation to Python. These features have been updated/developed in parallel to the development of the MEDEAS-EU version, which will incorporate most of them. These are:

- Full implementation of water use,
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- Expand options for policy targets,
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List of Tables

Table 1 : Module tags for Python code. ^aDemand include two types of demand: (1) monetary (1995\$) for sectors and households, and (2) energy demands. 21



List of Figures

Figure 1: Global water consumption (1995-2009) by type from WIOD database.....	12
Figure 2: Forrester diagram of the estimation of water use in MEDEAS.....	13
Figure 3 : Structure of the climate module in MEDEAS-World.....	16
Figure 4 : Carbon cycle representation in MEDEAS-W.	17
Figure 5 : Policy target recycling by mineral.....	19

