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

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

Project Nr: 691287

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

D4.1 (D13) Global Model: MEDEAS-World Model and IOA implementation at global geographical level

Version 3.0.0

Due date of deliverable: 30/06/2017 Actual submission date: 30/06/2017

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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:

UVa: Iñigo Capellán-Pérez (ICM-CSIC), Ignacio de Blas, Jaime Nieto, Carlos de Castro, Luis Javier Miguel, Margarita Mediavilla, Óscar Carpintero, Paula Rodrigo, Fernando Frechoso and Santiago Cáceres

Dissemination level : Public

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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 will integrate energy, raw materials supply and socioeconomic behavior in an energy systems simulation model.

Specifically, Deliverable 4.1 (Global Model) is focused on the development of MEDEAS model at global scale i. e. MEDEAS-World. 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 modeled in MEDEAS; section 3 describes the scenarios simulated to illustrate the behavior and typical results of the model, section 4 reports these results and briefly discuss them, 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 finally section 6 concludes.

The Deliverable 4.1 includes two versions of the global model which correspond to the versions delivered in June 2017 (version 1.0) and the final version to be translated to Python (version 1.1, November 2017). The Deliverable 4.1 includes the following documents:

1. the MEDEAS-World model version 1.0 in Vensim format (two files):
   "Deliverable 4.1 (D13)_Global Model_MEDEAS-W 1.0.mdl" and "inputs.xlsx",
2. a published version of the model for those users that do not have the proprietary version of Vensim:
   Deliverable 4.1 (D13)_Global Model_MEDEAS-W 1.0.vpm
3. Annex 1 that reports and explains all the equations of the model:
   "Deliverable 4.1 (D13)_Global Model_Annex1.pdf »
4. the MEDEAS-World model version 1.1 in Vensim format (two files):
   "Deliverable 4.1 (D13)_Global Model_MEDEAS-W 1.1.mdl" and "inputs.xlsx",
5. a published version of the model for those users that do not have the proprietary version of Vensim:
   Deliverable 4.1 (D13)_Global Model_MEDEAS-W 1.1.vpm
6. An annex documenting the performed updates for the final version to be translated to Python:

Deliverable 4.1 (D13)_Global Model_Annex final version for Python.pdf

The MEDEAS model will be publicly available in open software Python as from February 2018 on the project website (http://www.medeas.eu/model/medeas-model).

List of abbreviations and acronyms

BAU: Business-as-usual

BECCS: Bioenergy and CCS

BEV: Battery electric vehicle

BG: Buest guess

CBM: Coal-bed methane

CCS: Carbon capture and storage

CED: Cumulative energy demand

CGE: Computable general equilibrium

CHP: Combined heat power

Cp: Capacity factor

CSP: Concentrating solar power

CTL: Coal to liquids

EJ: Exajoule

ELF: Energy loss function

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

EROI: Energy return on energy invested

EROIext: EROI extended

EROIpou: EROI point of use

EROIst: EROI standard

ESOI: Energy stored on energy invested

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

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Executive summary

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 (or Integrated Assessment 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 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 are the most extensive and reach the highest degree of disaggregation. The model consists of a modular and flexible structure, where each module can be expanded/simplified/replaced by another version or submodel, new modules can be added, etc. Figure 1 shows the interrelations between the 7 modules represented by boxes, whose main characteristics are:

- Economy and population: the economy of MEDEAS is modelled following a post-Keynesian approach assuming disequilibrium (i.e. non-clearing markets), demand-led growth and supply constraints. The economic structure is capture by the integration of IOA (35 industrial sectors and households).
- Energy: this module includes the renewable and non-renewable energy resources potentials and availability taking into account biophysical and temporal constraints. In total, 5 final fuels are considered (electricity, heat, solids, gases and liquids) and a diversity of energy technologies are modelled. A net energy approach has been followed.
- Energy infrastructures represent the infrastructures of power plants to generate electricity and heat.
- Climate: this module projects the climate change levels due to the GHG emissions generated by the human societies, which also feed-back through a damage function.
- Materials: materials are required by the economy and MEDEAS especially tracks the material requirements for the construction and O&M of the energy infrastructures. The extraction demands are subsequently compared with the levels of available metrics of reserves and resources.
- Land-use: this is the less developed module of MEDEAS, and it mainly accounts for the land requirements of the RES energies.

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- 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.

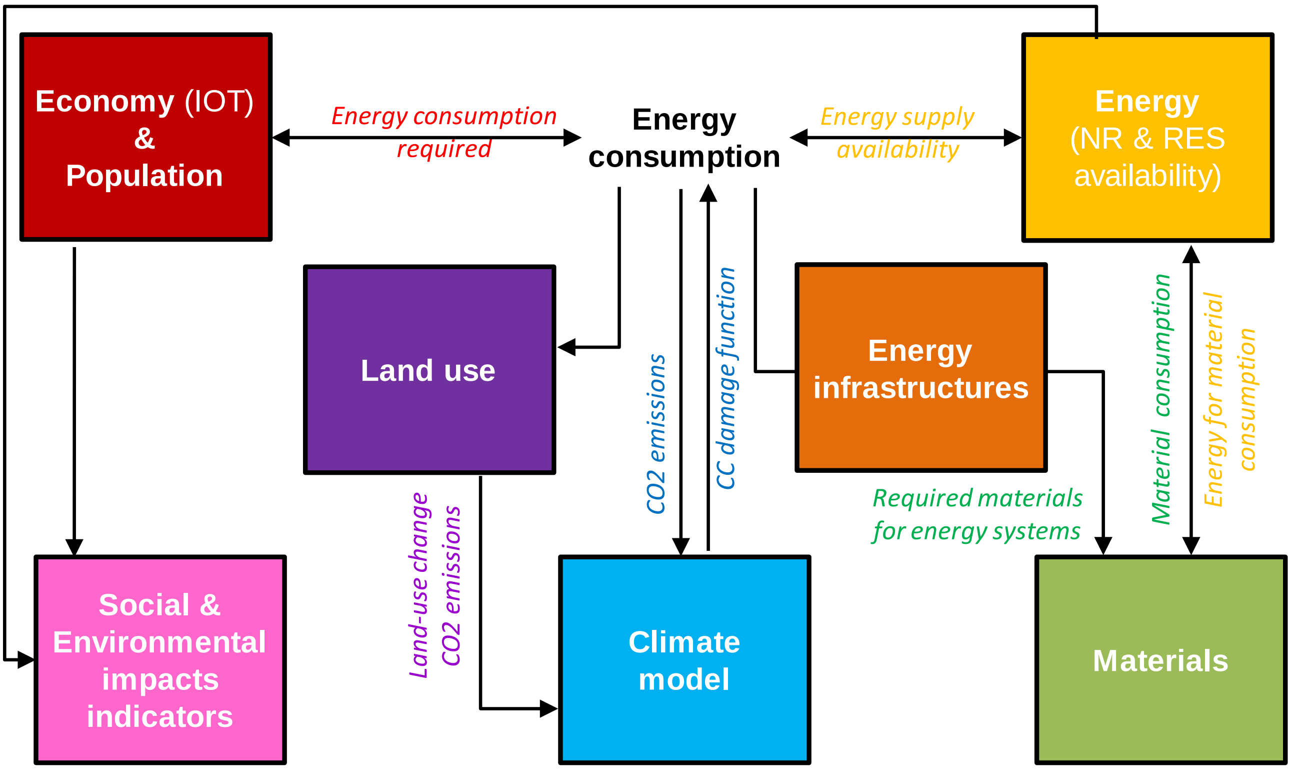

Figure 1: Overview of MEDEAS-World by modules and the modelled linkages between them

The model includes several novelties in relation to the literature:

- 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.

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- Comprehensive estimation of the EROI of those RES technologies for the generation of electricity with more potential.
- Estimations of the potential mineral scarcity,
- EROI estimation and feedback.
- The effects of climate change are feedback into energy consumption.
- Socio-economic indicators model implementation.

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

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.

The results presented in this report illustrate the potentiality of the model: the consideration of feedbacks and interrelations between submodules lead to the conclusion that current Green Growth scenarios, often promoted by institutions as the way to going forward to achieve a sustainable energy transition, may have serious drawbacks. Our results show that the solution of individual problems could lead to the creation of others. These dynamics cannot be revealed in the common models characterized by sequential structures.

Despite the challenges encountered with the model, there are still many limitations and uncertainties. In particular, further developments should address the inclusion of more dynamics in the economy module. Concretely, it is important to make A matrix evolve under scenarios, but endogenously as well. More dynamization would help to better model the allocation between different energy fuels and technologies. Moreover, the modelling of the interaction between energy supply and demand in cases of energy scarcity should be improved. For these and other reasons detailed in the previous section, the interpretation of the results must be done with caution. MEDEAS is not intended to predict the future, but rather to guide qualitatively the best options for the energy transition towards a low carbon economy. It is a tool to explore strategies, not specific policies, since the latter are applied at a different (reduced) political scale.

The MEDEAS model will be publicly available in open software Python as from February 2018 on the project website (http://www.medeas.eu/model/medeas-model).

Introduction

The main result of this deliverable is a simulation model based on system dynamics that integrates economic, energy and environmental variables. The geographical scale of the model is the world. The model has been programmed in the Vensim software for this first version. The simulation model can be read and run with Model Reader software that is freely distributable at no cost and licensed by Ventana Systems, Inc.

Conceptually, the model has been divided into 7 submodules: Economy, Energy, Infrastructures, Materials, Land Use, Social and Environmental Impacts Indicators and Climate Change. These submodules have been programmed in approximately 100 simulation windows and using more than 4000 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 effects of climate change are feedback into energy consumption.
f) Two standard scenarios have been modeled and implemented. Three other scenarios have been programmed.

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

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

One of the major obstacles that the development of the model has faced 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. One such case is the estimation of the economic, social or energy impacts that climate change may have. Progress in research in these fields of knowledge may limit 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 MEDEAS model will be publicly available in open software Python as from February 2018 on the project website (http://www.medeas.eu/model/medeas-model).

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Methodology

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. MEDEAS is a simulation model built in System Dynamics (Vensim DSS software for Windows Version 6.4E (x32)). The model consists of a modular and flexible structure, where each module can be expanded/simplified/replaced by another version or submodel, new modules can be added, etc. Figure 2 shows the interrelations between the 7 modules represented by boxes, whose main characteristics are:

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

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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.

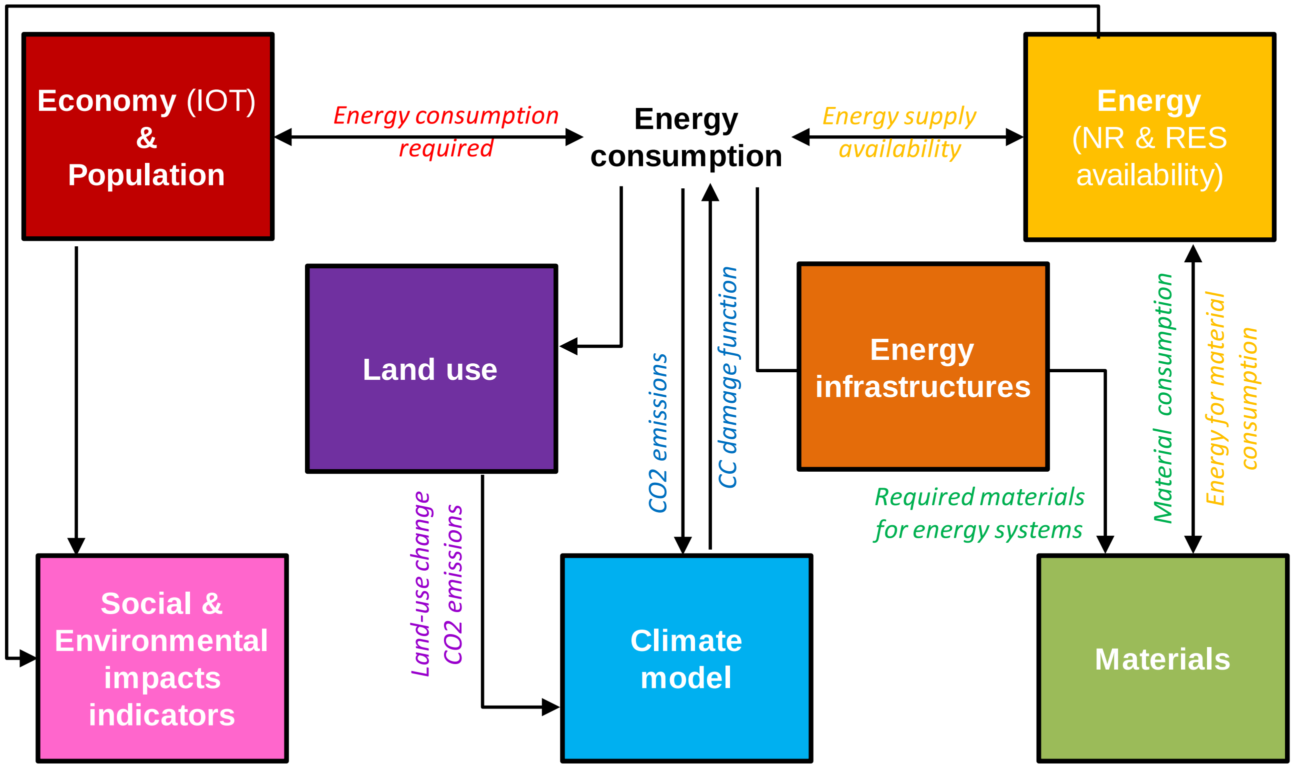

Figure 2: Overview of MEDEAS-World by modules and the modelled linkages between them

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 trough the final energy intensities by fuel. These final energy demands by final fuel are confronted with the available final energy from the energy module. This dynamic energy availability is given by stocks and flows limitations of non-renewable fuels –peak oil phenomena-, sustainable potential of renewables, realistic rhythms of technology deployment, etc. In the case that the final energy demands are lower than the final energy availability, the demand is fulfilled. If the opposite is true, the final demand adapts to the available final energy. In any case, the demand of the next time-period is estimated taking as reference the consumption in the previous time-period.

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The consumption of final energy by final fuels is covered by a mix of technologies (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.

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2.2. Economy module

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

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

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

–throughout technologies market competition- in the energy sector. Hybrid models, nonetheless, combine a detailed macroeconomic and energy technologies view.

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

Regarding this body of literature, MEDEAS economy module is defined as a simulation and hybrid model (see Figure 3). Furthermore, MEDEAS economy module is demand-led, sectorally disaggregated and based on a disequilibrium approach and Input-Output Analysis (IOA). MEDEAS consider demand-led approach more realistic than supply-led, since the latter implies non-reasonable assumptions about the productive factors' utilisation capacity. By adopting a demand-led approach, MEDEAS contributes to widen this demand-side body of literature. Moreover, it is a more realistic procedure, as demand represents the actual economic activity deployed by the productive factors, regardless they are in equilibrium or not. However, demand-led models tend to underestimate or directly not take into consideration biophysical supply-side constraints, so GDP is able to keep growing unhindered. The main contribution of MEDEAS in that way is the inclusion of a supply constraint which feeds back economy throughout the energy availability.

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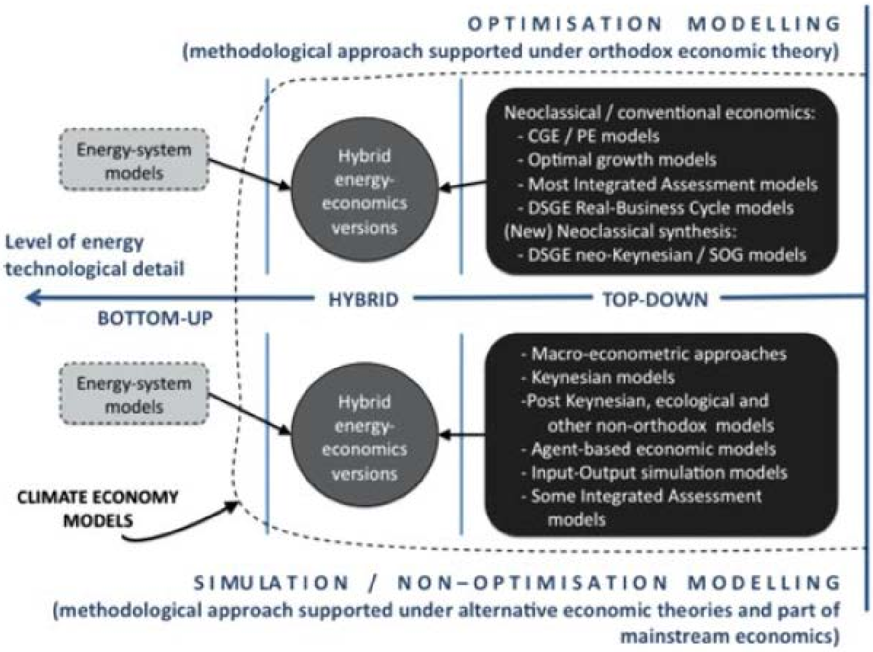

Figure 3 : Macro-economic modelling in IAMs. Source: (Scrieciu et al., 2013)

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).

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2.2.2. Overview of the economy module

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., 2013), 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., 2013)

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

Since MEDEAS is an energy-economy-environment model with a number of biophysical variables, it is reasonable to evaluate monetary values, as much as possible, in volume. As a result of deflation of WIOD, monetary values in the economy module are given in million USD chained linked volumes (1995). WIOD was selected as main source because it is a non-copyright database, at world level and with socioeconomic and environmental satellite accounts. 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.

Influences diagram of the economy module is shown in Figure 4. Economy module includes variables provided in monetary values, energy values and hybrid energy-economy values (mainly, energy intensities). Given a variation in demand (driven by changes and distribution of income) and a certain economic structure (A Matrix), production required to satisfy this demand is obtained. Throughout energy intensities (endogenously changing over time), energy required to satisfy demand is confronted with energy availability from the energy module. Then following the inverse pathway, it is calculated the real demand satisfied given the energy constraints. Finally, income is calculated according to different distributional scenarios.

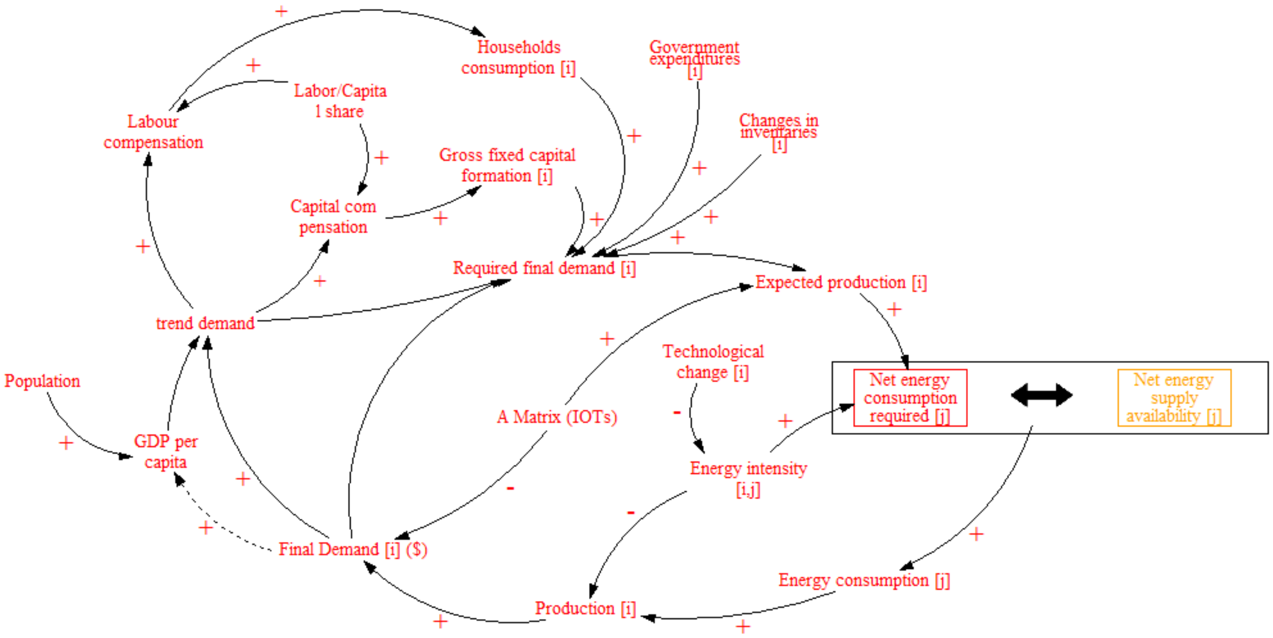

Figure 4: Influences diagram of MEDEAS Economy module. Source: own elaboration.

Therefore, this module comprises four noticeable stages (see Figure 5): i/ demand function; ii/ Input-Output Analysis (IOA); iii/ energy requirements; iv/ resulting rents to demand. Each stage is interrelated with others, providing the last one the inputs needed by the first to keep on the module running. Besides, stage three is the main nexus between the economy module and the whole model. Moreover, in Figure 5 is shown the Economy module's schematic influences diagram that represents its functioning.

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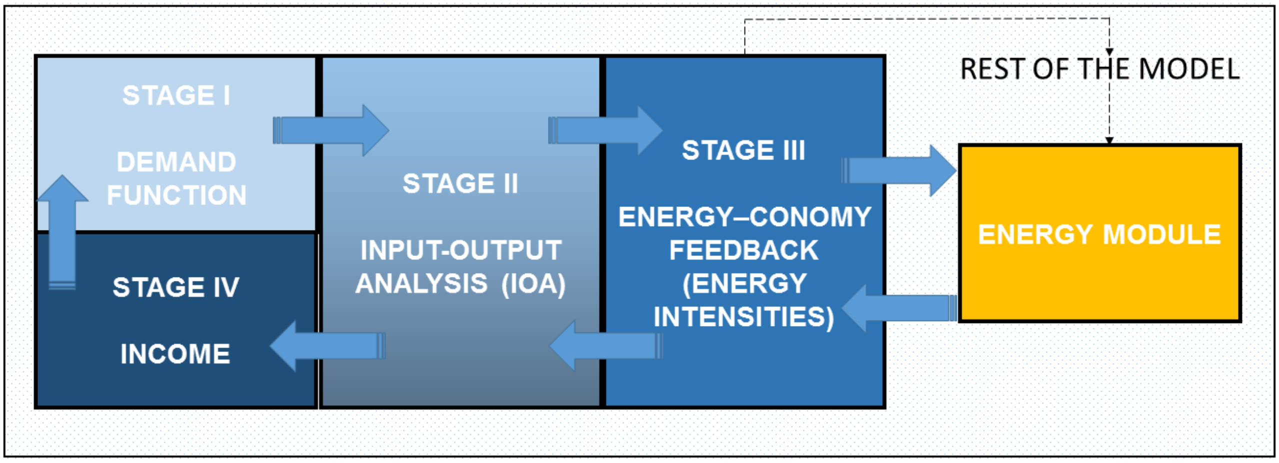

Figure 5: Stages in MEDEAS Ecnomy module. Source: own elaboration.

Therefore, in this section, the economy module is described regarding its different stages. In each one, all processes are carefully explained, taking into consideration not only the system dynamics programming but its economic foundations as well.

2.2.3. Description of the economy module

2.2.3.1. Demand function

Demand function is guided by the basic foundation that it has to be 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 predict the evolution of sectoral final demand. The following equation shows the basic structure of how final demand is obtained:

$$FD_i = HH_i + GFCF_i + GE_i + INVENT_i. \quad \mathrm{i} \in 1\ldots35$$

where HC stands for households' consumption, GFCF for gross fixed capital formation, GE for government expenditures and INVENT for changes in inventories. As final demand is calculated by sector, subscript i stand for the 35 industries. Whilst HC and GFCF can be determined –considering the limitations of data and the methodology itself- throughout an econometric function, different assumptions has 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 proportion that can be eventually increase or decrease through policies. The same approach is followed to obtain changes in inventories. Further developments of the model will allow 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 (82.78% of total final demand from 1995 to 2009). 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 predictions must run until 2050, there 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 its number of observations from 15 to 525 (15 years times 35 sectors). Moreover, it is a reasonable assumption that the final demand evolution of each sector has

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intertwines with the others. Thus, regressions for HH and GFCF are represented in the following equations:

$$lnHH_i = \beta_0 + \beta_1 Sec_i + \beta_2 lnLab. \qquad i \in 1 \ldots 35$$

$$lnGFCF_i = \beta_0 + \beta_1 Sec_i + \beta_2 lnCap_i. \qquad i \in 1 \ldots 35$$

Sec_i is a dichotomous variable whose value is 1 when calculating each sector and 0 with the other sectors and always in sector 1 and 0 for any other sector and always for sector 1. So, there are 34 different β_1 according to sector 2 to 35. Lab stands for labor compensation and Cap for capital compensation by sector. There is no economic justification to assume that wages paid in one sector will be expended 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 labor 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 below.

In Table 2 and Table 3 are shown the parameters of the robust data panel regressions with R^2 0.9989 and 0.9948 respectively. β_0 value is that in the first column (Coef.) and the last row (_cons). $\beta_1$values are given in the first column (Coef.) from sector 2 to 35. For sector 1, β_1 is always equal to 0. β_2 is provided by the value in the first column and first row (log_labworld for Lab and log_capworld for Cap). All β_1 are significant at 5%, but sectors 6 and 19 for GFCF and, in that cases, β_1 equals 0.

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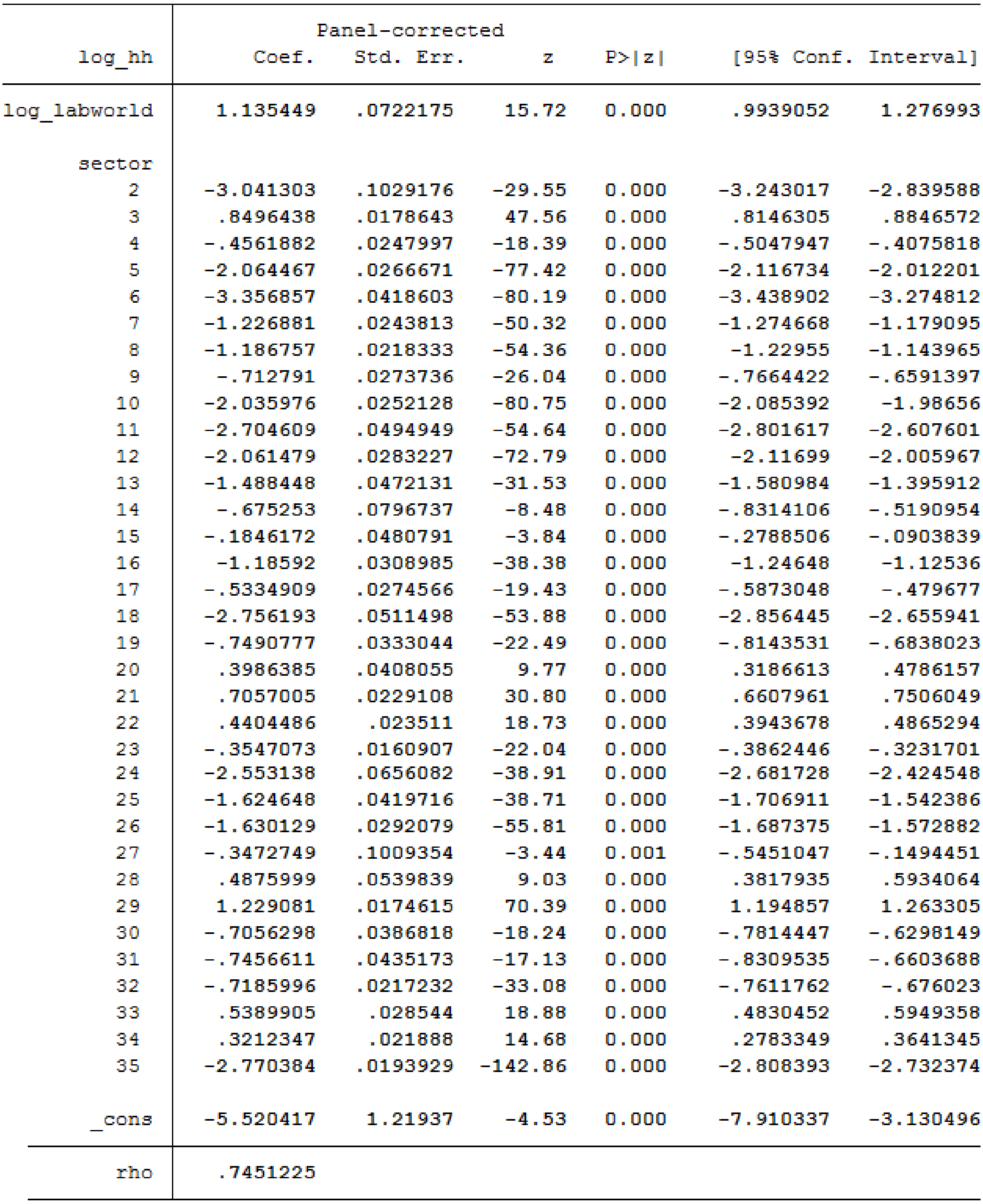
Table 2: Panel data regression for Households consumption. Source: own elaboration.



```
------------------------------------------------------------------------------
             |           Panel-corrected
      log_hh |      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
------------------------------------------------------------------------------
```

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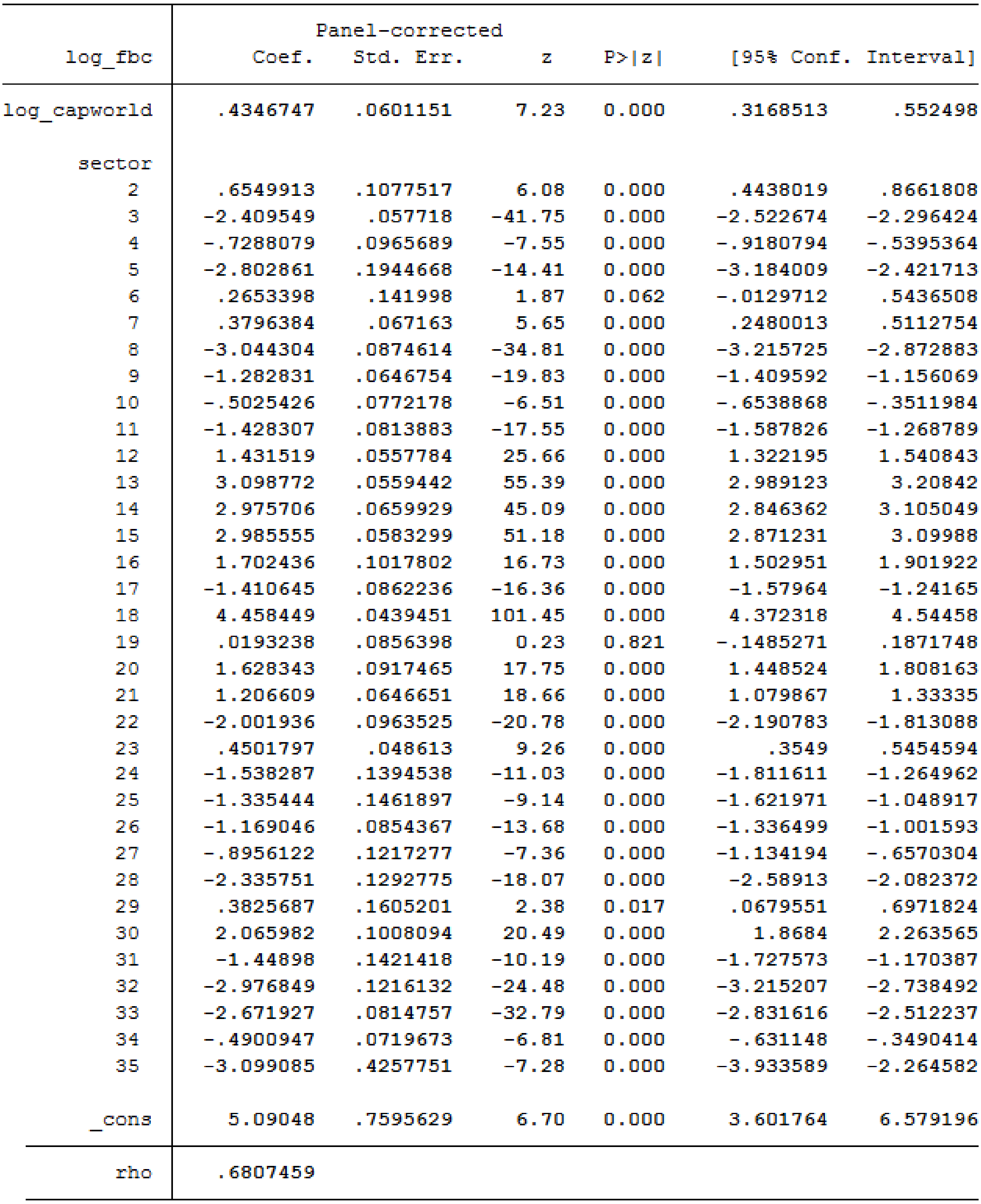
Table 3: Panel data regression of Gross fixed capital formation. Source: own elaboration.



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

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

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

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

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

Like in the energy-economy feedback, primary income scenarios can be activated or, conversely, consider it as static with its 2015 value. 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 2015, OECD data has been used to smoothly reach the 2015 distribution.

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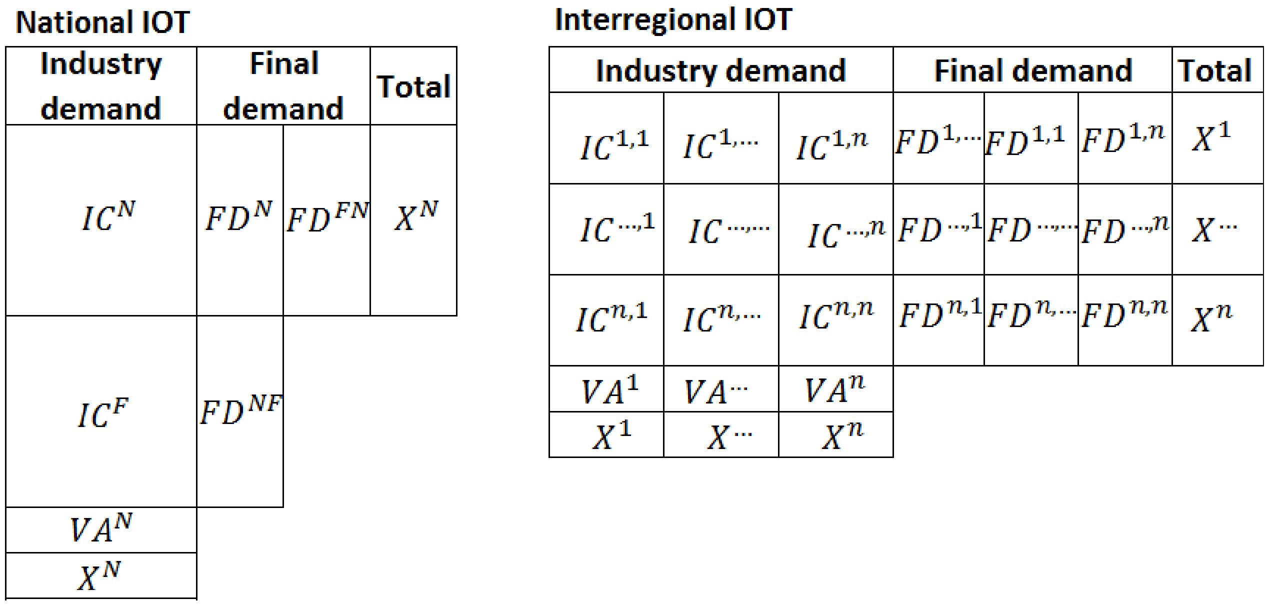
2.2.3.2. Input-Output Analysis (IOA)

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

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



National IOT

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

Interregional IOT

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

Figure 6: Schematic national and interregional Input-Output Tables. IC: Intermediate consumption; FD: Final demand; VA: Value added; X: Production. National IOT superscripts. N: National; FN: foreign in national; NF: National in foreign. Interregional IOT superscripts. Regions: 1…n. Source: own elaboration.

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

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

Industry demand	**Final demand**	**Total**
IC^W	FD^W	X^W
VA^W		
X^W		

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

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

$$a_{ij} = \frac{z_{ij}}{x_j} \qquad \text{i,j} \in 1\ldots35$$

and, in matrix notation:

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

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

$$X = AX + FD$$

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

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

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

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

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

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2.2.3.3. Energy-Economy feedback

Most energy-economy-environment models consider economic growth independent from biophysical limits. In MEDEAS, economy cannot trespass the boundaries settled by nature. Economy module is subject, at least, to an indirect and a direct feedback from the whole system. The indirect feedback is provided by the impacts of climate change that, in MEDEAS, are disseminated throughout energy, as described in section section 2.5.3. 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, using a hybrid Input-Output approach, energy required to satisfy demand is obtained:

$$\hat{e} = \hat{E}\hat{x}^{-1} = \begin{pmatrix} \frac{E_{ij}}{x_i} & 0 \\ 0 & \frac{E_{nn}}{x_n} \end{pmatrix} = \begin{pmatrix} e_{ij} & 0 \\ 0 & e_{nn} \end{pmatrix}, \qquad i \in 1\ldots35;\ j \in 1\ldots5$$

$$E = \hat{e}x = \hat{e} * L * D$$

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 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).

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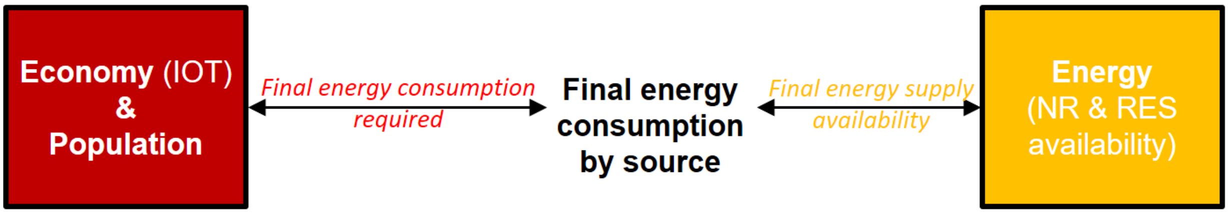

Figure 8. Energy-Economy feedback in MEDEAS. Source: own elaboration.

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 is calculated considering that the scarcer source is the one that most conditions the sectorial production process. This shortage coefficient equals 1 when final energy consumption (FEC) satisfies demand, i.e. there is no supply restriction. In this case –energy demand is higher than energy supply- energy consumption just reaches the energy supply and the shortage coefficient is lower than 1, reducing the proportion of energy demanded which is actually consumed by each sector.

$$FEC_{i,j} = shortage\ coefficient * FED_{i,j} \qquad i \in 1 \ldots 36;\ j \in 1 \ldots 5$$

$$FED_i = \sum FED_{i,j} \qquad i \in 1 \ldots 36;\ j \in 1 \ldots 5$$

$$shortage\ coefficient_i = \begin{cases} 1 & FEC_i = FED_i \\ <1 & FEC_i = FES_i \end{cases}$$

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 efficiency (${e^{-1}}_{ij}$) and the final energy actually consumed (${E'}_{ij}$), feasible production is obtained (${X'}_i$). Then, a set of feasible productions according to each final energy source is collected. The model is programmed to choose the minimum feasible production, as the scarcest final energy source is what limits the most, being consistent with the complementarity approach above mentioned.

$${e^{-1}}_{ij} * {E'}_{ij} = {X'}_i$$

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

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:

$$X' = AX + FD'$$

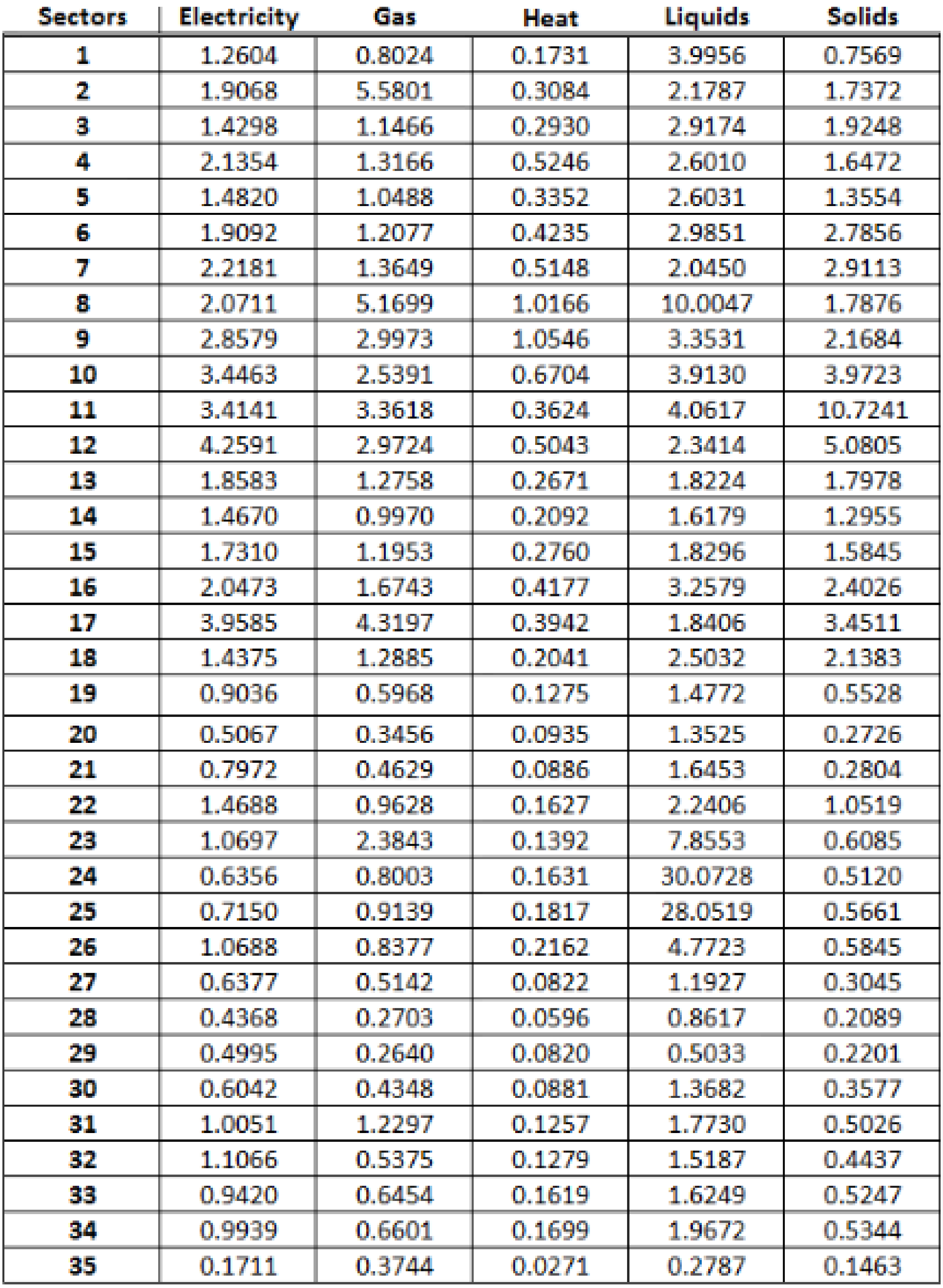
$$FD' = X(I - A)$$

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, the economy module is feed-backed by the energy availability (as well as by climate change impacts and EROI, see sections 2.4.6 and 2.5.3), 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., 2016; Höök and Tang, 2013; Wang et al., 2017). The underlying assumption here is that this availability of resources matters, and that the functioning of the real economy 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 4 and are calculated as êL: 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 is the liquids consumption of sector 1 (Agriculture, Forestry, Hunting and Fisheries) to changes in demand. Or how much liquids must be demanded by transport sectors (24 and 25, inland and water transport) in order to satisfy an additional USD$ of demand.

Table 4: Sectoral final energy sensitiveness by sources. Source: own elaboration.



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

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Finally, it is worth a brief comment on the evolution of energy intensities, described in detail in sections 2.2.4 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.

2.2.3.4. Income

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, these identities can be established:

$$\mathrm{GDP=FD=\sum GVA}$$

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, a different $\alpha_{lab/cap}$ according to the storylines of each scenario can be selected. As the summation of both labour and capital share equals 1, scenarios just change labour share and then, capital share is considered as 1-α_{lab}. In the model, labour compensation is calculated as a flow, similarly to final demand.

$$\Delta Lab = \ \alpha_{lab,t+1}GDP_{t+1} - \ \alpha_{lab,t}GDP_t$$

$$\Delta Lab = \alpha_{lab,t}GDP_t\ (\Delta\mathrm{GDP} + \Delta\alpha_{lab} + \Delta\alpha_{lab}\Delta\mathrm{GDP})$$

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. Then, by multiplying it by the evolution of GDP, we obtain the labour and capital compensations which enter back as inputs in the demand function, described above.

2.2.4. Dynamic modeling of final energy intensities in MEDEAS

Energy intensity is a key issue in the MEDEAS model. In general terms, 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. 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 energy types quoted 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 briefly 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 need of each type of energy for each economic agent to obtain its 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 temporal evolution of energy intensities 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 its EROEI. Both examples can lead to an increase in

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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.

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

Once the historical data of the energy intensity matrix has been available, its modeling has been developed, trying to explain its historical behavior and justifying its foreseeable future evolution.

Available historical data show stable trends over time and some point variations. In order to model the dynamic behavior of the energy intensities we look for the tendencies that can be justified by structural reasons and are not considered specific variations that are considered due to temporary reasons.

The historical trends of data in energy intensities are considered to be due to processes such as technological improvement, which may continue in the future, although a limit is necessary. For example, a zero energy intensity cannot be reached.

Figure 9 shows an example of energy intensities in some sectors for the electricity.

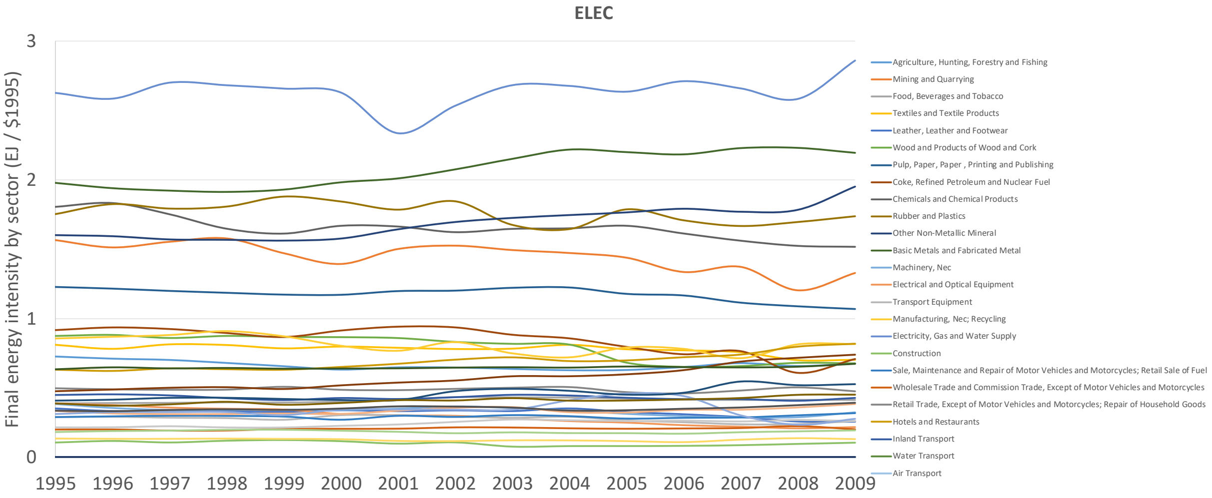

Figure 9: Historical evolution of electricity intensity by sector.

On this inertial trend, it is considered that different changes can be produced due to the market conditions of the final energy types or due to the energy policies.

The changes that can occur in the future are:

a) Accelerating the change in energy efficiency due to policies or market 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 10 shows a simplified structure of the energy intensities model.

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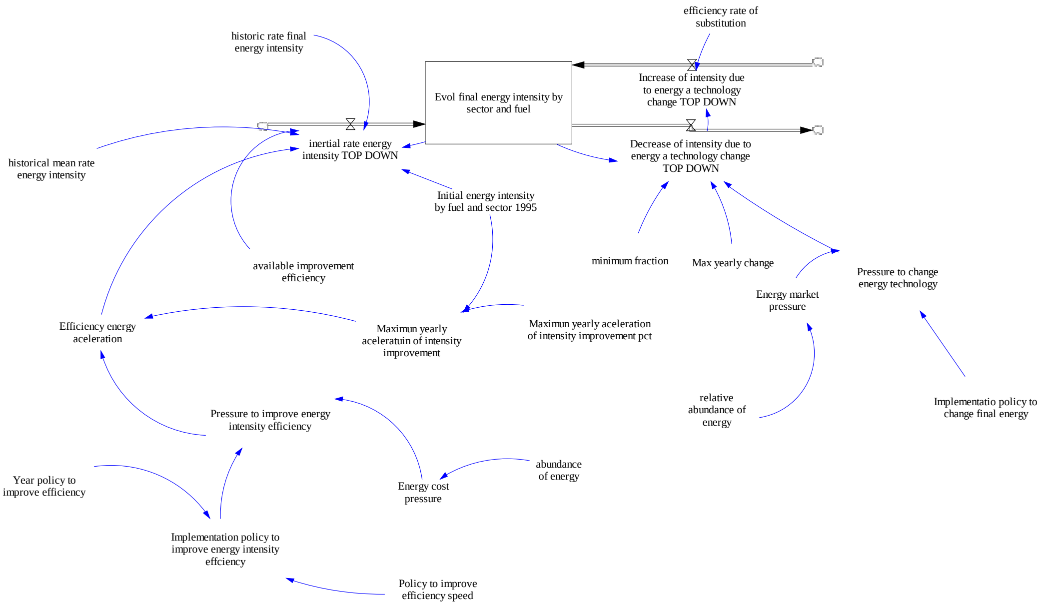

Figure 10: Simplified structure of the energy intensities model.

In this first version some limits have been modeled for the absolute maximum changes and for the maximum annual changes. These parameters have not been determined and may be estimated in the future for each economic sector and final energy type. Likewise, the steps of policy implementation in OT and MLT scenarios have been considered. All the parameters of this part of the model can be chosen according to the forecasts 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 2.3.1), the energy supply (section 2.3.2), the energy resources availability in MEDEAS (non-renewable resources in section 2.3.3 and renewable-resources in section 2.3.4), the modelling of electricity generation (section 2.3.5) and heat generation (section 2.3.6), the modelling of transportation (section 2.3.7) and the modelling of non-energy use (section 2.3.8). Primary energy in the model refers to the direct equivalent method.[1]

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[1] 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., 2013; Timmer et al., 2012) (which ultimately was built from the IEA database (IEA, 2016a)). Table 5 shows the equivalence between sources of different databases and MEDEAS.

Table 5: Equivalence between MEDEAS final energy categories and the WIOD and IEA categories. Losses and non-energy use of materials are not considered.

MEDEAS	WIOD	IEA
SOLIDS	HCOAL	Anthracite
		Other bituminous coal
		Coking coal
		Patent fuel
		Sub-bitumious coal
	BCOAL	BKB
		Coal tar
		Lignite
		Peat
		Peat products
	COKE	Gas coke
		Coke oven coke
	WASTE	Industrial waste
		Municipal waste (renewable)
		Municipal waste (non-renewable)
	OTHRENEW	Charcoal
		Non-specified primary biomass and waste

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MEDEAS	WIOD	IEA
		Primary solid biomass
LIQUIDS	CRUDE	Crude oil
		Natural gas liquids
		Refinery feedstocks
		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

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MEDEAS	WIOD	IEA
		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 (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, 2016a) 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 11 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 2.3.1.3 in relation to the corrections performed to account for the non-commercial heat in MEDEAS.

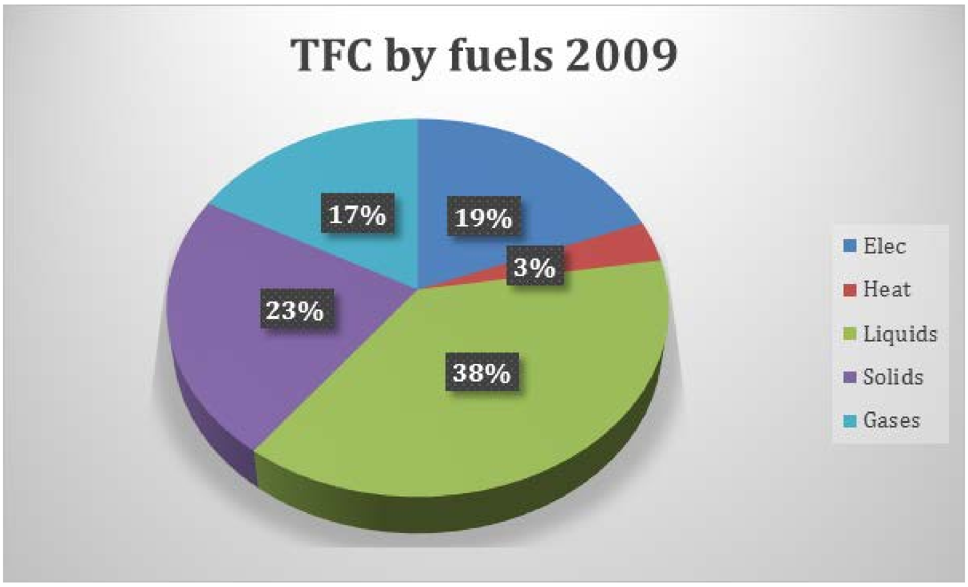

Figure 11: TCF by fuels 2009. Source: WIOD database.

Figure 12 shows the historical evolution 1995-2014 for each MEDEAS final energy category:

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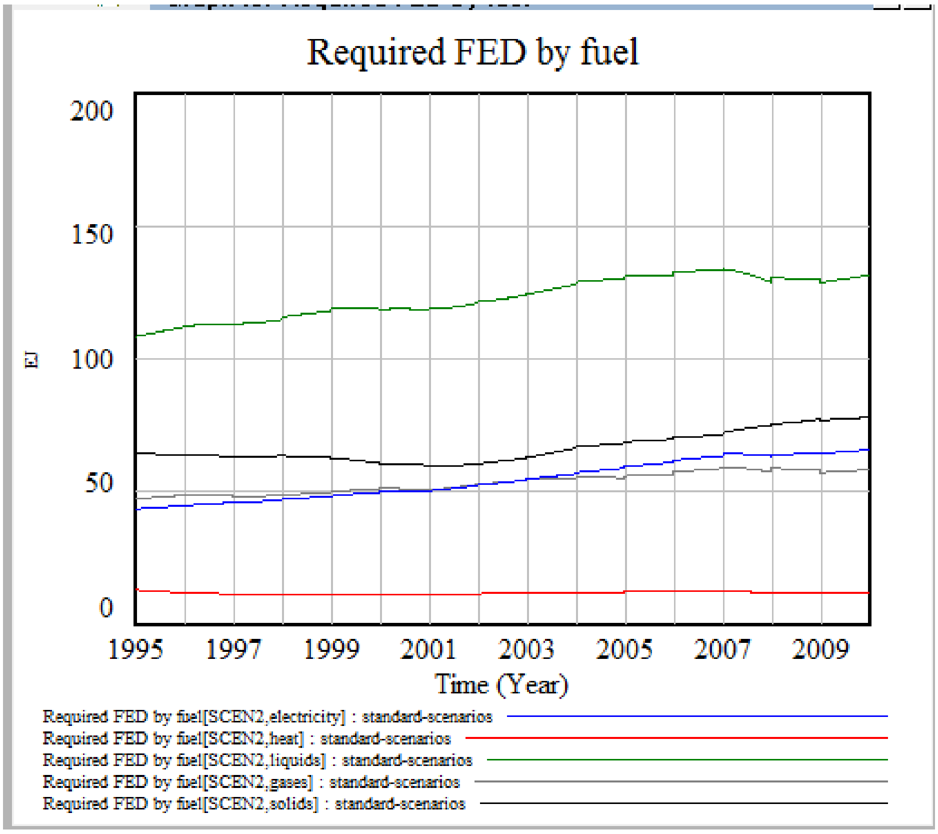

Figure 12: Historic FED by fuel after adjusting WIOD data from IEA balances. Heat refers solely to commercial heat.

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 13).

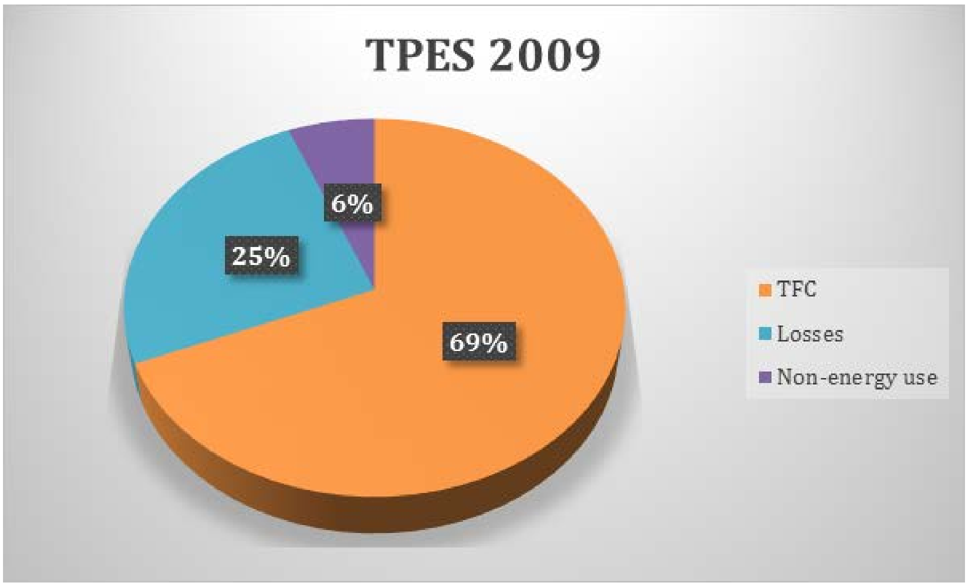

Figure 13: TPES 2009. Source: (IEA, 2016a).

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The modelling of losses in MEDEAS is described in detail in next section 2.3.1.2.

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 14, 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:

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

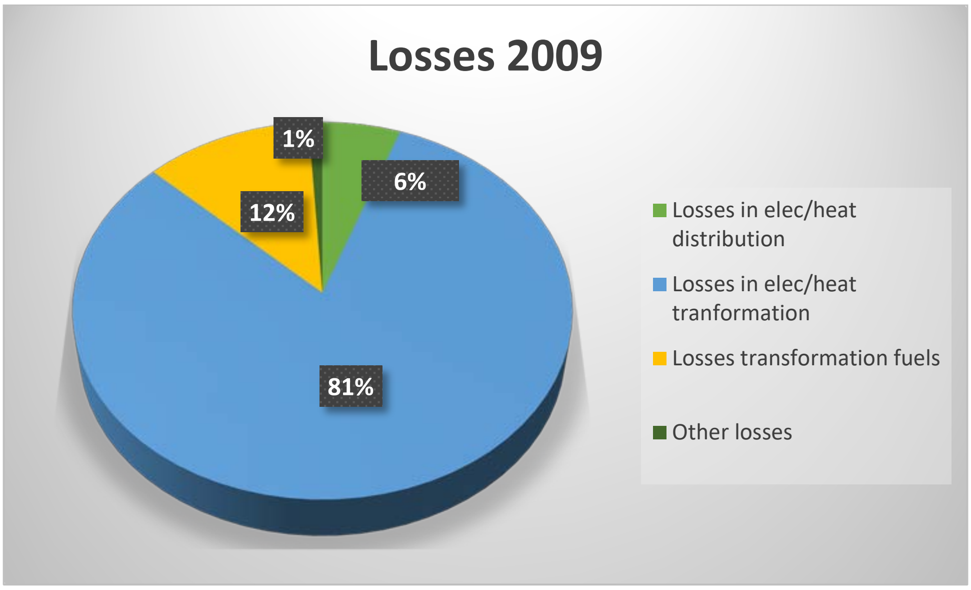

Figure 14: Losses in 2009. Source: (IEA, 2016a).

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 2.3.6 for the modelling of transformation losses.

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

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Table 6. Parameters for the modelling of energy distribution losses

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

.

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

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

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

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

Table 7. Parameters for the modelling of energy transformation losses.

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

Oil and coal transformation losses depend on the extraction.

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

Table 8. Parameters for the modelling of gain gas in transformation processes losses.

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

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

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

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

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

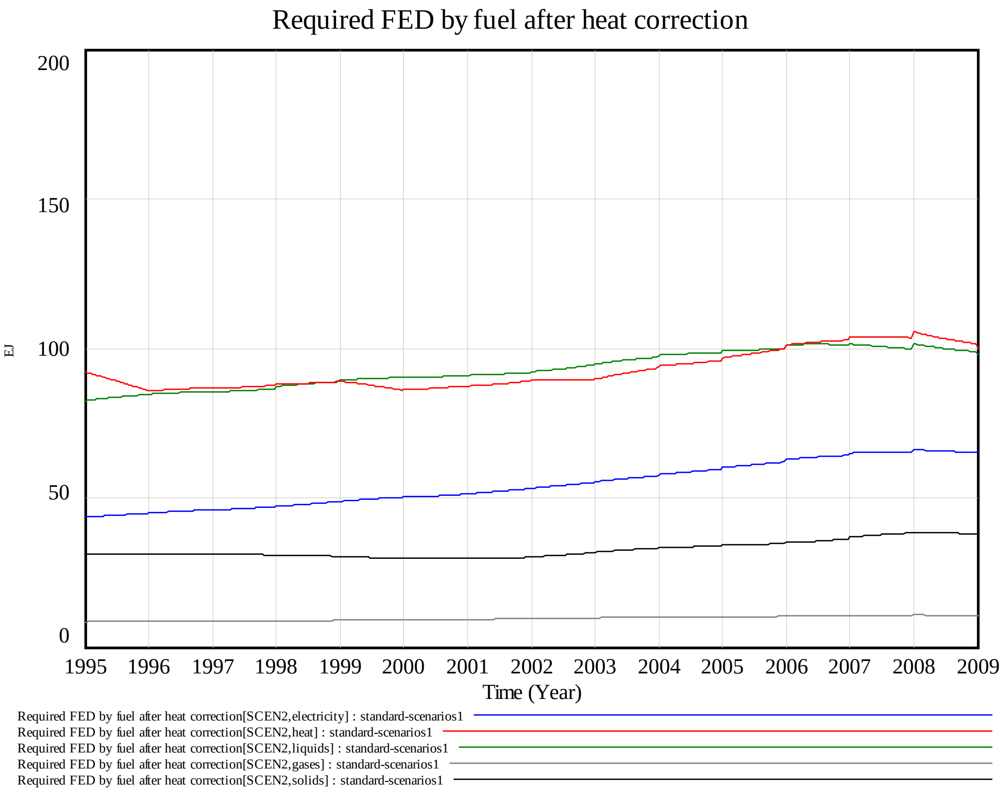

Figure 15: FED by fuel after heat correction

2.3.2. Energy supply in MEDEAS

In MEDEAS primary total energy demand is covered with different primary energy sources (see Table 9)

Table 9 : 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
		Charcoal
		Waste
	RES	Primary solid biofuels (modern)
		Primary solid biofuels (traditional biomass)
Liquids	NRE	Conventional oil
		Unconventional oil

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		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),[2] for the sake of simplicity in this model version all heat demand and supply is aggregated.

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

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2.3.3. Non-renewable energy resources availability

MEDEAS considers the following non-renewable primary energy resources:

- Conventional oil: refers to crude oil and NGLs.
- Unconventional oil: includes heavy and extra-heavy oil, natural bitumen (oil sand and tar sands) and oil shales. Biofuels, CTL, GTL and refinery gains are modeled separately (see sections 2.3.3.5 and 2.3.4.1).
- 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 2.8). 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 16 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.

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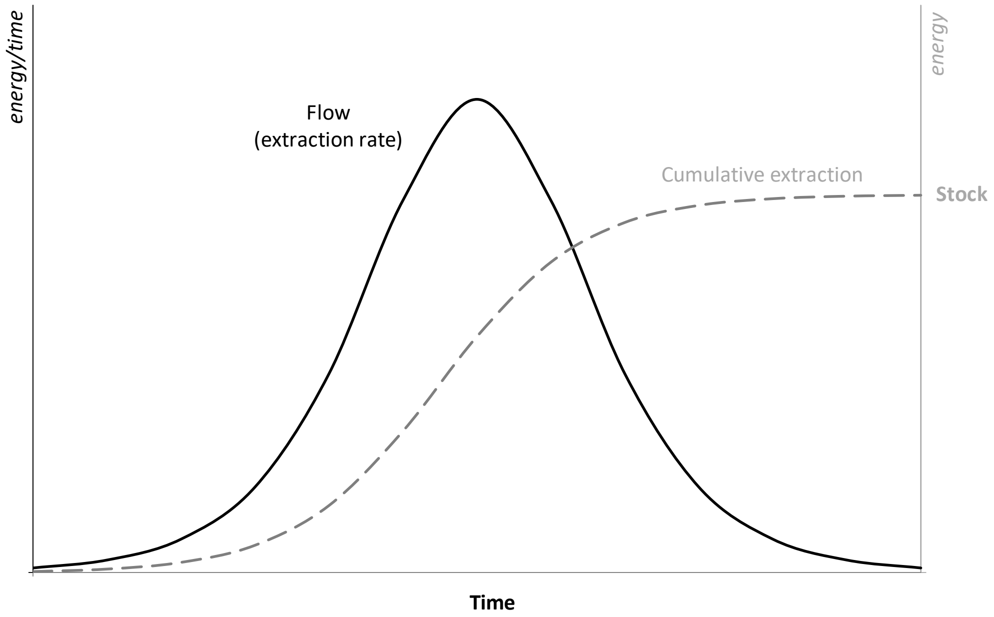

Figure 16 : (Kerschner and Capellán-Pérez, 2017): Simplified representation of the depletion of a non-renewable resource in the absence of non-geologic constraints. Stocks and flows of energy relative to time.

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 (Aleklett et al., 2010; ASPO, 2009; EWG, 2013, 2008, 2007, 2006; Höök et al., 2010; Laherrère, 2010, 2006, Maggio and Cacciola, 2012, 2012; Mohr, 2012; Mohr et al., 2015; Mohr and Evans, 2011, 2009, 2009; Patzek and Croft, 2010; Zittel, 2012). These curves (see Figures 7-14) 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

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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 17a). 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 17b).

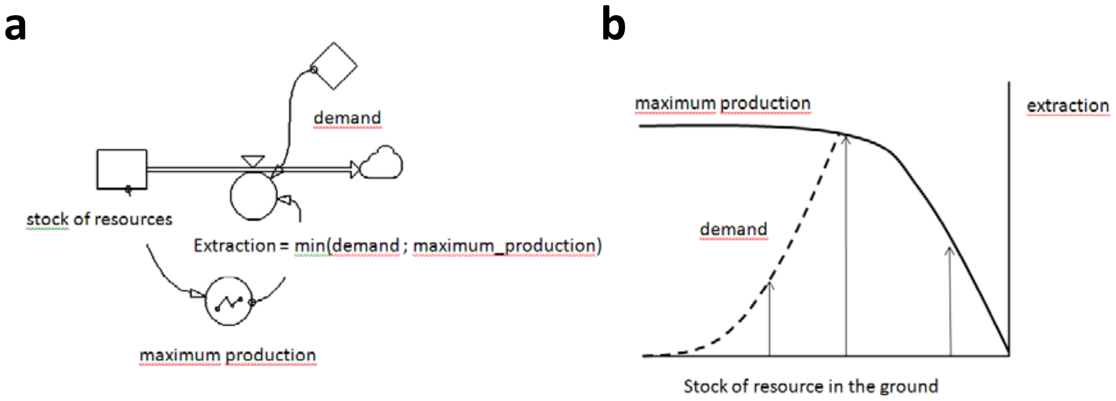

Figure 17 : (Mediavilla et al., 2013): Integration of depletion curves in the model. (a) SD model. (b) A curve of maximum extraction (solid) compared with the demand (dashed).

As illustration, Figure 18a shows the depletion curves as a function of time and Figure 18b the associated curves of maximum extraction as a function of the RURR as applied in (Capellán-Pérez et al., 2014).

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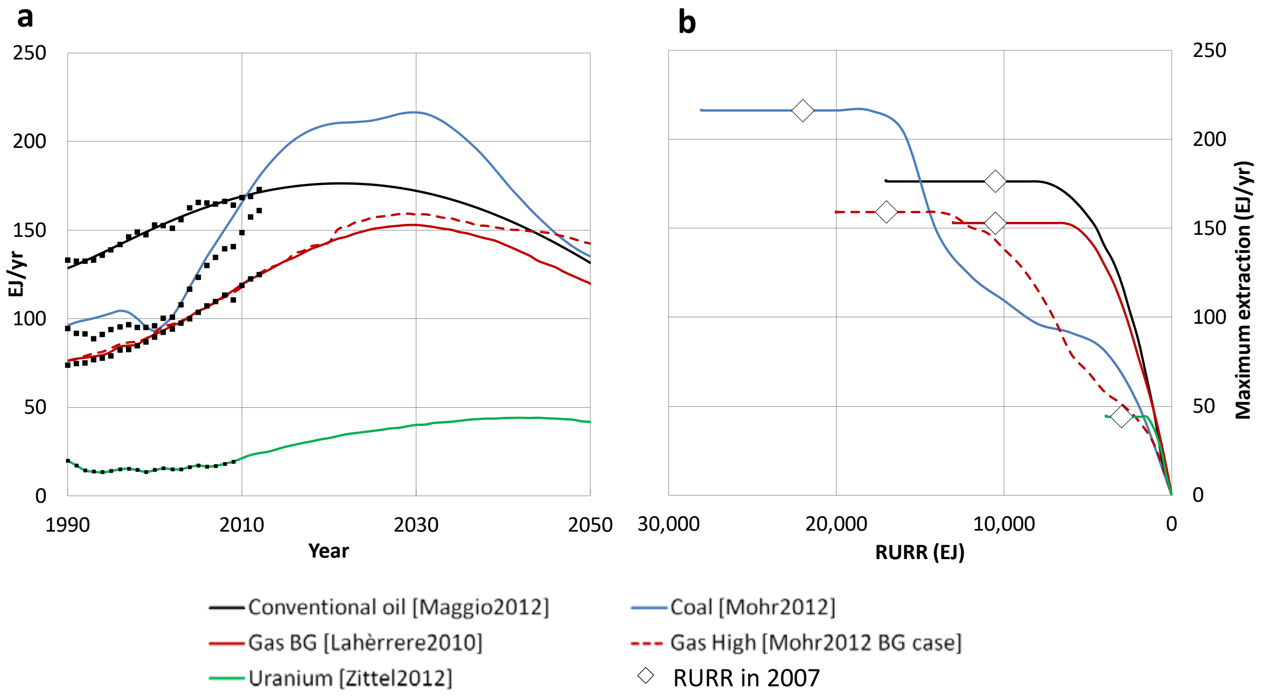

Figure 18 : (Capellán-Pérez et al., 2014): Non-renewable primary energy resources availability: (a) depletion curves as a function of time from the original reference; (b) curves of maximum extraction in function of the RURR as implemented in the model. The y-axis represents the maximum achievable extraction 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 2.3.3.2.1), natural gas (section 2.3.3.2.2), coal (section 2.3.3.2.3) and uranium (section 2.3.3.2.4). 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 2.3.3.4).

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2.3.3.2. Literature review of depletion curves by fuel

The following subsections review the depletion curves of non-renewable energy resources found in the literature by fuel together with a brief discussion: oil (section 2.3.3.2.1), natural gas (section 2.3.3.2.2), coal (section 2.3.3.2.3) and uranium (section 2.3.3.2.4). 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 19 shows the depletion curves for oil found in the literature compared with the projection of the Current Policies Scenarios of the IEA (WEO, 2012). Due to the lack of standardization, we have collected projections from solely conventional oil to total oil (ie., including unconventional oil). Among the depletion curves, the main foreseen trend is that global oil extraction will reach a peak followed by an irreversible decline in the next years (e.g. (ASPO, 2009; EWG, 2013, 2008; Laherrère, 2006; Maggio and Cacciola, 2012)), whereas few estimates find profiles that follow an undulating plateau (Aleklett et al., 2010; Skrebowski, 2010). Analyses do not expect to substantially exceed the maximum of 90 Mb/year. In turn, only the IEA estimates that future oil extraction will be growing by the year 2035. The estimate of Laherrère (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.[3] Aleklett et al., (2010) critically assessed the global oil production forecast of the IEA's WEO (2008), producing an alternative estimate by introducing correction factors to account for geological factors not included in the report. Maggio & Cacciola (2012) provide three estimates associated to three different URR levels; its lower projection is similar to that of ASPO (2009). EWG projections are the most pessimistic among the set analysed, projecting a step decline from the date of the assessment.

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[3] 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.

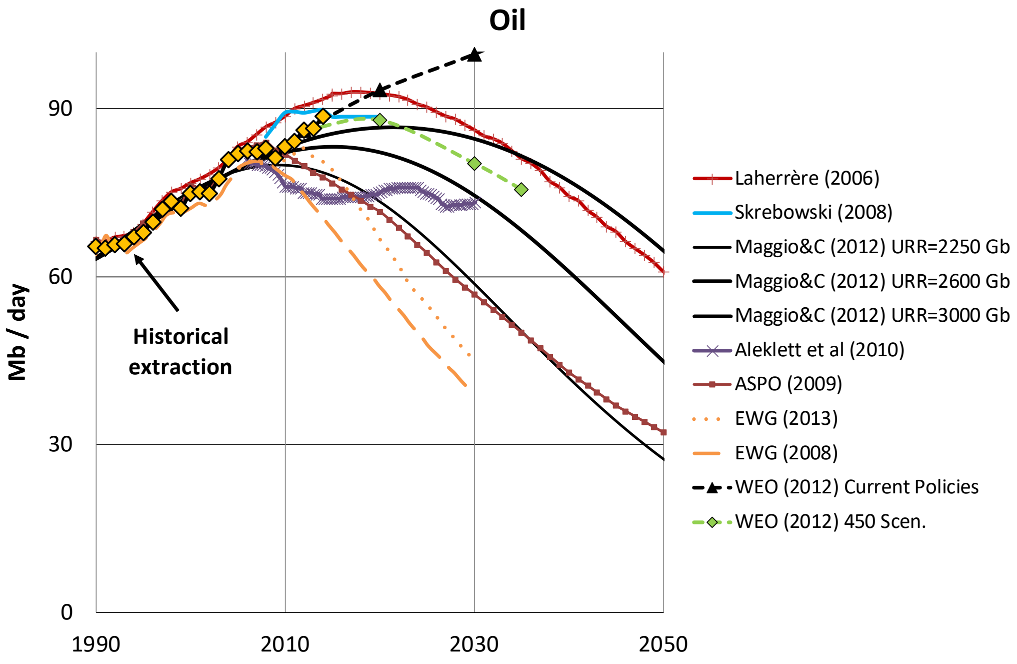

Figure 19: Depletion curves for oil by different authors and comparison with (WEO, 2012) scenarios "Current Policies" and "450 Scenario". Historical data (1990-2014) from BP (2015). There is a lack of standardization in the literature. For each study, "oil" refers to only crude oil (including NGLs) (Maggio 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 20). Although the numbers vary at the end of the century, the difference in extraction levels in 2050 between the highest and the lowest case is just around 20% (54 vs 66 EJ/yr). However, given the current obstacles to the global-scale deployment of unconventional oil even Mohr et al (2015)'s lower scenario may prove too optimistic (Murray, 2016).

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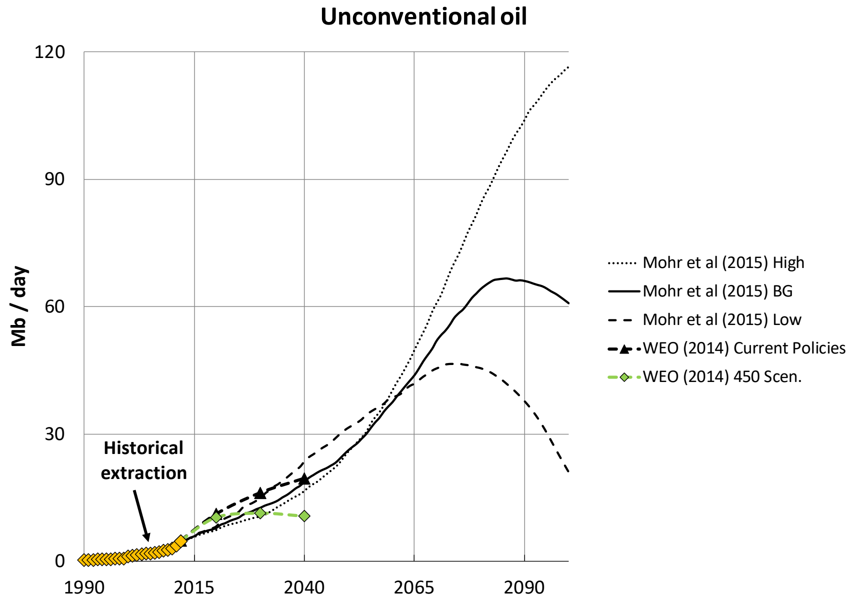

Figure 20: Depletion curves for unconventional oil from Mohr et al. (2015), WEO (2014) projections and historical extraction (1990-2012) from Mohr et al (2015).

2.3.3.2.2. Natural gas

Figure 21 shows the results of collecting estimates for total natural gas (ASPO, 2009; Laherrère, 2010; Maggio and Cacciola, 2012; Mohr, 2012; Mohr et al., 2015; Mohr and Evans, 2011) compared with the projection of the Current Policies Scenarios of the IEA (WEO, 2012). We observe that ASPO (2009)'s projection for the last years is below recent historical data of extraction, and coincides with the lower case from Maggio & Cacciola (2012). Maggio & Cacciola (2012) found that, for different RURR levels, the maximum extraction rate would not trespass 140 TCF/year, reaching its peak before the mid-century. Mohr (2012)’s projections for natural gas (which are very similar to Mohr and Evans (2011)’s), offer a wide range between their “low case” and “best guess”, although both depict a peak at around 2025-2030 between 130 and 150 TCF/year. Lahèrrere’s (2006) estimate broadly falls between Mohr (2012) two lower cases, although with a greater steepness after reaching the peak. The “high case” from Mohr (2012) assumes that very large amounts of unconventional gas (coal bed methane, shale gas and tight gas) will be available in the future (RURR of 11 ZJ) in comparison with the other estimates (e.g. RURR of 2.1 ZJ considered by Lahèrrere (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

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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.

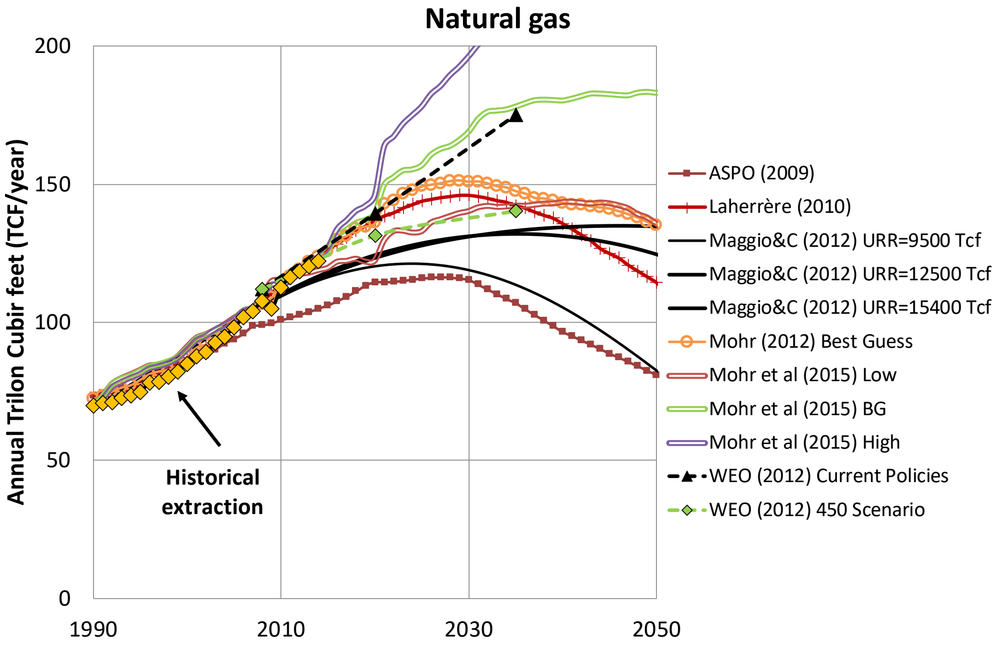

Figure 21: Estimations of total natural gas extraction by different authors and comparison with (WEO, 2012) scenarios “Current Policies” and “450 Scenario”. Historical data (1990-2014) from BP (2015).

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As for unconventional oil, few studies have focused on unconventional gas. Figure 22 shows the low, best guess and high depletion curves from Mohr et al (2015).

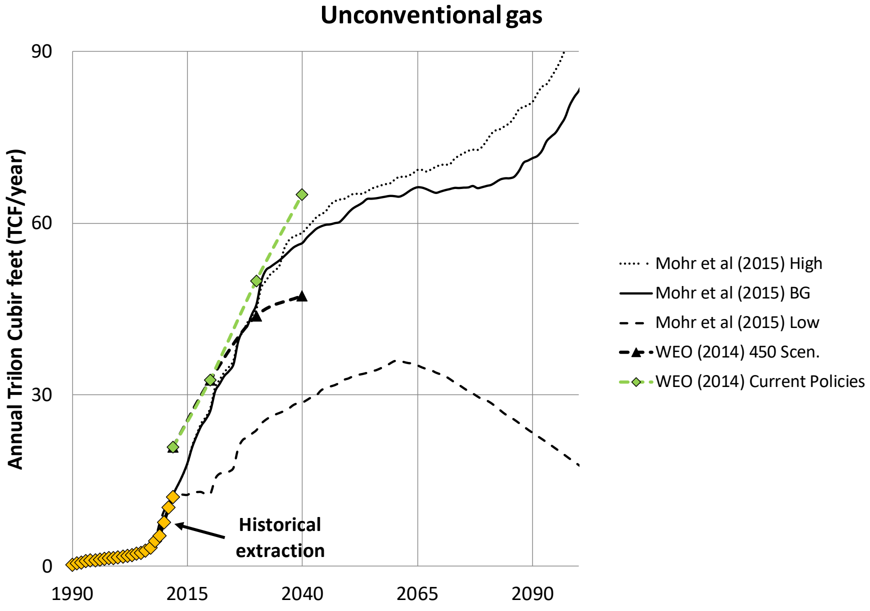

Figure 22: Estimations of unconventional natural gas extraction from Mohr et al (2015), WEO (2014) projections and historical extraction (1990-2012) from Mohr et al (2015).

Natural gas energy content per volume

Gas reserves are usually reported in volume units (e.g. tcf[4]). However, and similarly to oil, different agencies apply different energy equivalence attending to different composition of the gas, etc.

	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

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

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Table 10: Equivalence between volume and energy applied by different agencies and authors. *Equivalence used by de Castro (2009).

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

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., 2016; Ritchie and Dowlatabadi, 2017).

Figure 23 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)).

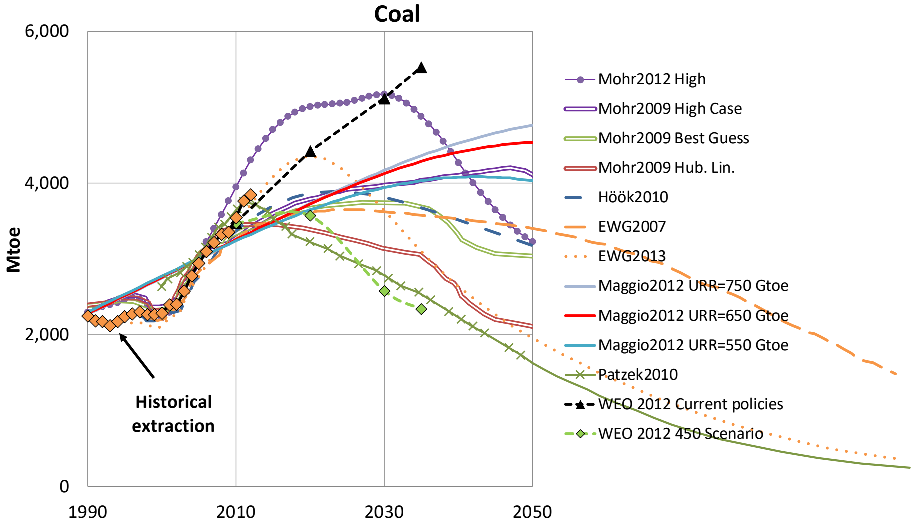

Figure 23: Estimations of coal extraction by different authors and comparison with (WEO, 2012) scenarios “Current Policies” and “450 Scenario”. Historical data (1990-2014) from BP (2015). (1 Mt = 0.4844 Mtoe (Höök et al., 2010)).

Figure 24 represents the forrester 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”.

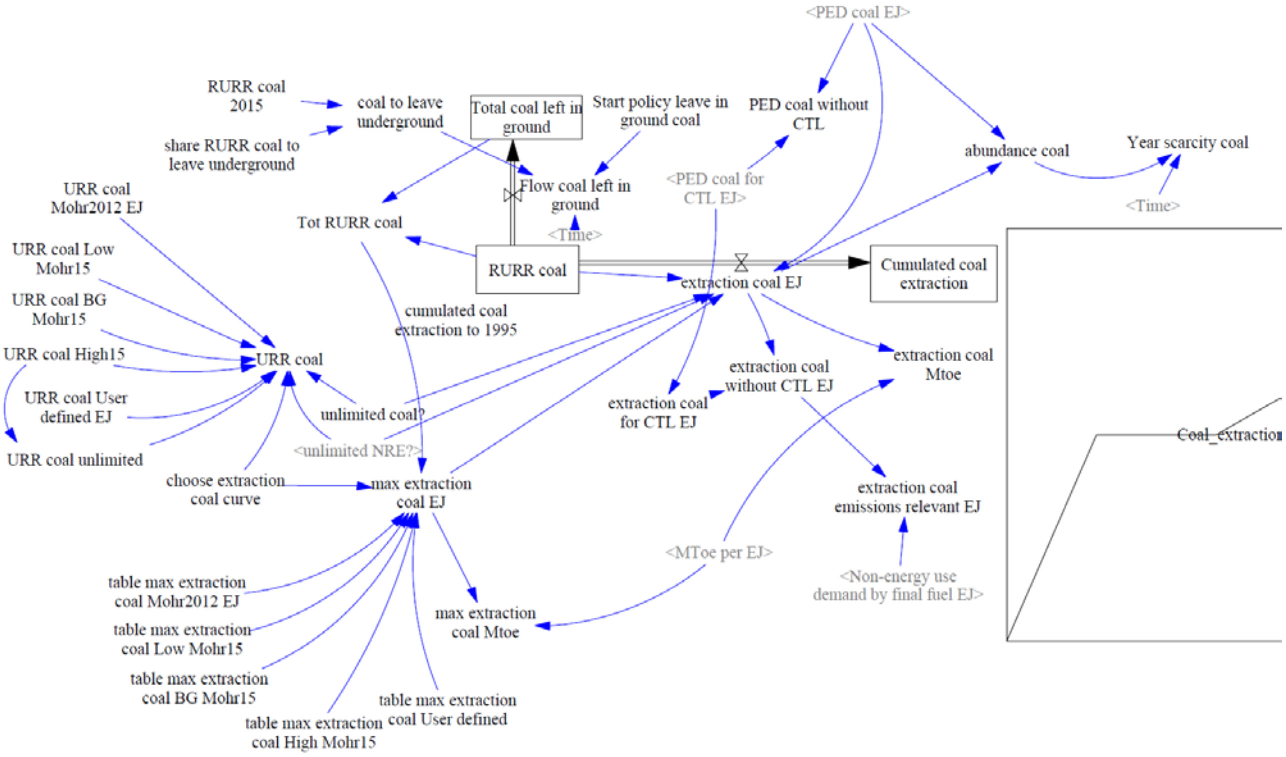

Figure 24: Forrester diagram of coal extraction.

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2.3.3.2.4. Uranium – nuclear fuels

Figure 25 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).

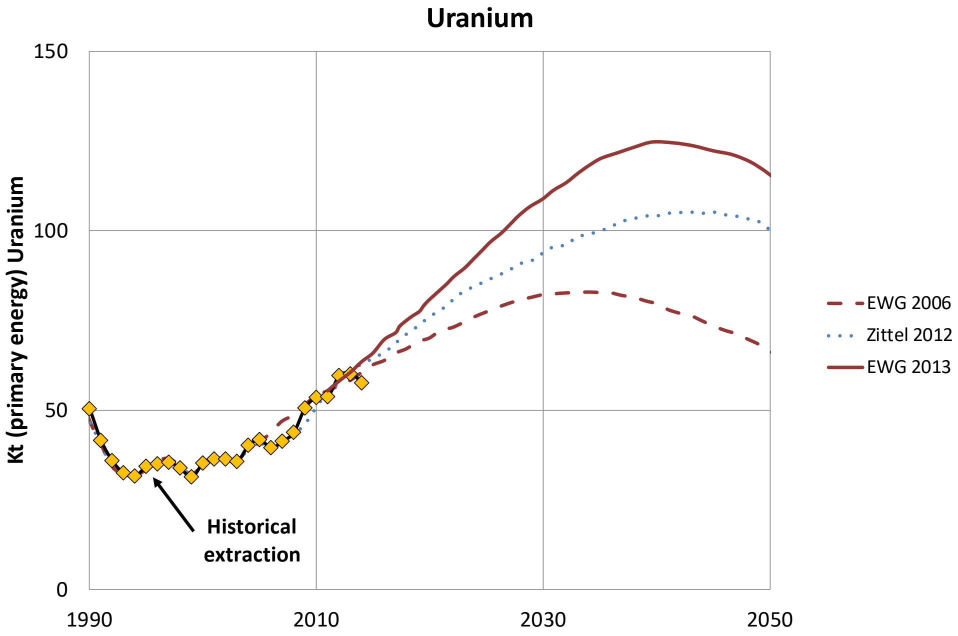

Figure 25: Estimations of uranium extraction by different authors. Historical data (1990-2014) from WMD (2016); conversion from kt U3O8 to ktU following EWG (2006).

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

2.3.3.3. Depletion curves available in MEDEAS

Table 11 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 11: 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

Resource	Reference	Description	URR	
			(Mass)	(ZJ)
	(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 26 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.

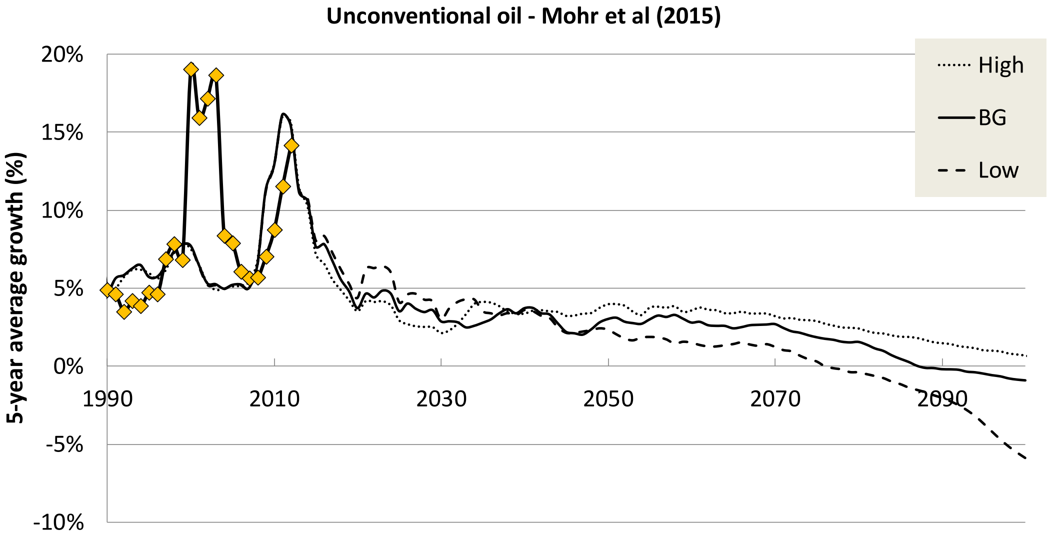

Figure 26: 5-year average growth (%) of unconventional oil for the high, BG and low scenarios from Mohr et al (2015). Historical extraction (1990-2012).

Unconventional gas

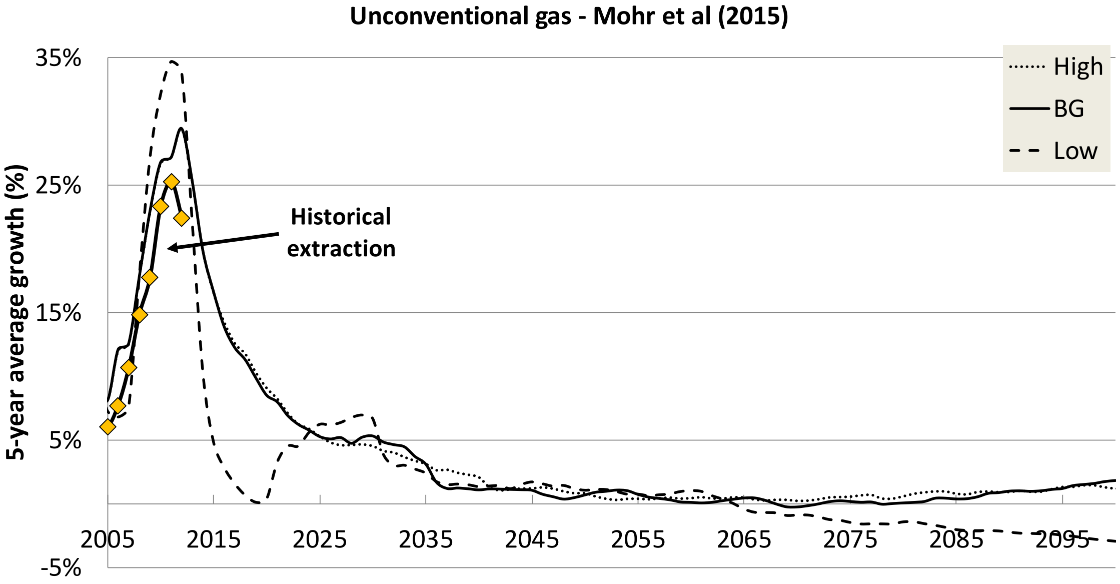

Figure 27: 5-year average growth (%) of unconventional gas for the high, BG and low scenarios from Mohr et al (2015). Historical extraction (1990-2012).

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2.3.3.5. CTL and GTL

CTL (*Coal-to-Liquids*) and GTL (*Gas-to-liquids*) refer to the transformation of coal and gas into liquid hydrocarbons. Different technologies currently exist,[5] 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, 2016a). Usually growth projections from international agencies are relatively modest (e.g. +11%/yr for GTL in the *New Policies Scenario* of (WEO, 2012)), due to their high cost and the common assumption that no significant liquids/oil restrictions will exist in the scope of their projections. MEDEAS reacts to an eventual liquid scarcity by boosting these sources of energy.

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

There are many ways to liquefy natural gas, and several pilot plants, trial projects and research initiatives exist. However, only two companies – Sasol and Shell – have built large scale commercial plants (>5,000 b/d capacity). The GTL industry is currently essentially immature and many important patents are held by relatively few companies (Wood et al., 2012). Unlike CTL plants, the construction and operation of large scale GTL plants is now a reality, with increasing momentum. After the experiences of Sasol's Mossgas GTL plant in South Africa and Shell's Bintulu plant in Malaysia the first decade of the 21st century has witnessed the construction and start of the Oryx 34,000 b/d GTL plant and the Pearl 140,000 b/d plant, both in Qatar. Moreover, a 34,000 b/d GTL plant was built in the Escravos region in Nigeria and started its operation in summer 2014. From 2000, the average global growth trend has been slightly over +16% per year (IEA, 2016a).

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

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CTL and GTL are modelled as exogenous growth technologies, the annual growth in installed capacity can be selected from the user. Given the high GHG emissions of these processes, in MEDEAS there are not considered as a suitable substitutes for oil liquids.[6]

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, 2016a). 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, 2016a).

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

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2.3.4. Renewable energy sources (RES) availability

Renewable energy is usually considered as a huge abundant source of energy; therefore, the technological limits are assumed to be unreachable for decades, and the concern is on the economic, political or ecological constraints (de Castro et al., 2011; IPCC, 2011; Kerschner and O'Neill, 2016). However, the large scale deployment of renewable alternatives faces serious challenges in relation to their integration in the electricity mix due to their intermittency, seasonality and uneven spatial distribution requiring storage (Lenzen, 2010; Smil, 2008, p. 362; Trainer, 2007), their lower energy density (de Castro et al., 2011, 2013b, 2014; 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., 2011, 2013b, 2014; 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 2.3.4.1 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 2.3.4.3 focuses on the assumptions related to the RES for electricity generation. Finally, section 2.3.4.4 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.[7] Peatlands[8] are the most efficient terrestrial ecosystems in storing carbon. Degradation of peatlands is a major and growing source of anthropogenic greenhouse gas emissions. Peatlands are important natural ecosystems with high value for biodiversity conservation, climate regulation and human welfare (Parish et al., 2008). For these reasons, MEDEAS does not considered this energy source will contribute to a sustainable energy mix in the future.

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

2.3.4.1.1. Uses of bioenergy

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

2- Conventional solid biomass refers to modern uses of solid biomass for heat and electricity, excluding plantations in marginal lands and residues, i.e. mainly from tree plantations. Since current conventional modern bioenergy use for heat and electricity (18+4 EJ/yr harvestable NPP respectively (IEA, 2016a; 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

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[7] 4th generation (algae) is not considered due to the high uncertainties of the technology and the long-term of its eventual commercial appearance (Janda et al., 2012). Moreover, preliminar tests show that capturing CO2 by microalgae to produce biodiesel has 2.5 times higher GWP than fossil diesel with other environmental impacts also significantly higher (Cuéllar-Franca and Azapagic, 2015).

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

also allow to use bioenergy resources in a more sustainable way, although this would be limited by the fact that most of the traditional biomass is infact extracted in an unsustainable way.

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

4- Residues (agricultural, forestry, municipal, industry, etc.). Currently, only biogas and MSW[9] exist at commercial level. Biogas potential is assumed to focus on the promotion of small plants for agricultural and industrial residues, as well as animal dung which provide major ecological co-benefits (WBGU, 2009). Current final use share and efficiencies are assumed constant given its past evolution. The 3rd generation biofuels (cellulosic) are still in R&D and doesn't appear in the standard 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 2.3.4.1.2 focuses on the followed assumptions to model dedicated crops for biofuels in MEDEAS given the complexities and detailed modelled in MEDEAS.

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[9] 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 2.8).

2.3.4.1.2. Dedicated crops

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

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

However, the new land that we could convert to agriculture is 200-500MHa (FAO, 2009; Schade and Pimentel, 2010), or 386MHa in a sustainable way, converting abandoned agricultural land (Campbell et al., 2008; Rockström et al., 2009). This means that it may be not possible to meet the current trends of demand for food if the degraded land continues to grow, as more than 350MHa will be lost if present trends continue (Foley et al., 2005; Pimentel, 2006). Simultaneously, a recent review found that <2ºC stabilization scenarios in IAMs require a range of 380-700 MHa by 2100 for BECCS (considering high-productivity dedicated energy crops), which represents 7–25% of current global agricultural land, and 25–46% of arable plus permanent crop area, a range of land demand which is the magnitude order than land identified as abandoned or marginal (Smith et al., 2016). However, the deployment of such vast amounts of bioenergy crops faces biophysical constraints due to the requirement of large areas, high fertilizer and water use, and that likely compete with other vital land uses such as agriculture of biodiversity conservation (Fuss et al., 2014; Scott et al., 2013; Smith, 2016). In the light of these facts and considering that currently almost 15% of the world population is undernourished (FAO, 2012), a very large surface for bioenergy (or other land-intensive RES such as solar, see section 2.3.4.3) at global level is not compatible with sustainable future scenarios.

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

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

In relation to the potential land for dedicated crops for bioenergy, taking into account the future land requirements for food, urbanization and biodiversity conservation, the scenarios implemented in MEDEAS standard version take two values: (1) roughly two-fold present occupation (taking as reference the conservative estimate) for the standard scenario (100 MHa) and (2) a high scenario considering up to 200 MHa (see Table 12). 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 2.8).

Figure 28 represents the Forrester diagram of the 2nd and 3rd generation biofuel production in land competing with other uses, as well as the biofuel production in marginal lands:

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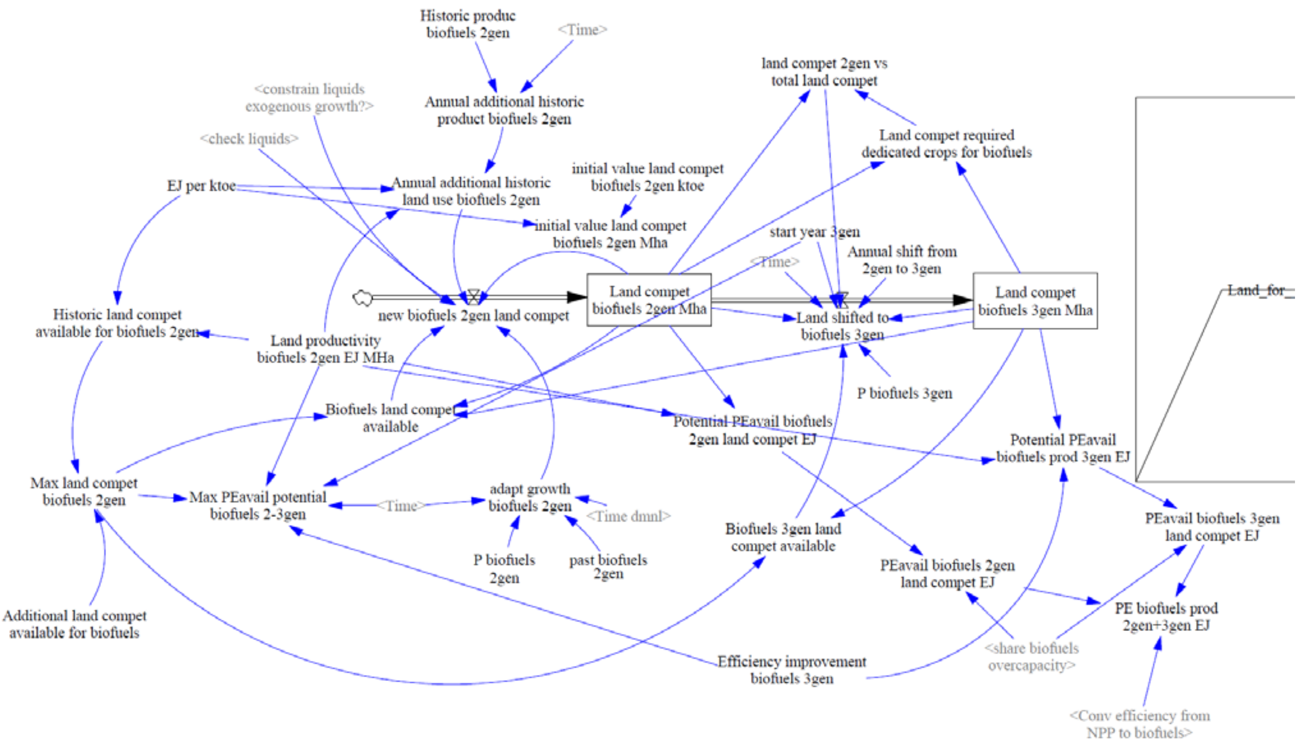

Figure 28: Forrester diagram of the modeling of the bioenergy in land subject to competition in MEDEAS.

2.3.4.1.3. Summary of bioenergy uses

Table 12 summarizes the potential for bioenergy for heat and liquids considered in the model (for the biomass for electricity see next section):

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Table 12: Techno-sustainable potential of bioenergy by technology and final energy use considered in MEDEAS.. NPP: Net Primary Production. The following conversion factors from NPP (harvestable) to final (gross) power are assumed: 80% for heat, 20% for electricity and 15% for liquids (de Castro et al., 2013a). However it should be noted that the efficiencies in real power and heat plants are lower considering factors such as non-optimal operation (e.g. low Cp), use in CHP plants, etc.

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

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

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

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

d Assuming current final energy use shares and efficiencies (IEA, 2016a).

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.[10] 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.

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

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2.3.4.2. RES for heat other than biomass

MEDEAS considers 3 RES technologies for the supply of heat: solid bioenergy, geothermal and solar thermal. The modelling is similar than for the RES electricity technologies, but distinguishes between commercial and non-commercial uses of heat due to the reporting of the IEA balances (see section 2.3.1.3).

Figure 29 shows the Forrester diagram of the extraction of (primary energy) from thermal RES.

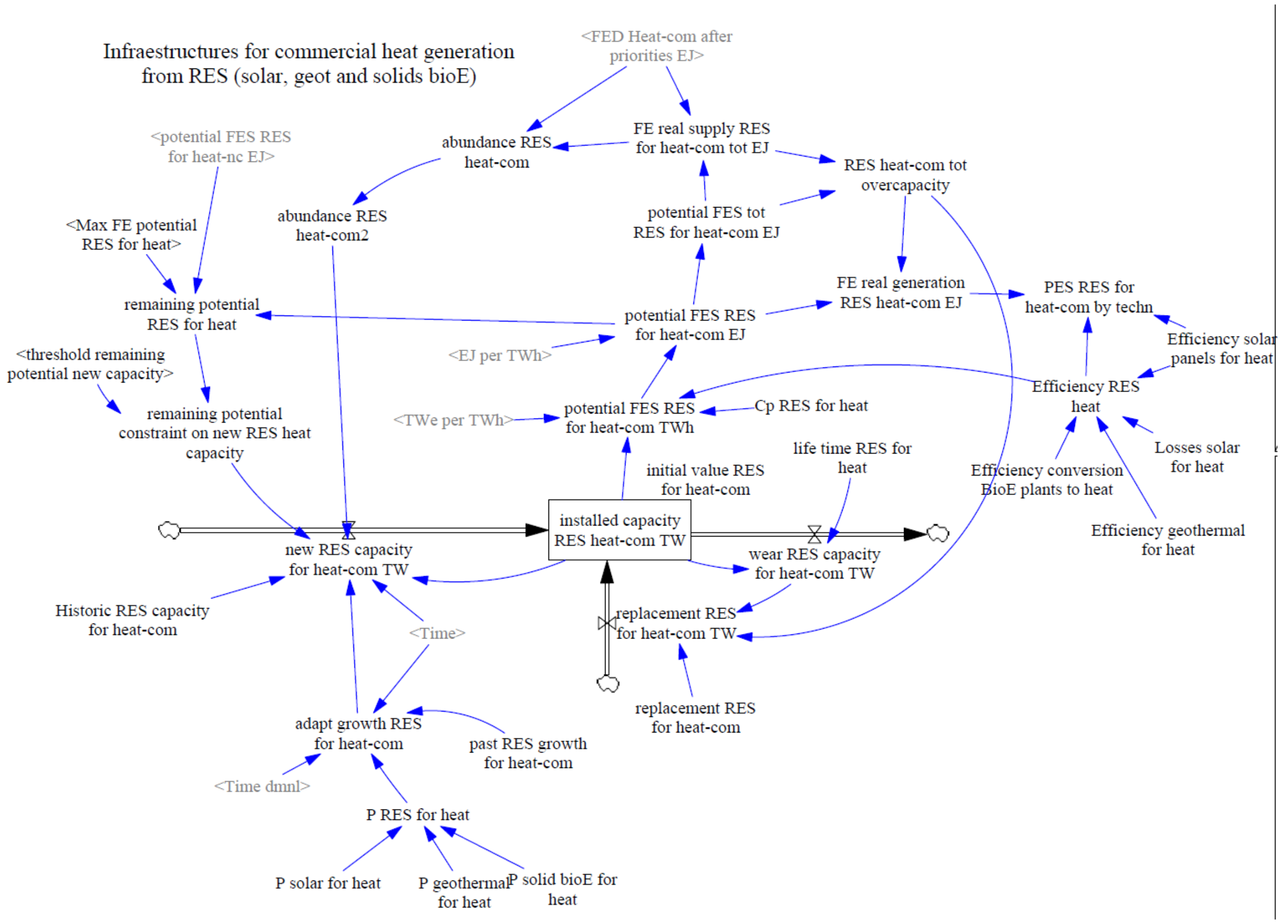

Figure 29: Forrester diagram of the extraction of (primary energy) from thermal commercial RES.

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:

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

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 2.3.4.5).

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 2.3.4.3).

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

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Table 13: Techno-sustainable potential of non-electric renewable sources excluding bioenergy.

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

Thus, combining the data from Table 12 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/m2 and that 1% of the continental ocean platforms might be occupied by human infrastructures (the density of occupation by human infrastructure in land is 1-2% and entire platforms like Artic and Antarctic are not accessible to human occupation), a rough potential of 0,25 TWe is considered. The estimation of the real and future density power of solar infrastructures including PV and CSP (4-10

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times lower than most published studies) leads to a potential of around 65-130 EJ/yr (2-4 TW_e[11]) (de Castro et al., 2013b) in 60-120 MHa.[12]

Hydroelectricity is limited by a total gravitational power of rain of 25 TW (Hermann, 2006). Our estimation of technological potential is around 1 TWe; other studies have found that the economic potential is 1-1.5 TWe, being the sustainable potential around 80% of this range (0.8-1.2 TWe) (EUROELECTRIC, 2000). Given the constraints that the variability of RES for electricity impose to the system, we assume an available potential in MEDEAS of 1 TWe.

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

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

In relation to electricity generation from bioenergy, as discussed in the precedent section, we assume a shared potential of bioenergy for both heat and electricity. Thus, depending on the scenario (i.e. final energy demands, policies, etc.), the model will assign a different use for heat and electricity from bioenergy. With the standard assumptions and in the extreme scenario where all the bioenergy potential for heat and electricity would be allocated for electricity production, < 9 EJ/yr (< 0.3 TWe , see Table 12) could be delivered from bioenergy with the standard assumptions in MEDEAS (see section 2.3.4.1). 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 12). Accordingly, sustainable policies often give priority to heat generation from biomass (Bermejo, 2014).

Table 14 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).

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

[12] 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).

Table 14: Data of electric renewable in the model. “TWe” represents the gross annual power electric production: TWh/8760.

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

[a] The investment cost for solar PV after 2030 is set to the same level than wind onshore, since we judge that it is unlikely that solar PV technologies will manage to be less expensive in the future than wind given their higher technological complexity. In fact, in recent years, the price of solar modules has fallen significantly due to efficiency improvements but also to dumping and excess capacity effects in the crisis. [b] (Boccard, 2009; BP, 2016; De Castro and Capellán-Pérez, 2017; EIA, 2009; IRENA db, 2017; REN21, 2016). [c] We assume that offshore wind has a +50% higher Cp than onshore wind. [d] The oceanic investment cost is maintained constant after 2030 since we judge too optimistic that these technologies might reach a low cost in the order of the ones of wind offshore. [e] Assuming

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current final energy use shares and efficiencies (see Table 12); the infrastructure of generation for biogas is not explicitly modelled.

Considering the data presented in Table 14, 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 2.3.4.4 "Modelling of intermittency of RES variables").

We consider the power density of RES in order to estimate their land occupation (although for solar PV and CSP it is the inverse: the land (Mha) dedicated for these technologies is set for each scenario and the annual delivered power estimated subsequently). We apply data based on studies that take into account real present efficiencies and surface occupation of technologies (de Castro et al., 2013b; Smil, 2015). For the capacity factor (Cp) of solar PV and wind, we apply a couple of studies that focus on the estimation of this parameter applying a top-down analysis of real-life systems in large areas rather than usual, laboratory values that happen to substantially overestimate this parameter in working conditions. Thus, Prieto and Hall (2013) estimate the Cp of solar PV in Spain, a country with good insolation and with a significant solar power installed. Boccard (2009) found that, although for more than two decades, the Cp of wind power measuring the average energy delivered has been assumed in the 30–35% range of the name plate capacity, the mean realized value for a region as Europe in the period 2003-2007 was below 21%. Arvesen and Hertwich (2012) confirmed the existence of a general tendency of wind power LCAs to assume higher capacity factors than current averages from real-world experiences. An estimation of the real Cp of wind onshore at global level from data from BP (2017) reveals that in the last decade it never surpassed

0.16, thus the extrapolation of the estimation from data from Boccard (2009) for the rest of the world are optimistic (this leaves room in MEDEAS so that the future efficiency could increase ~30%, from 0.16 to 0.21 due to technological improvements). For the rest of sources we apply standard values from the EIA US (2008). Table 14 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 15 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 15: Techno-ecological potential of RES for heat and electricity.

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

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2.3.4.5. Modelling of intermittency of RES variables in MEDEAS

The most abundant RES for the generation of electricity, solar and wind (see section 2.3.4.3), 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 2.3.4.5.1). Finally, section 2.3.4.5.2 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., (2017a)). Overcapacities are limited by the economic profitability of the power plant (i.e. large overcapacities imply low Cp). From a net energy perspective, overcapacities tend to lower the EROI, which could similarly affect the net energy profitability of the plant. Due to

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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,[13] 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.[14] To cope with their intermittency, MEDEAS incorporates 4 mechanisms:

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

The review of the literature showed that while a ~20-35% share of variable RES may require relatively low levels of storage and overcapacity, a system with intermittent RES over 40-50% substantially increases these requirements, i.e., there is an exponential relationship when approaching the full intermittent energy mix (Capellán-Pérez et al., 2017a; Delarue and Morris, 2015; Ferroni and Hopkirk, 2016; François et al., 2016; NREL, 2012; REN21, 2017; Weitemeyer et al., 2015).[15] 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).

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

[14] 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, 2017). For this reasons it is also considered as a variable RES.

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

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 30 represents the share of installed power storage vs. (1) variable RES installed capacity (red curve), and vs. (2) total RES installed capacity (blue curve) as a function of the share of total RES penetration in the electricity mix. We note that the first point relative to the current levels (20% of total RES penetration in the electricity mix) corresponds with the highest level of share of installed power storage. This feature suggests that the storage requirements estimated by this study might be underestimated.

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

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

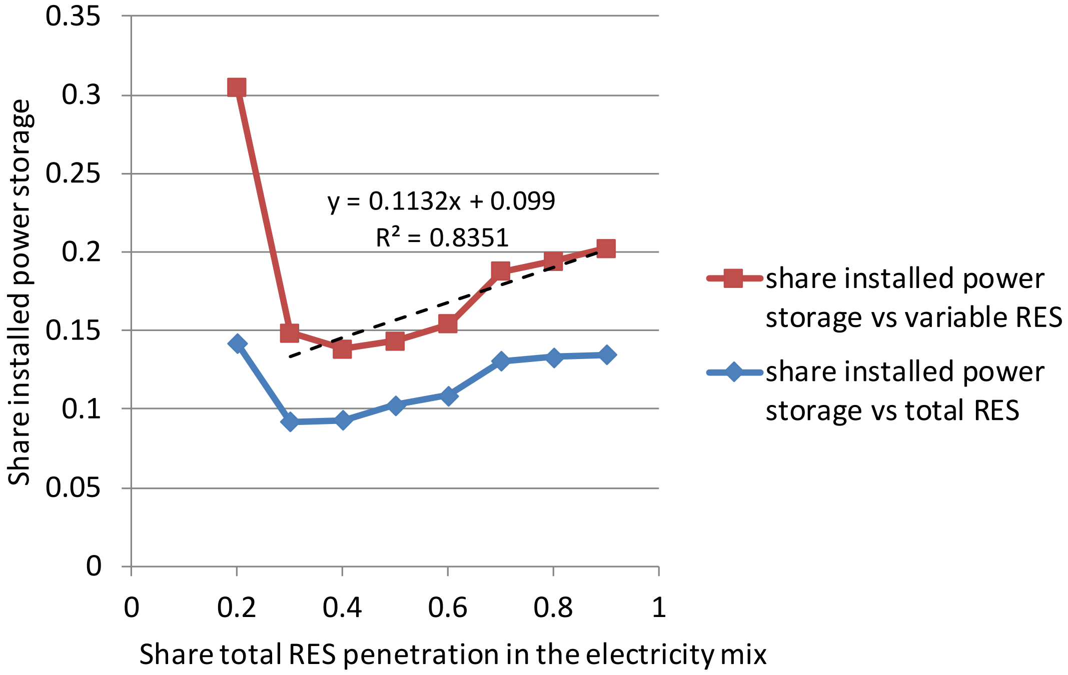

Figure 30: Share of installed power storage vs. (1) variable RES installed capacity (red curve), and vs. (2) total RES installed capacity (blue curve) as a function of the share of total RES penetration in the electricity mix.

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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 optimium 100% RES mix (wind+solar) would reach 660 times the current PHS installed capacity in the country, far from the feasible potential. (Trainer, 2013) estimated for Europe that generation from PHS would have to be scaled up by a factor approaching 20, which is again higher than the estimated theoretical potential for PHS (Gimeno-Gutiérrez and Lacal-Arántegui, 2015).[16] Note that the storage requirements estimated by each study depends on the area of the region studied and on the onsideration (or not) of other mechanisms to adapt to variability.

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 infraestructure.

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 (2016b) estimates that “125,000 cars could be equivalent to 300 MW of flexibility – a medium size pump storage plant or a successful stationary demand side response program”. Given that the ESOI of PHS is higher than EV batteries for most of the potential of PHS, the current version of MEDEAS assigns priority to the electric storage of PHS. In the case that more storage is required the EV batteries could then be used. However, an extensive use of EV batteries for electricity storing would wear very fast the batteries, effectively reducing its lifetime. For example, increasing their Cp 10x would translate into 20,000 cycles. Thus, in MEDEAS we assume that the electric batteries for EV can be used for

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

electricity storage at a same Cp than for driving, i.e. that each battery would be able to function 10 years without wear (4,000 cycles) (more details in section 2.4).

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

Overcapacities of RES power plants

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

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 31 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.[17]

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

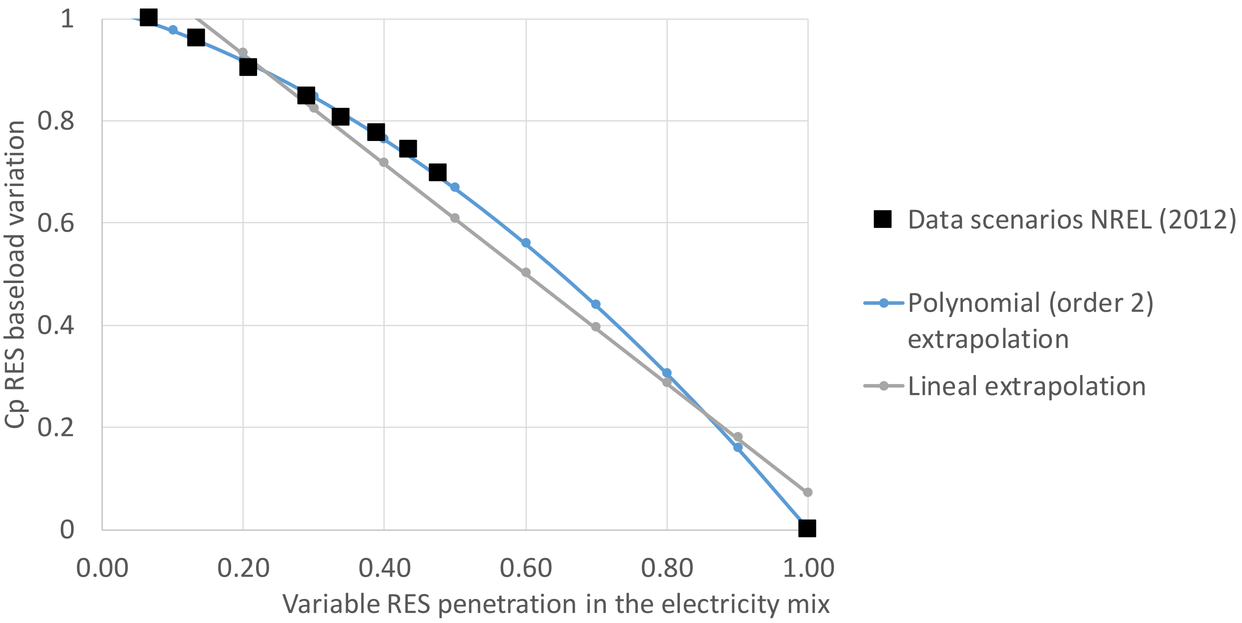

Figure 31: Capacity factor reduction of baseload plants (including RES and non-RES power plants) in relation to the initial point of "negligible" variable RES penetration as a function of the increasing level of penetration of the electricity generation of RES variables. Source: own calculations from NREL (2012) data (Figure 2-2), and polynomial and lineal extrapolation until 100% (Cp baseload=0%).

We estimate the overcapacity of variable RES following the study from (Delarue and Morris, 2015). NREL (2012) study could not be applied for this estimation since several shortcomings were identified in the methodology, such as the unrealistic assumption that key characteristics of the energy system remain constant with the increase in the penetration of RES technologies in the electricity mix (such as the Cp of the variable RES), or the consideration of CSP as dispatchable source of electricity (CSP has in fact a higher seasonal variability than solar PV (De Castro and Capellán-Pérez, 2017)).

Figure 32a 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 32b shows the correspondent reduction in the Cp of the variable RES power plants and interpolation assuming that Cp=1/(1+overcapacity). Hence, we assume that in the case the variable RES would cover 100% of the electricity generation, an overcapacity of almost +200% (3 times) would be required for those power plants running on variable RES technologies, equivalent to a reduction of almost 3 times in their Cp. Weitemeyer et al., (2015) reach a similar conclusion for Germany assuming PHS

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requirements of more than 30 times the current installed capacity (in combination with 200% overcapacity).

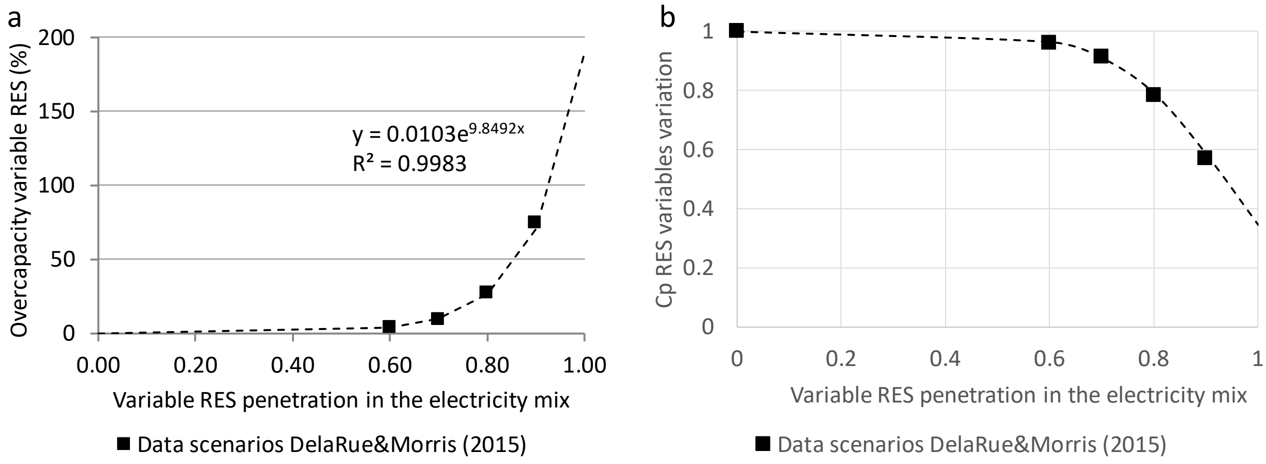

Figure 32: Overcapacities of RES variables: (a) Overcapacities of variable RES as a function of the variable RES penetration in the electricity mix from (Delarue and Morris, 2015) and exponential fit; (b) Reduction in the Cp of the variable RES power plants and interpolation.

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

Grid development

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

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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 14). 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[18]) 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

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

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 Table 16). 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 16: Integration cost adapted from (Holttinen et al., 2011).

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

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 17 shows the technology-specific employment factors considered from (Greenpeace et al., 2015). These factors are usually from OECD countries, as this is wherethere is most data. In peripheral countries it typically means more jobs per unit of electricity because those countries have more labour intensive practices. On the other hand, we do not take into account “learning adjustments or ‘decline factors’”. We assume that the evolution of both factors in long-term will cancell out.

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Table 17: Employment factors considered in MEDEAS. Source: (Greenpeace et al., 2015).*For CSP, the original data from Energy [R]evolution report seems to low (2.2 jobs/MW for manufacturing, construction and installation, and in this case data for this technology from (REN21, 2017) was used instead.

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

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2.3.5. Electricity generation

Distribution losses must be added to the estimated final electricity demand in order to compute the electricity generation demand. An analysis of the period 1980-2010 reveals that these losses were approximatively 9.5% of the electricity consumed (US EIA db, 2015) (Figure 33). When checking this relation for the past years an error inferior to 1% was obtained.

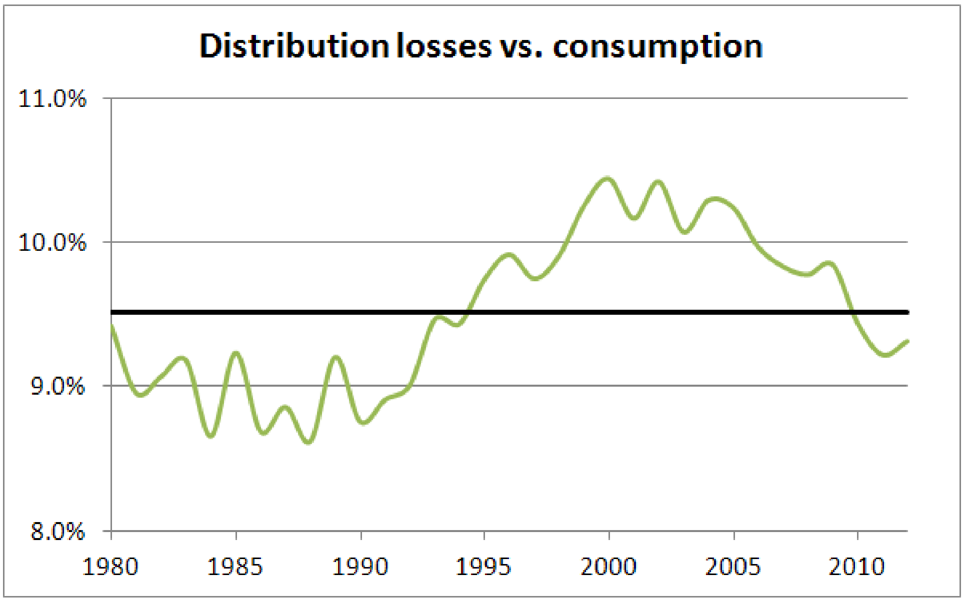

Figure 33: Distribution losses vs. consumption at global level (1980-2012) (US EIA db, 2015).

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 34):

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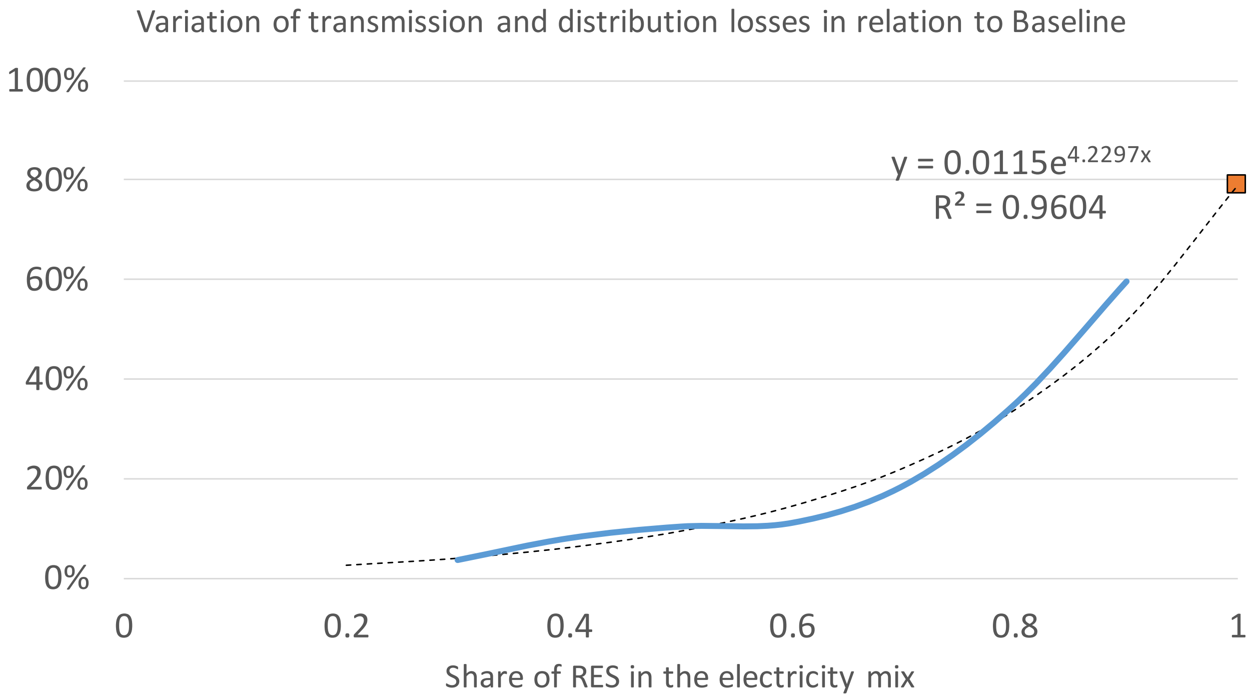

Figure 34: Variation of electricity transmission and distribution losses as a function of the share of RES in the electricity mix. Source: own work from (NREL, 2012).

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

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

The model also accounts for the additional energy due to the electrification of transportation (see section 2.3.7). 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, 2016a):

Table 18: Assumptions for the efficiency of fossil and nuclear power plants.

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

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

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 19), while reaching (or close to) grid-parity costs in many locations (REN21, 2014).

Table 19: 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, 2016a) (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 Forrester diagram (Figure 35) of the infrastructure of RES technologies for electricity generation (vectorial programming).

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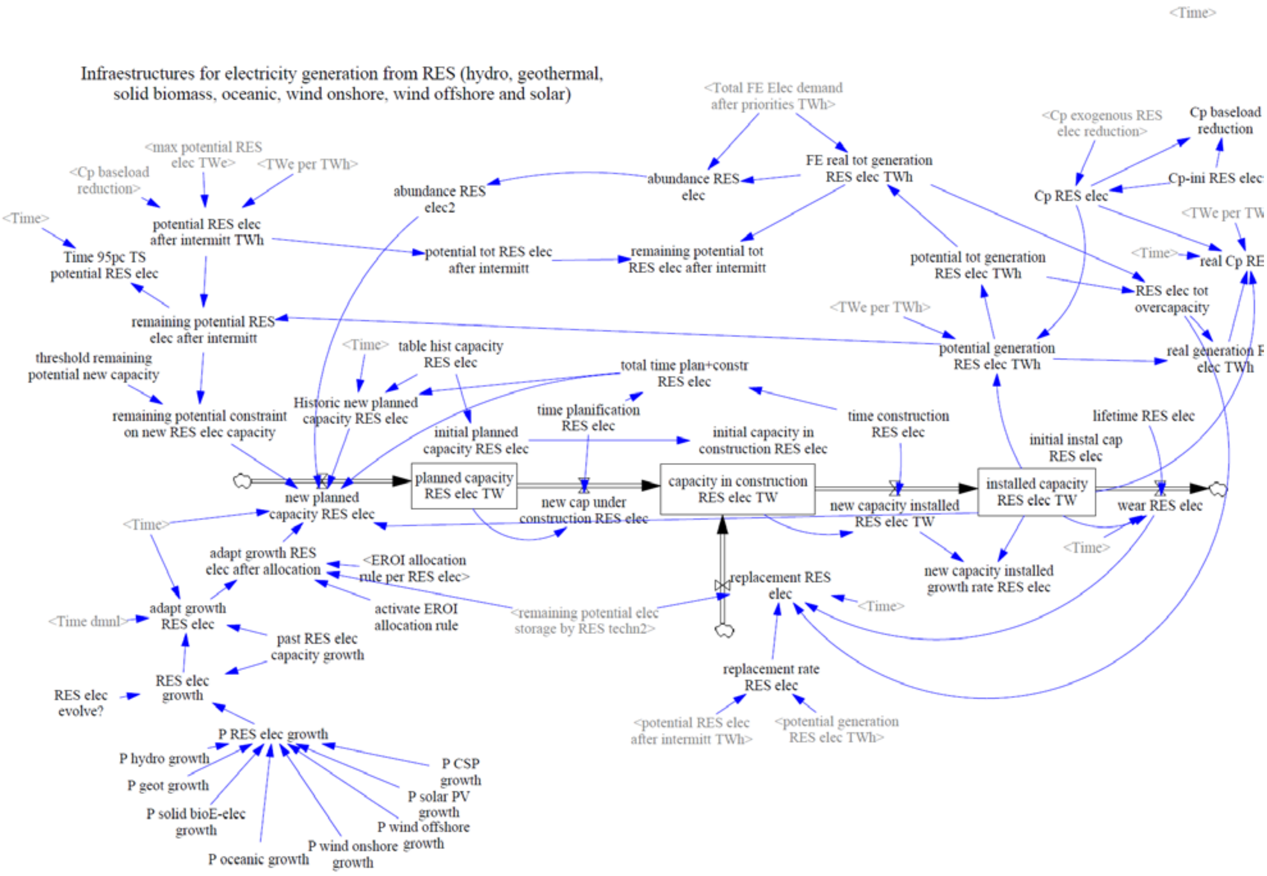

Figure 35: Infrastructure of RES technologies for the generation of electricity (vectorial programming).

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*):

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

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Figure 36 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 19 in section 2.3.5.1).

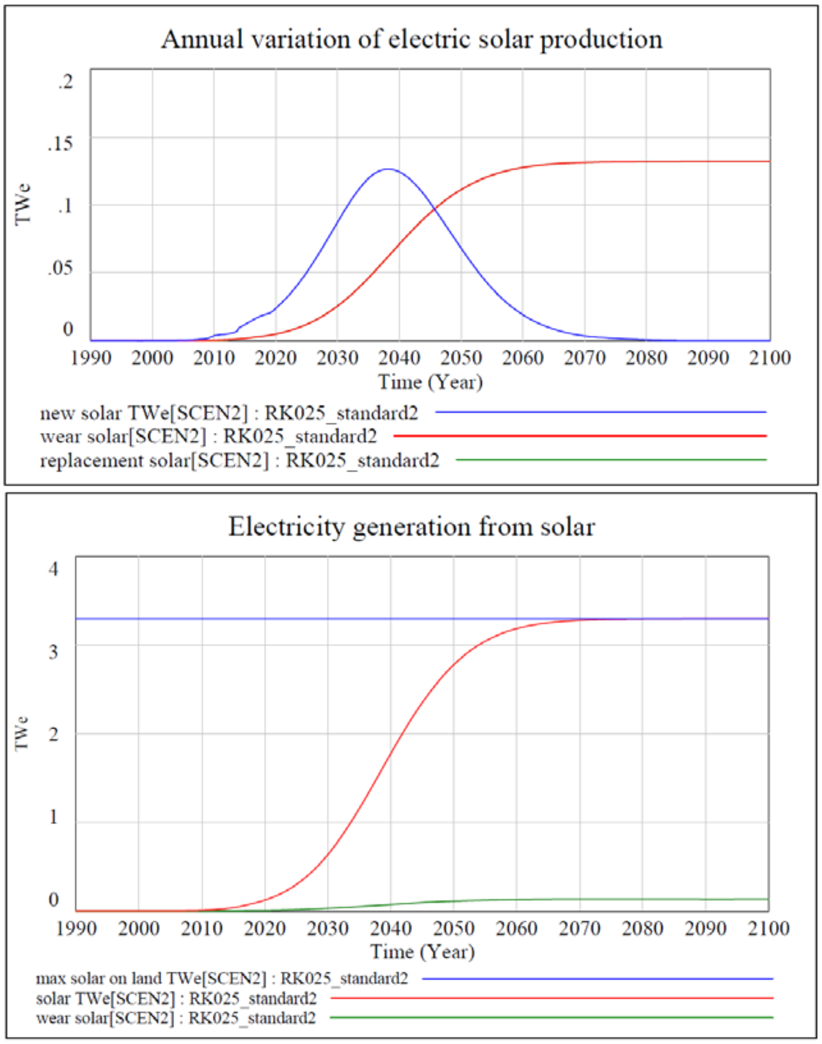

Figure 36: Total electric solar production (TWe). In this figure we represent the dynamics of the previous equation considering a very rapid growth of solar (+19%, as in scenario 1). While being far from the potential limit, exponential growth drives the growth of new solar power. As the total solar 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

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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 37). 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.).

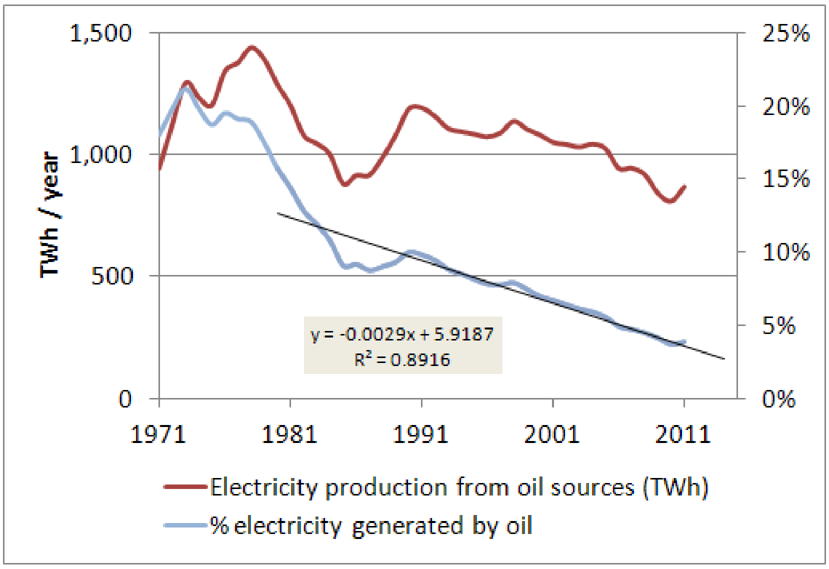

Figure 37 (own analysis from (World Bank database, 2015)): Electricity production from oil sources (TWh) and as percentage of the total electricity production.

2.3.5.3. Nuclear power scenarios

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

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

Global nuclear power plant capacity is explicitly represented in MEDEAS. Since nuclear power plants require a depletable input to operate (uranium), the electricity produced by uranium is modelled by three structures for representing: the exogenous demand of each scenario (TWh), the installed capacity (GW) and a submodule of uranium extraction similar to the ones for other non-renewable energy extraction (see Figure 23). Ultimately, the electricity generation is the minimum between the available uranium and the existing infrastructure.

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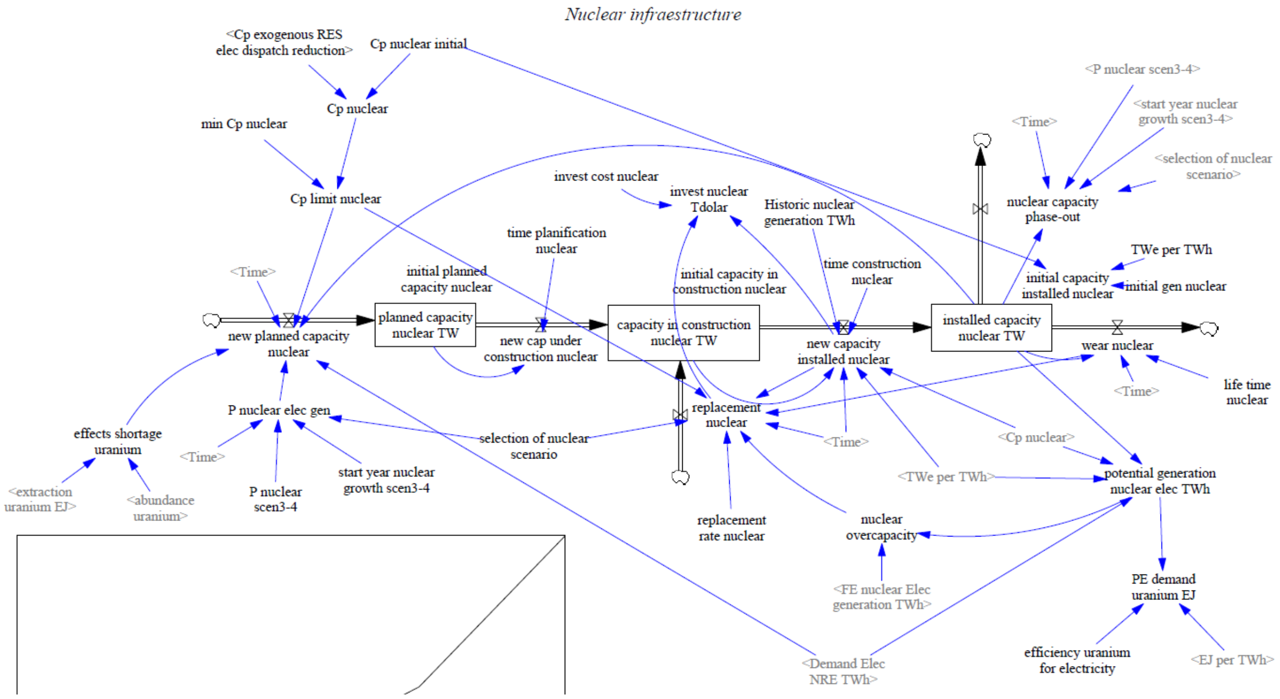

Figure 38: Forrester diagram of electric generation from nuclear power.

As a result, in those scenarios where the nuclear capacity is expanded, uranium availability might constraint supply, eventually generating transitory problems of overcapacity. It is assumed that there are not new nuclear capacity additions when the demand of uranium exceeds its availability. For the sake of simplicity, in this model version it is assumed that decommissioned power is always replaced. Under this modeling, capacity constraints do not operate. However, as a result of the penetration of the electric intermittent RES the Cp of the nuclear plants falls which ultimately causes the decrease in the annual average output per installed capacity. A Cp minimum of 60% is set due to the specific characteristics of nuclear power plants which cannot operate a low Cp levels.

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

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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 2.3.6.3. 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 enduse sectors (IEA, 2014).

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

Commercial heat is defined in IEA statistics as heat that is produced and sold to a different end user. The heat is produced through co-generation or heat plants and is often distributed through district heating networks. The heat can also be bought and sold, for instance between neighbouring industrial complexes. The transaction associated with purchased heat produces a reliable data point for national administrations to collect in a consistent manner, hence the category “heat” is reserved for these quantities in IEA statistics. Most heat is not sold, however, because it is produced and consumed directly on-site, through space heating for homes or industrial processes on a manufacturing site. Due to the variety of end uses, useful heat outputs are rarely measured unless there is a commercial need or financial incentive to invest in measuring the useful heat outputs at the end-user level (IEA, 2014). Due to this discrepancy, a correction is introduced in MEDEAS to estimate the heat demand of non-commercial applications (see section 2.3.1.3).

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 39). We assume the same losses for non-commercial heat due to the lack of available data.

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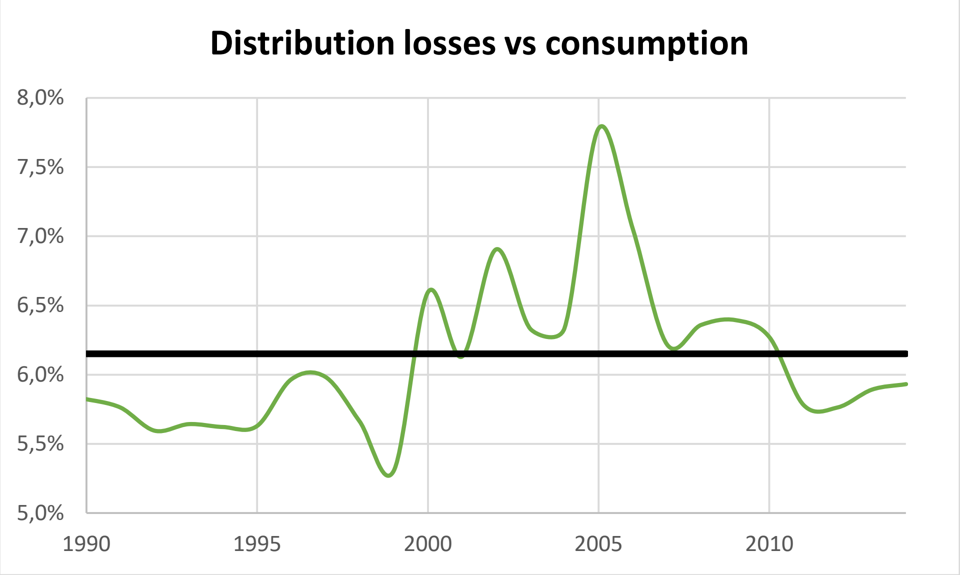

Figure 39: Distribution losses vs. consumption at global level for commercial heat (1990-2014) (IEA, 2016a).

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, 2016a). 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

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in other applications (see Figure 40). 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.).

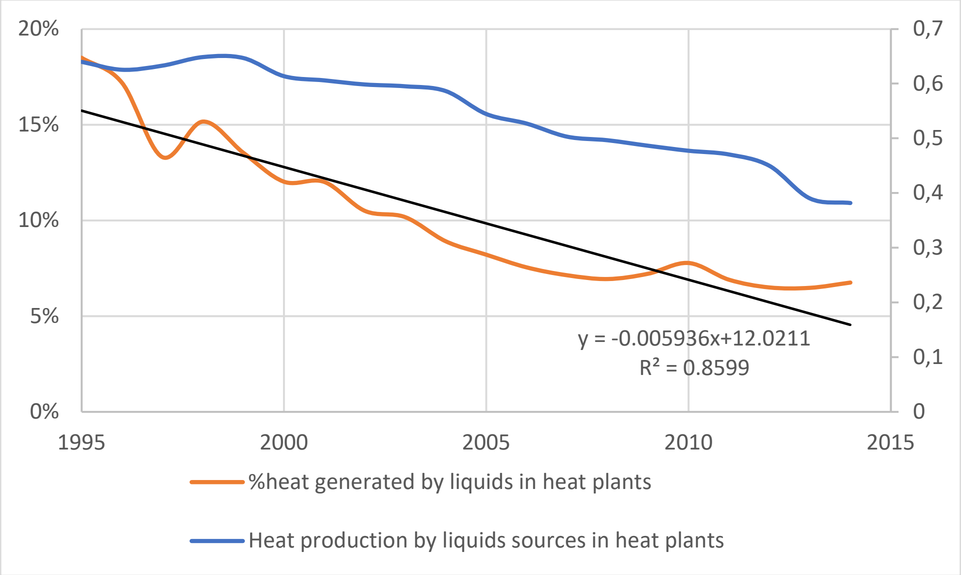

Figure 40: Heat production from oil sources (TWh) and as percentage of the total heat production (own analysis from (World Bank database, 2015)).

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 24).

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 20: 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	Recent trends (2012-2015)

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		(2000-2014)	
Solid biofuels	(IEA, 2016a) and own estimation	+3.6%	+11.5%
Solar heat	(IEA, 2016a), (SHC, 2016) and own estimation	+14.4%	+12.7%
Geothermal heat	(IEA, 2016a), (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 happen because in heat demand the priority is given to RES sources. The demand not covered by RES sources is covered by fossil fuel Heat plants and CHP plants. Among these plants, the priority is given to CHP plants because their efficiency is better than only heat/electricity plants

Then, heat production in CHP plants depends of heat demand for NRE. Historic data shown that arround 46.5% of the heat demand not covered by renewable sources is covered by CHP plants (Figure 41):

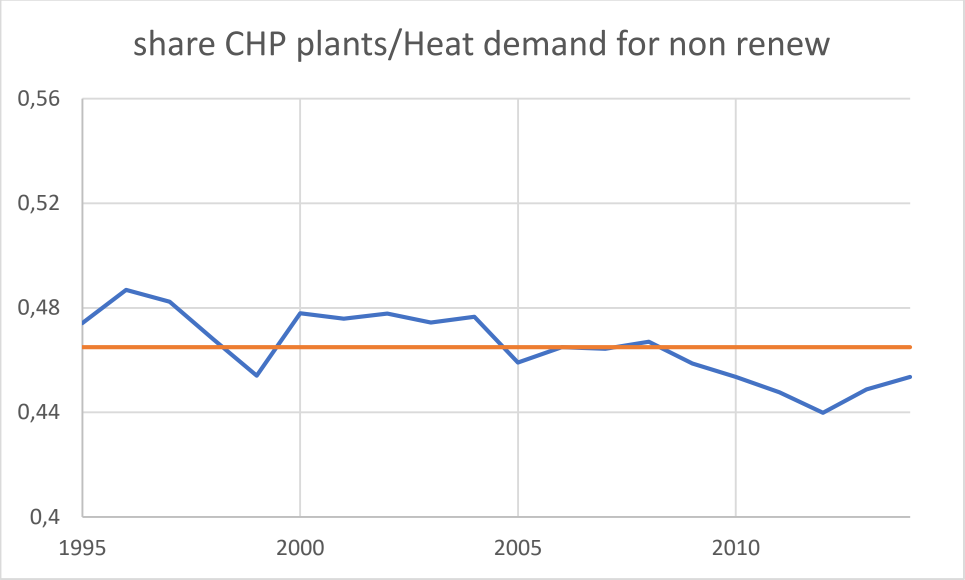

Figure 41: share of Heat demand without RES sources covered by CHP plants

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

At the same time, CHP plants produce electricity. The following efficiencies derived from (IEA, 2016a) are used to calculate the electricity produced in each plant.

Table 21. CHP plants efficiencies for heat for the 2014: Own elaboration from (IEA, 2016a).

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

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

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

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2.3.7. Transportation

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

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

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

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

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

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

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

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

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

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

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

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

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

Therefore we might define the following constants:

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

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

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

A similar approach might be used for electricity, since:

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

If

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

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

And:

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

In a similar way, for gas vehicles:

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

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

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

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

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

Which enable the calculation of A_1 and A_2 constants.

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Using the previous equations the model is defined in the diagram of Figure 42. 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.

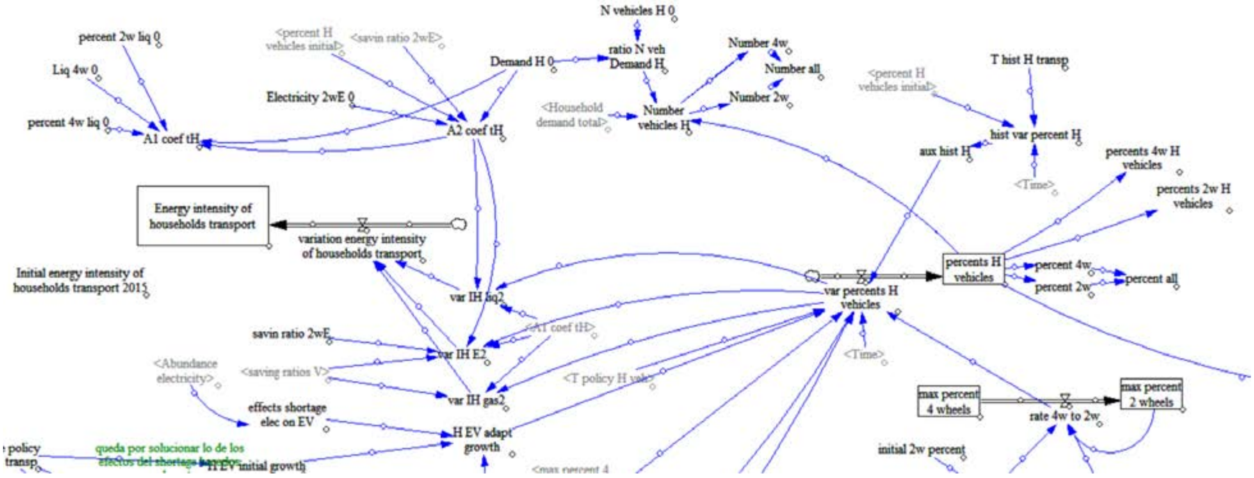

Figure 42: Forrester diagram of the household transport subsystem.

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

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

And assuming this ratio in constant though the simulation, therefore

$$\begin{aligned} & Number\ of\ vehicles\ tipe\ i\ (t) \\ & = Household\ Demand(t) \cdot ratio\ N\ veh\ demand\ H \cdot percent\ vehicle\ type\ i(t) \end{aligned}$$

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).

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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

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the following are constant and can be estimated via the initial values of number of vehicles of each type in the initial year:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$+CX_{bus} \cdot sr_{gas\ bus} \cdot \frac{d}{dt}\%bus_{gas}$$

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

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

The model is defined in the diagram of Figure 43. The percentages of vehicles of each type (vector percent T vehicles) are the drivers of the subsystem and vary according to the desired policies. The change of these percentages (var percent T vehicles) modifies the variation of energy intensities of Inland Transport.

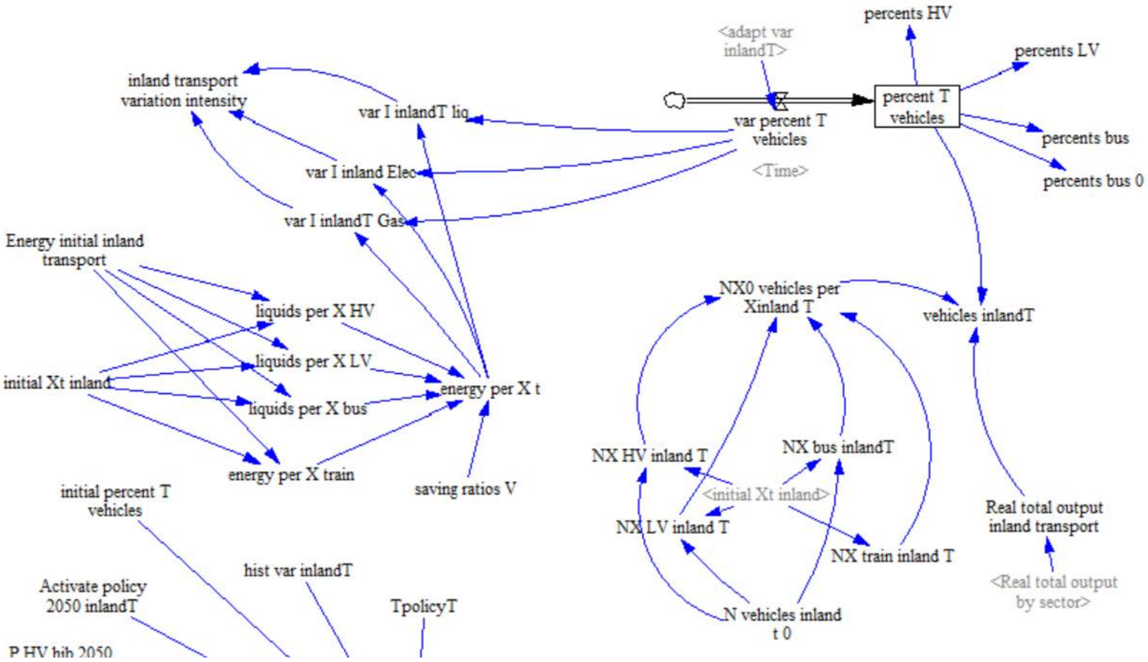

Figure 43: Forrester diagram of the household transport subsystem.

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

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2.3.7.1.3. Batteries for electric vehicles methodology

Batteries are an important component of the transport systems since they might pose a restriction on material and they might be used as a storage for the electric network. Since the number of vehicles is already estimated the number of batteries can be calculated quite straight forward. Figure 44 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.

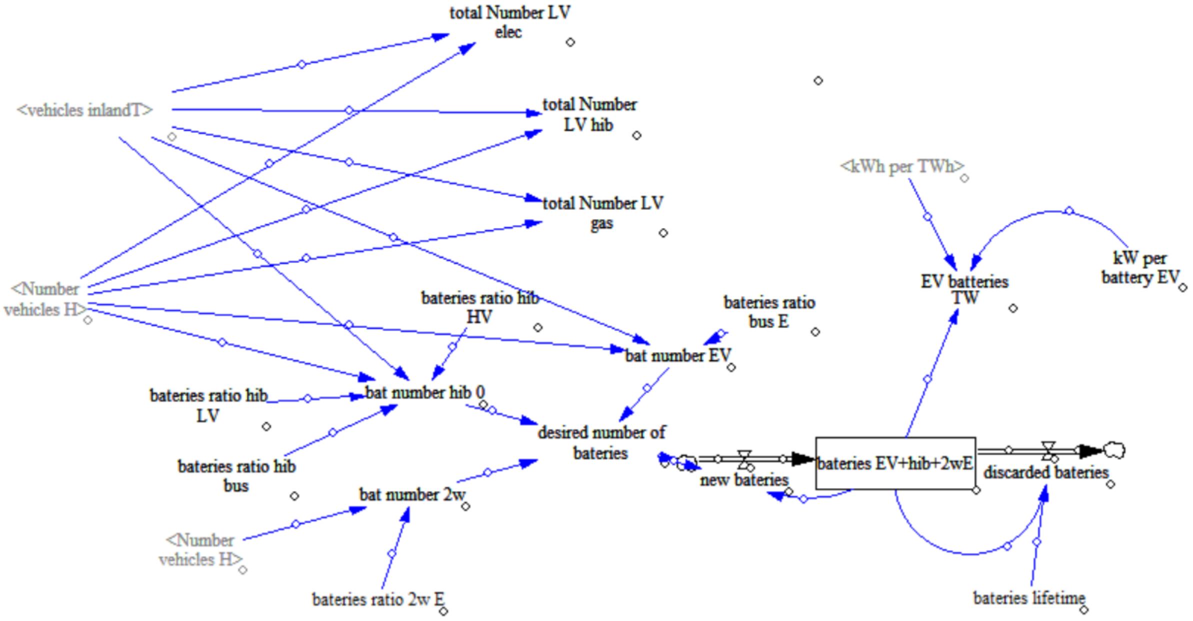

Figure 44: Diagram of the batteries submodule.

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 45) 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 46) *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).

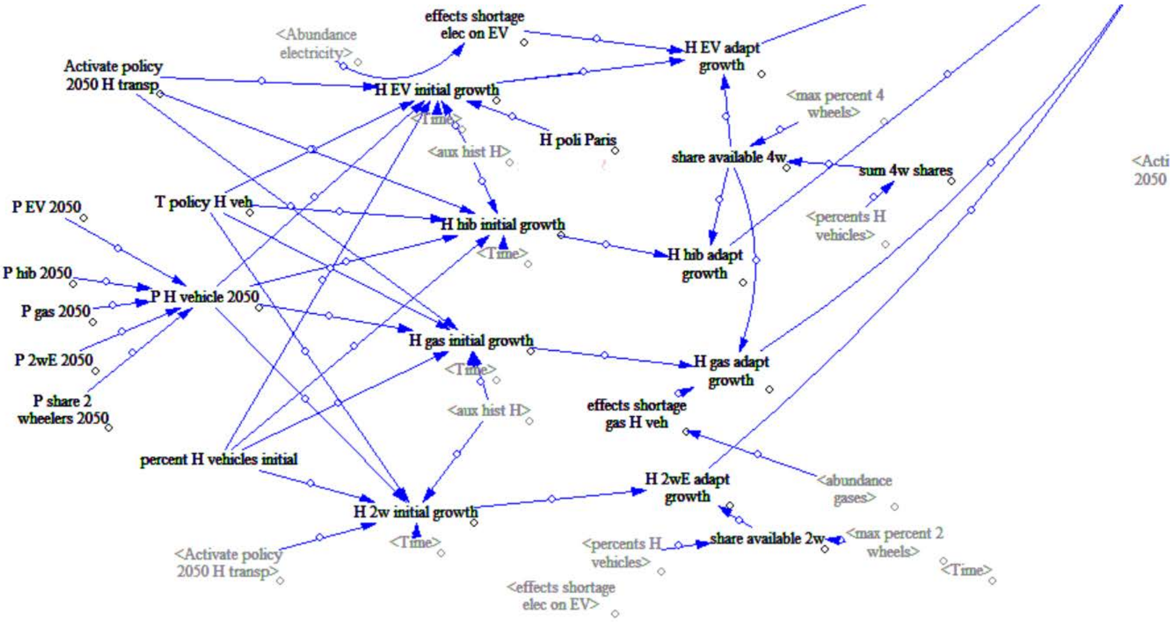

Figure 45: Diagram of the policies of Households Transport subsystem

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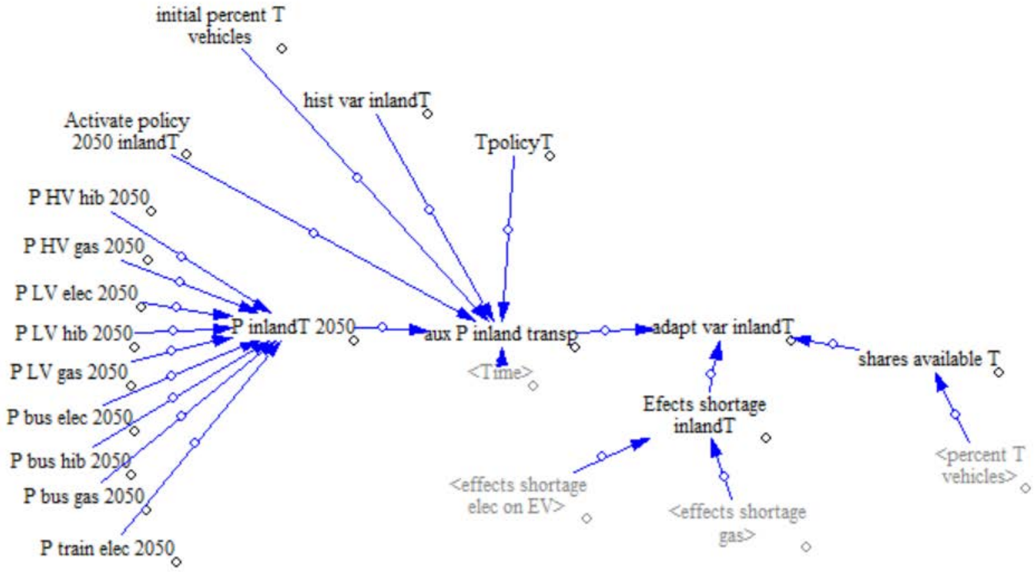

Figure 46: Diagram of the policies of Inland Transport subsystem

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 2.3.7.1.

2.3.7.2.1. Electric vehicles data

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

The prospects for electric vehicles (EVs) are highly uncertain, as the breakthrough to fully commercial models has yet to come and consumers would have to adjust to the characteristics of the new vehicles. MEDEAS considers BEV (battery electric vehicles) and PHEV (plug-in hybrid vehicle) that are the types of electric vehicles that represent the bulk of the electric transportation for light duty vehicles (IEA, 2016b). 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

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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, 2016b) forecasts between 20 and 150 million electric cars in 2030, seting 100 million as the target of Paris agreements, which represents a strong growth from present values (see Figure 47). This value could be stablished as an optimistic policy for households and light cargo EV growth.

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

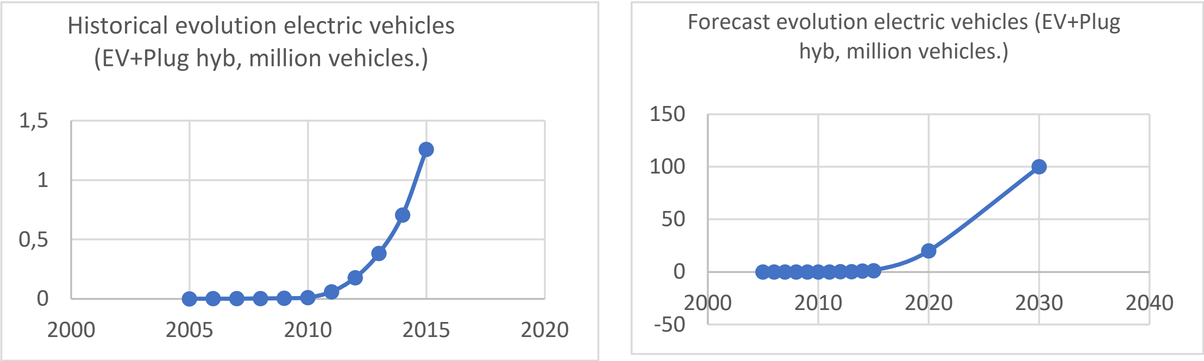

Figure 47: Historical evolution of EV+PHEV vehicles. (Own elaboration based on data from (IEA, 2016b))

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 48) in a constant pace of growth that can be considered linear in time. Hybrid vehicles in 2015 where 0,14% of the household vehicles and 0,04% of the heavy vehicles (IEA, 2016b) therefore its evolution in heavy vehicles is slower than in light ones and it could be realistic to apply policies with an initial delay.

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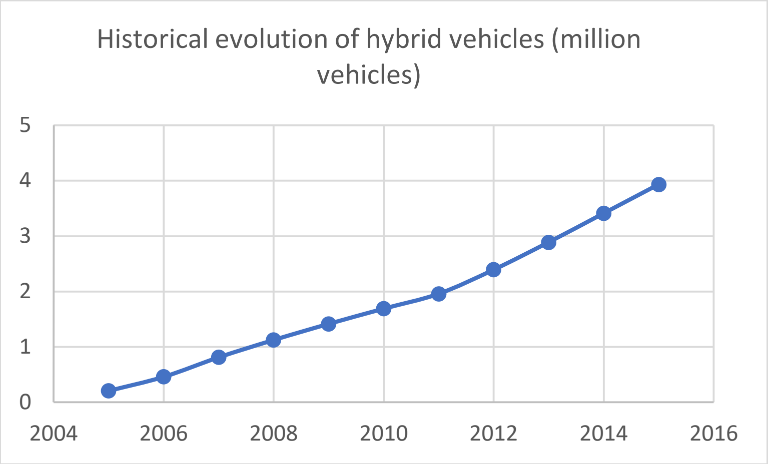

Figure 48: Historical evolution of hybrid vehicles worldwide (own elaboration based on data from (IEA, 2016b))

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)[19] 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

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

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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.

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, 2016b) (see Figure 49) show that 173 million electric two (ant three) wheelers are in stock in 2015 (the large majority of them in China), which is 21% of total two wheelers.

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

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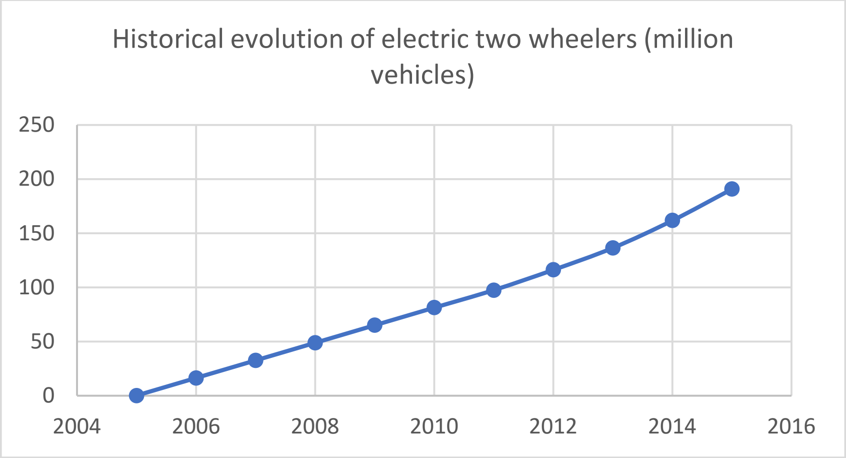

Figure 49: Evolution of the stock of electrical two wheelers worldwide. Own calculations based on data from (IEA, 2016b).

2.3.7.3. Saving ratios

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

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

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

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

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

Gas vehicle efficiency is similar to the one of liquid based vehicles. In (Hekkert et al., 2005) the tank to wheel efficiencies of gasoline and natural gas vehicles are set in the range 16%-25% for both,

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therefore the saving ratio of NGV is 1. In (Pelkmans et al., 2001), a similar conclusion is reached for gas buses operated in a case study of real traffic conditions. We assume that the same ratio can be applied to other types of gas vehicles.

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

A summary of the values estimated for saving ratios is shown in Table 22.

Table 22*:* Saving ratios estimated for different vehicles and fuels compared to liquid-based equivalent vehicles.

	electric	**hybrid**	**gas**
Light four wheelers	0,33	0,6	1
Heavy vehicles and buses	0,5	0,6	1
Two wheelers	0,21		
trains	0,6		

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 (2016b) estimates that "125,000 cars could be equivalent to 300 MW of flexibility – a medium size pump storage plant or a successful stationary demand side response program". The number of batteries is stimated in MEDEAS using the number of electrical vehicles calculated as described in sections 2.3.7.1.1 and 2.3.7.1.2.

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

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

All these data give an estimation of the ratio of batteries wheight needed froe each vehicle compared to the standard battery of electric light household cars shown in Table 23.

Table 23: Ratios of battery size relative to light purely electric vehicles.

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

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2.3.8. Non-energy use consumption

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

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

Table 24 reports the values of the parameters a and b for each final fuel.

Table 24: Results of regressions of final fuel non-energy use demand as a function of GDP.

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

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2.4. Materials module

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

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

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

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

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

This section is structured as follows: section 2.4.1 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 2.4.2 describes the rationale and the approach to represent the supply of minerals in the model. Section 2.4.3 describes the modelling of recycling policies. The last three sections of this paragraph are related to EROI: section 2.4.4 documents the EROI estimation per electricity generation technology, section 2.4.5 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, 2017; Pihl et al., 2012), etc. In relation to the electric grids, the additional requirement of grids (i.e. “overgrids”) were estimated considering that the RES reach a high penetration in the electric mix, the losses due to Joule effect and the maintenance of grids. In relation to the electric vehicle batteries we also estimate the energy requirements to maintain the vehicle fleet. All considered data are energy data, i.e. no energy values were derived from monetary costs. Additionally, in the case of uncertainty about potential double accounting, material requirements were not included. Hence, our estimations can be considered conservative/optimistic.

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

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

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

Table 25 summarizes the applied methodology for each RES variable electricity generation technology:

Table 25 : Material requirements per RES variable electricity generation technologies considered in MEDEAS.

Name in MEDEAS (representative technology)	Reference(s) and comments
CSP (CSP with molten-salt storage without back-up)	Main reference: (De Castro and Capellán-Pérez, 2017). Realistic Cp of 0.25 and a lifetime of 25 years. Mirrors coated with a silver reflective layer despite (despite the potential scarcity of this mineral in the future). If considering aluminium mirrors instead, the CED would increase by ~8% (De Castro and Capellán-Pérez, 2017) and the efficiency of the system (equivalent Cp) would decrease by ~14% (García-Olivares, 2016), which would lead to a lower EROI ~80% lower ($EROI_{CSP}(Al) = EROI_{CSP}(Ag)*0{,}86/1{,}08$). For the data: diesel, evacuation lines, gravel (roads, protection…) and heavy machinery data from PV have been considered. Given that the density of material requirements (kg/m2) of CSP are ~2x comparing to PV, this approximation is thus conservative. +1.5% of additional losses has been conservatively considered as Joule effect to account for small devices (pumps, valves, etc.) which other authors have estimated in 2.5% of the CED of the construction phase.
Solar PV (Fixed-tilt silicon PV)	Main reference: (Prieto and Hall, 2013); completed with (MEDEAS, 2016a) Annex 9 and other sources. Material data have been extracted and re-calculated from Prieto and Hall (2013) excluding data indirectly estimated from economic parameters (which could eventually be considered in a calculation of $EROI_{ext}$).

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

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

Electric vehicle batteries (LiMn2O4 bateries)	Main references: data from components of the battery of Nissan Leaf, and data of its composition from (ALIVE, 2016; Dunn et al., 2012; Li et al., 2013). Batteries use graphite, phosphorus and fluor which are not included in the list of 58 materials of Table 27. These have been added in the category “wires” since their energy requirements are approximately equivalent. The grid correction factor (Joule effect) has been set to 1.1 accounting for the losses during the processes of charging and discharging the batteries. No O&M considered, no wear. The charged battery delivers 21.3 kWh which would allow to cover 117 km. Assuming a lifetime of 10 years, 2,000 cycles (equivalent to almost 150,000 km for a battery of 80kW and 210kg of weight (i.e. 12.5 batteries per MW)). Thus, the equivalent Cp is 0.0055 (80KW*10years*31.5E6sec/year). The energy output in the lifetime is 138.24GJ (including 10% of losses over the whole lifetime since the capacity is reduced after 2,000 cycles), which delivers an average electric power per battery of 439W assuming a Cp of 0.0055 (80KW*0,0055=439W). In relation to their use as ellectric storage devices, in principle they could be used the rest of the time when the EV is not being used (i.e. 1-0.0055), which could be a significant potential. However, their extensive use would wear the batteries, effectively reducing its lifetime. For example, increasing their Cp 10x would translate into 20,000 cycles. Thus, in MEDEAS we assume that the electric batteries for EV can be used for electricity storage at a same Cp than for driving, i.e. that each battery would be able to function 10 years without wear (4,000 cycles).

Additionally, the material requirements for the additional grids to be constructed to integrate the renewable variable electricity generation as well as for the O&M of the grid are estimated. For the sake of simplification, in this model version we estimate the material requirements for grids as a function of the installed power of renewable variable electricity generation technologies (CSP, solar PV, wind onshore and wind offshore). The materials required for new grids are thus assigned to 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 26 documents the assumptions followed to estimate the material requirements of the electric grids in MEDEAS:

Table 26 : Material requirements for electric grids related to the RES variable electricity generation technologies

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

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

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 27 below for the detailed results.

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Table 27: material requirements (kg) per new MW installed. Source : own compilation.

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

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 2.4.3). Thus, for each mineral i, given its recycling rate (RR), its demand and extraction in mines are related as follows:

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

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

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

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

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

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

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 28 reports the 19 minerals analysed as well as their currently estimated level of reserves, resources and end-of-life-cycle recovery rate (EOL-RR). This set includes most of the minerals considered in (EC, 2010).

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Table 28: 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).

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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, NaNO2 and KNO3), we have analysed the impact of increasing the energy consumption for its extraction and refining 3-fold on the total energy cost of the energy plant (i.e. CED of the $EROI_{st}$, see section 2.4.4). After this, just three minerals emerge from the set as potentially problematic: copper, sodium nitrates ($NaNO_3$) and potassium nitrates (KNO_3). Thus, this 3-fold increase in the energy consumption for the extraction of copper would translate into an overcharge of +6.6% in the CED of the batteries and +4% in the CED of wind offshore (the technologies more affected). For the sodium and potassium nitrates, if mineral reserves would be depleted they could be obtained from organic sources with an overcharge in the CED of the CSP of at least +18%.[20]

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).

2.4.2.2. Implementation in MEDEAS

The demand of materials of the 6 energy systems and the rest of the economy (see section 2.4.1) 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 28).

---

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

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

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

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

2.4.3. Modelling of recycling policies in MEDEAS

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

Recycling rates can be defined in many different ways, from different perspectives (product; metal; metal in product) and for many different life stages; sometimes the term is even left undefined. In MEDEAS we apply the End-of-Life-Recycling Rate (EOL-RR), i.e. the percentage of a metal in discards that is actually recycled. Figure 50 reports the roughly estimated values of EOL-RR for all the elements of the periodic table at global level (UNEP, 2011). Table 28 reports the values used in MEDEAS for the minerals considered.

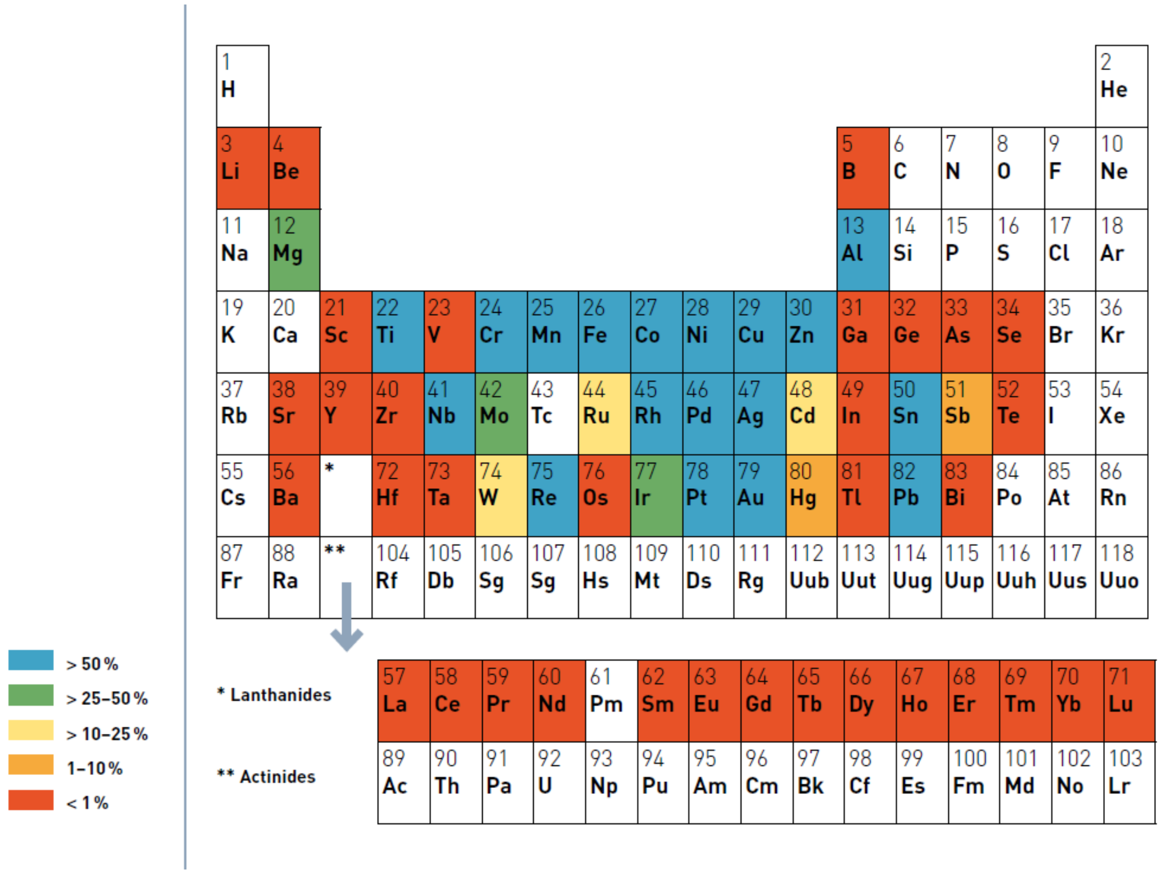

Figure 50 (UNEP, 2011): EOL-RR for sixty metals.

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

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

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recycling for the 19 minerals considered from current values (see Table 28) 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 28), the mean of the minimum and maximum is used.
- Given the lack of data for the reycling rates of the variable RES technologies at global level, and acknowledging that these modern technologies have likely a lower recycling rate due to the aforementioned reasons, we set the initial (current) EOL-RR rates for minerals for these technologies as been 1/3 of those of the aggregated economy.

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

Figure 51 shows the loop diagram of this policy:

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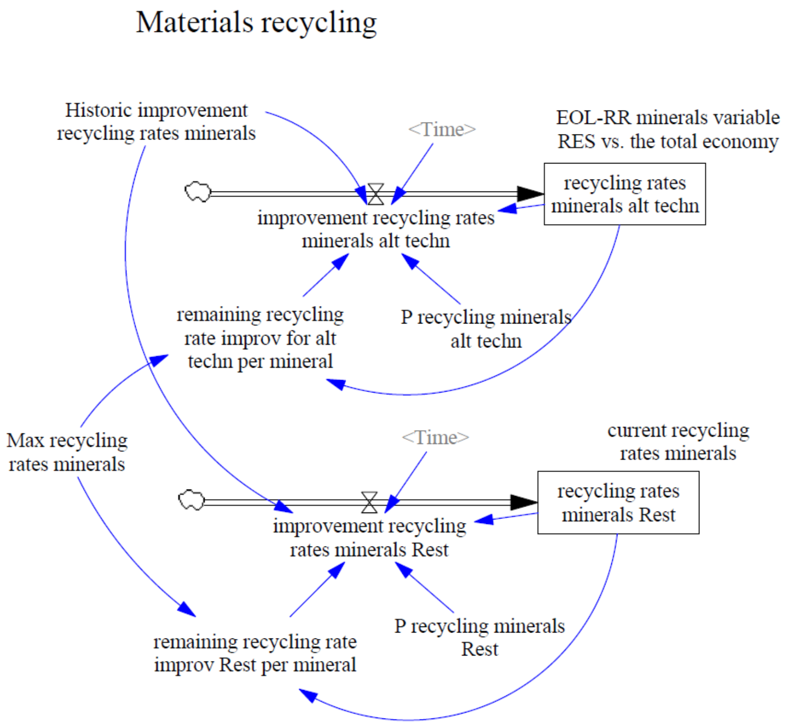

Figure 51 : Loop diagram of the mineral recycling policy in MEDEAS.

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 2.4.4.1),
- Dynamic approach for RES variables since we do have their disaggregated material requirements (section 2.4.4.2). The EROI from a static approach is also computed for the sake of comparison and in order to integrate the allocation function (see section 2.4.5).

2.4.4.1. EROI of RES dispatchables for electricity generation

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

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

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

i: electricity generation technology.

Annual elec output: Annual electricity output.

Cp: capacity factor.

Installed new cap: installed new capacity.

Lifetime: lifetime of the installed infrastructure.

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

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

$$EROI_i =$$

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

The previous equation can be directly applied for those technologies of electricity generation for which the material requirements for both new installed capacities and O&M are explicitly modelled (which correspond with the RES variables: solar PV, solar CSP, wind onshore and wind offshore) since MEDEAS dynamically estimates the CED$^{\text{New cap}}$ and CED$^{\text{O\&M}}$. 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[21]), we assume that the operation and maintenance are independent of the Cp and the self-consumption

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[21] 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 2.3.4.3).

losses are negligible. The current total CED per capacity (EJ/TW) per technology over the lifetime of the infrastructure ("Static EROI over lifetime") can be then derived as follows:

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

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

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

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

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

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

Both previous equations applying the "static" approach can still evolve over time considering the dynamic evolution of the capacity factor of each technology Cp$_i$(t) and the quality factor of the electricity g(t). And for the case of RES variables, CED can also vary depending on the recycling policies (see section 2.4.3).

- RES dispatchables:

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

- RES variables:

$$EROI_i(t) =$$

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

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

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2.4.4.2. EROI of RES variables for electricity generation

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

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

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

Cp(t) depends on the level of overcapacity.

$CED^{New\ cap}(t)$ and $CED_{O\&M}(t)$ depend on the recycling rates of the minerals (check consistency between numerator and denominator to be both in EJ). This parameter would capture the increasing energy cost of the decreasing ore grade of minerals in the case of having been included (see section 2.4.2).

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

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

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

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

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

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

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

Assuming that the initial EROI of hydro is 50:1 and its initial Cp 39.2%, the initial ESOI of PHS would be 12.7:1. We assume that the ESOI of the PHS decreases linearly until 5:1 when its maximum potential is reached (0.25 TWe, see section 2.3.4.5):

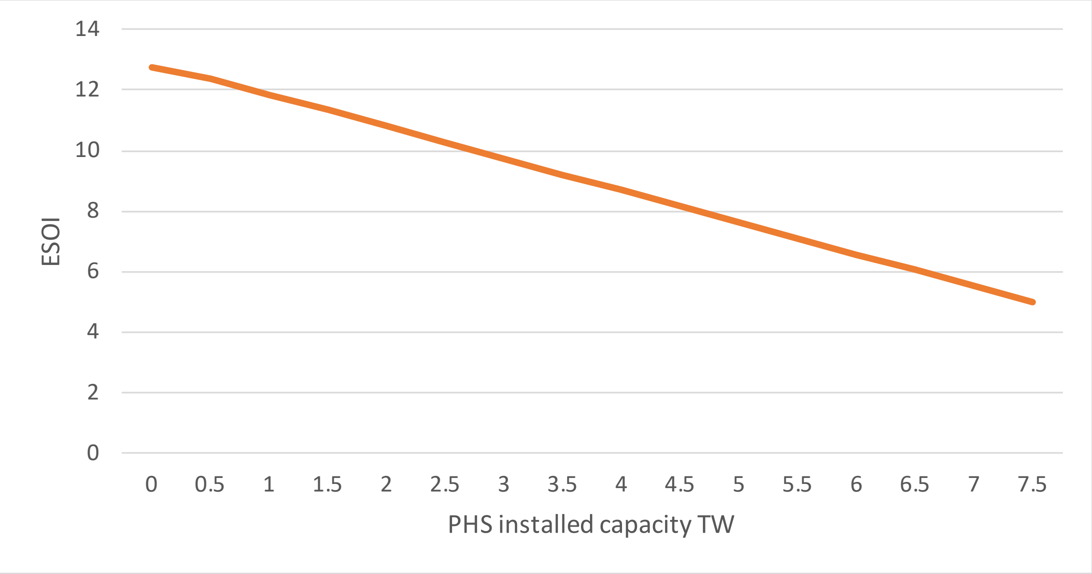

Figure 52: ESOI of PHS as a function of the installed capacity.

- EV batteries. ESOI=6.1 (own estimation, see section 2.4.4).

Given that the ESOI of PHS is higher than EV batteries for most of the potential of PHS (see Figure 52), 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 2.4.5).

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

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

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

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

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

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

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 2.4.4.2).

Table 29 : Energy consumption per unit of material consumption for virgin and recycled materials.

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

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Figure 53 shows the contribution of each of the 58 materials to the $CED^{New\ cap}$ and $CED^{O\&M}$ of each RES variable technology (assuming current mineral recycling rates). It can be observed that the main materials are: steel, cement, Al, electric/electronic components, Fe and site preparation for wind onshore (>80%); steel, site preparation and Al for wind offshore (>80%); glass, silicon wafer modules, Te, Fe, Al and diesel for solar PV (>90%); and synthetic oil, steel, Fe, site preparation and mined NaNO3 (>75%).

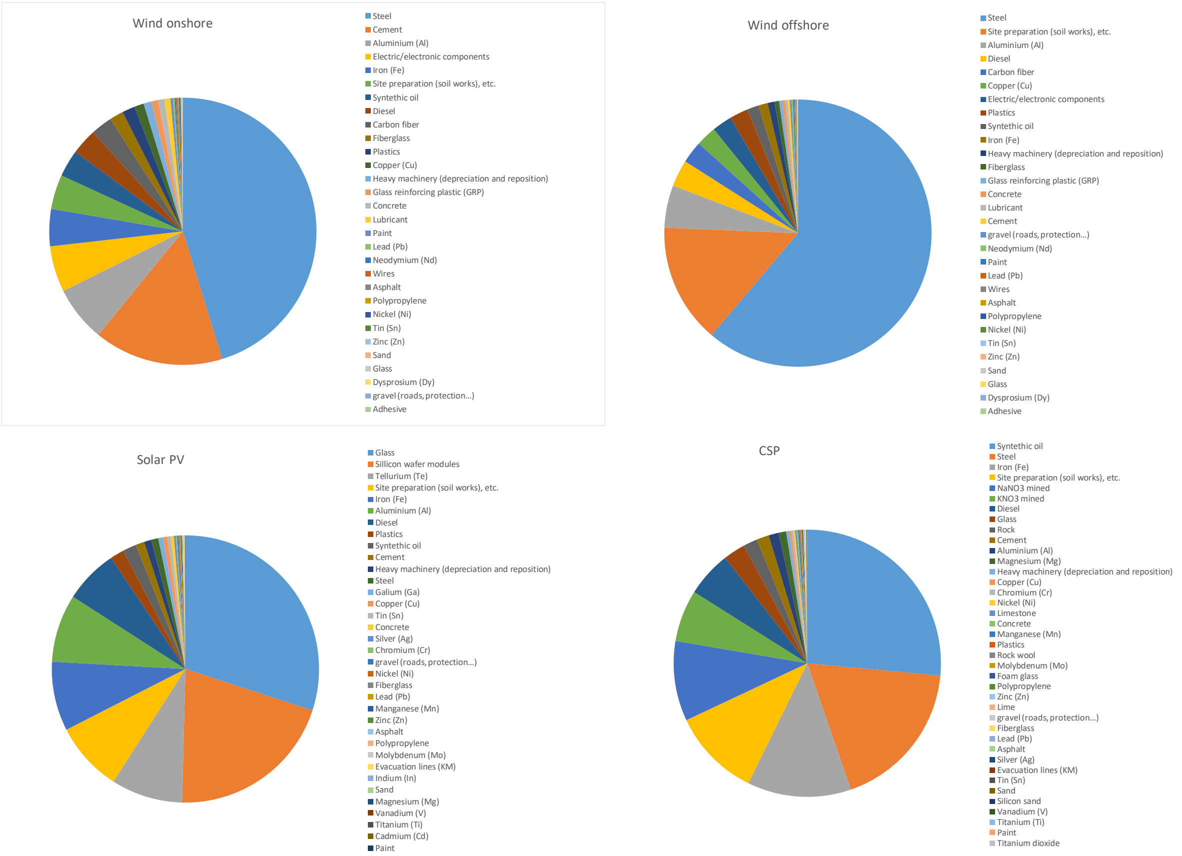

Figure 53 : CED for new installed capacity and operation and maintenance activities (O&M) per material and RES technology. If a material is not used then it is not showed in the legend. In the case of RES variables, it also includes also the material requirements for overgrids high power and inter-regional grids.

2.4.4.4. Summary of results

Table 30 reports the value of the EROI over lifetime (i.e. static definition) for the different electricity generation technologies considered in MEDEAS. Two considerations:

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

Table 30 ; EROI over lifetime for each of the RES technologies for electricity generation considered in MEDEAS. We take g(year=2015)=0.66) from MEDEAS. See section 0 for the recycling rates considered for estimating the EROI of dispatchable RES. Values of EROIpou can be estimated as EROIst-1. * EROIst including additional grids and storage is scenario dependent is not reported here.

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

Oceanic technologies such as tidal and wave are in an early phase of commercialization level and available data of the performance and LCA of real plants are very limited (MEDEAS, 2016a). For this reason, we have roughly estimated the EROI of these technologies taking wind offshore as a reference given the relative similarities betwen both technologies. The review of the literature reveals that ocanic plants are usually characterized by a Cp between similar levels than wind offshore to 50% lower (IRENA, 2014a, 2014b). As for the other electricity generation technologies, the expected Cp (projects) tends to be higher than the Cp from real plants (e.g. for the wave power plant of Mutriku in Spain, a Cp expected of 0.23 (Torre-Enciso et al., 2009) and a real Cp <0.1).

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Moreover, oceanic technologies are more material intensive in the construction phase (roughly >1000Tn/MW[22]), and necessitate higher O&M requirements due to higher exposure to salt water (submerged or in permanent contact). Thus estimating that the CED of these technologies might be around 1/3 higher than the CED of wind offshore (likely conservative), and accounting for a Cp 50% lower, the EROI of oceanic technologies can be estimated to be around half of the wind offshore EROI.

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

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

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

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

- 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, 2017; Hall and Klitgaard, 2012; King, 2016).
- Computing the dynamic EROI of each technology allows to prevent potential issues related with a "too fast" implementation of alternative technologies, i.e. the so-called "energy trap" (Kessides and Wade, 2011; Zenzey, 2013). Other net energy analyses in the literature have taken a static EROI approach (e.g. (Dale et al., 2012b; Sgouridis et al., 2016)) considering constant parameters such as Cp and g that in reality evolve with the penetration of RES in the electricity system. By computing both the static and dynamic EROI in MEDEAS we capture thus both perspectives: the total energetic cost over the lifetime (which drives the allocation of technologies, i.e. allowing to self-regulate the system) as well as the instantaneous «energy loss » at any time.
- Modelling from a net energy perspective allows to explore the implications for the whole system of the evolution of the EROI of the energy system. While the EROI levels are « high », 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

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« inteligent/correcting controls » (which could well be the case of the global socio-economic system), this process might produce a collapse of the system (Brandt, 2017). This way, the model allows to endogenously estimate the relevant EROI threshold (see section 2.4.4).

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.

<u>Description of the allocation rule implemented in MEDEAS</u>

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

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

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

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

The allocation rule in MEDEAS is defined assuming to fulfil the conditions represented in Table 31. This way, when the ratio between the EROI of each technology and the $EROI^{elec}_{tot}$ as estimated in the previous equation is 1:1, the growth in new planned capacity of this technology corresponds with the exogenous assumption defined by the scenario (variable "adapt growth RES elec"). We

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recall that the modelling considers that the growth in new planned capacity is affected by the proximity to fulfilling the maximum potential (see section 2.3.5.1).

Table 31: Assumptions to build the allocation rule of renewable technologies for producing electricity in MEDEAS.

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

A logarithmic expression was chosen in order to more rapidly remove from the mix those technologies which are characterized by a worse EROI ratio in relation to the EROI$^{elec}_{tot}$ (see Figure 54). 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.

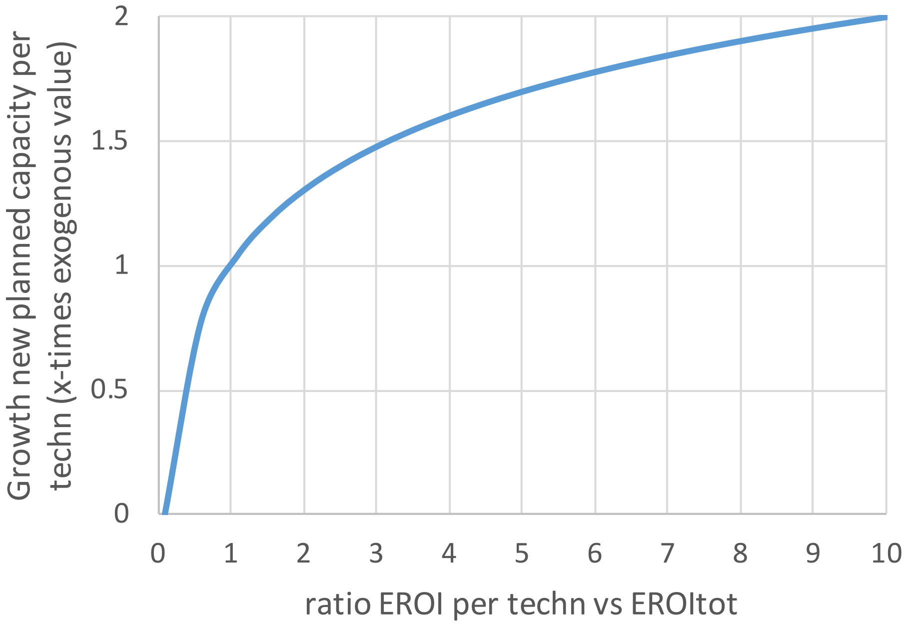

Figure 54 : Growth in new planned capacities per technology as a function of the ratio of its EROI and the EROIelectot.

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

Given the lower EROIst values of RES (see section 2.4.4) in comparison with the NRE ones (Hall et al., 2014), it is likely that the integration of this feedback has the potential to substantially affect the dynamics of the model. In fact, if properly integrated, a declining EROI should be able to trigger a collapse of the system below a certain threshold (<10:1 Hall et al., (Hall et al., 2009; Prieto and Hall, 2013), <5:1 (Brandt, 2017)).

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

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

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

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

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

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

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

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

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

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

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

Operating :

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

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

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

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

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

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

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

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

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

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

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

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

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

t_0=2015

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

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

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2.5. CO_2 emissions and climate submodule

2.5.1. Estimation of GHG emissions

The model computes the CO_2 and CH_4 emissions associated with the extraction and burning of fossil fuels (see Table 32). While CO_2 emissions are produced during the combustion of fossil fuels, CH_4 emissions are originated by the losses of methane during extraction, processing, transmission and distribution, notably of natural gas. Biofuels are far from being neutral carbon emitters due to Indirect Land Use Changes (ILUC); hence, in accordance with (European Commission, 2010; Fargione et al., 2008; Haberl et al., 2012; Searchinger et al., 2008), we assign a similar emission level than natural gas. Emission factors are considered constant over time.

Table 32: CO_2 and CH_4 emissions factor for non-renewable resources used in the model. Peat is assigned the same factor as for shale oil (IPCC, 2006). (1toe = 42GJ, i.e. 1tCO2/toe = 23,8gCO2/MJ). *In the absence of data, it was assumed the same emission coefficient of CH_4 than the respective conventional fuel from (Howarth, 2015) for CTL, GTL and unconventional oil.

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

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Resource		**Reference**	**Emission coefficient**	
			CO_2 [gCO_2/MJ]	CH_4 [gCH_4/MJ]
	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_2/MJ vs. 91.4 for the average of total unconventional oil. Since we have all unconventional oils in an aggregated manner, a function corrects the emissions related to total unconventional oil assuming that shale oil would follow the share in relation to total unconventional oil as estimated by (Mohr and Evans, 2010) (Low Case) for 2050 and 2100 (linear interpolation). Thus, the emission factor for unconventional oil considering shale oil higher emissions would be:

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

See below Figure 55.

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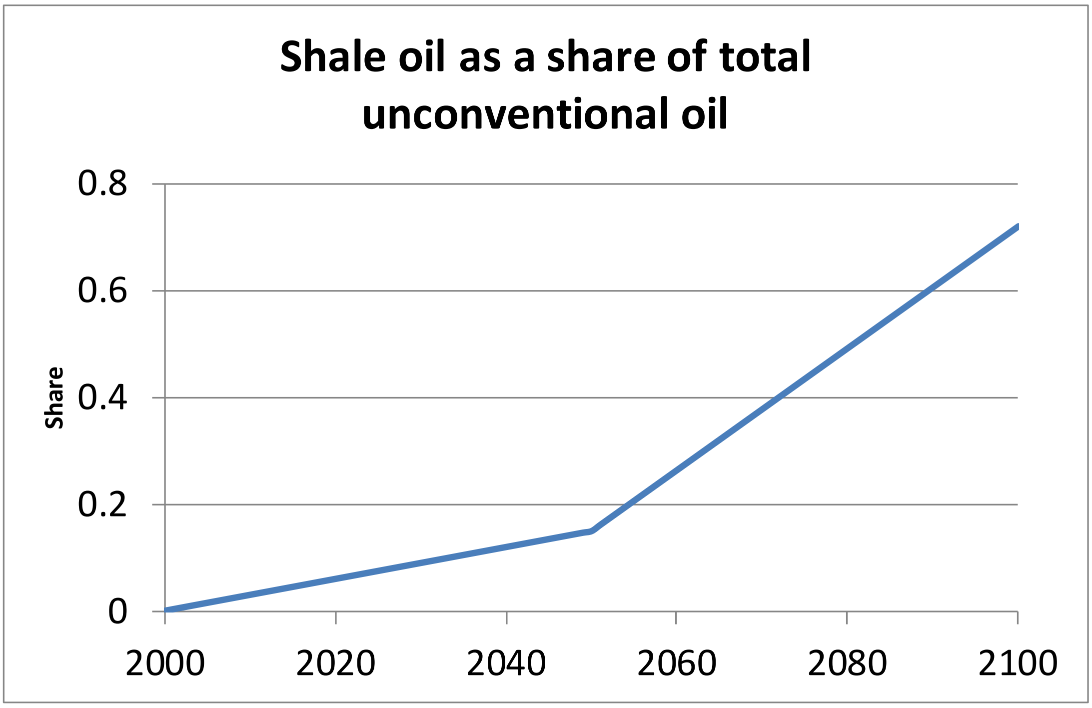

Figure 55: Shale oil as a share of total unconventional oil as estimated by (Mohr and Evans, 2010) (low case).

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2.5.2. Carbon cycle and climate model

In this model version we implement the afforestation as the only CO_2 sequestration policy. As reference we use the work from (Nilsson and Schopfhauser, 1995) that analyzed the changes in the carbon cycle that could be achieved with a large global afforestation program covering 345 MHa. Thus, a maximum carbon capture of 1.5 GtC/year 50 years after the start of the program would be attained. Other technologies such as CCS are not considered in this study due to their uncertain development and benefits (Fischedick et al., 2008; Scott et al., 2013).

This model version includes a simplified representation of the climate. The climate submodel of DICE-1994 (Nordhaus, 1994, 1992) has been implemented (with updated parameters from the DICE-2013R (Nordhaus and Sztorc, 2013) which allow to compute for CO_2 concentrations,[23] radiative forcing and temperature change. Exogenous assumptions for land-use change emissions and other GHGs are also considered.

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

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[23] In comparison, the previous methodology based on assuming that, in the period studied, the ocean and ground will continue to absorb 45% of total emissions as in the past (Canadell et al., 2007) is in good agreement with the DICE climatic submodel version up to 2050, however beyond the mid-century the discrepancies reach discrepancies of around 20%.

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".[24] In fact, the literature review of environmental catastrophes shows that such events strongly impact the GDP level right after the catastrophe, and that even decades later after such events the GDP level is lower than the level which would have been reached without catastrophe (Hsiang and Jina, 2014; Kousky, 2014).

Policy-recommendations to propose sustainable alternatives to the current trends are usually derived from the application of energy-economy-environment models, or Environmental Integrated Assessment Models (IAMs). However, there is a large discrepancy between natural scientists' understanding of ecological feedbacks and the representations of environmental damage (if any) 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, 2016).

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

---

[24] As described by (Kousky, 2014): "This is a reference to Frédéric Bastiat who, around 1850, wrote about a shop owner whose window was broken. Some onlookers convinced everyone that it was actually better for the economy because now the window-fixer would be employed and he would pay others, and so on, creating ripple effects in the economy. Our intuition suggests that the simple destruction of capital should not be a net benefit, and the error in the fallacy is the neglect of the fact that had the shop owner not needed to repair a window, he would have used the funds elsewhere—the broken window did not create new economic activity, but just diverted funds from one use to another. Similarly, owners of homes destroyed by tornadoes or hurricanes would have spent money elsewhere that they instead have to use for rebuilding."

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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_2e concentrations and total radiative forcing as drivers of climate change alteration instead of temperature increases since:
    - Global environmental change is not solely driven by temperature increase (e.g. ocean acidification is driven by CO_2 concentration increase); climate is defined by many factors such as humidity, winds, solar radiation, etc.
    - Thus, the PB of climate change is defined by these two variables (350 ppm and +1.0 W/m^2 relative to pre-industrial levels) (Steffen et al., 2015),
    - The large uncertainty on equilibrium climate sensitivity do not affect the policy-making process (focus on targets such as the carbon-budget (IPCC, 2014b)).
(5) No discounting of impacts (inter-generational equity).

The implementation of the damages from environmental/climate changes in MEDEAS is performed through the integration of an ELF that reduces the overall net energy delivered to the society, assuming that when climate change reaches a certain threshold not compatible with humanity as it is nowadays configured, the energy losses would reach 100% of the total energy supply (see Figure

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56). 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.

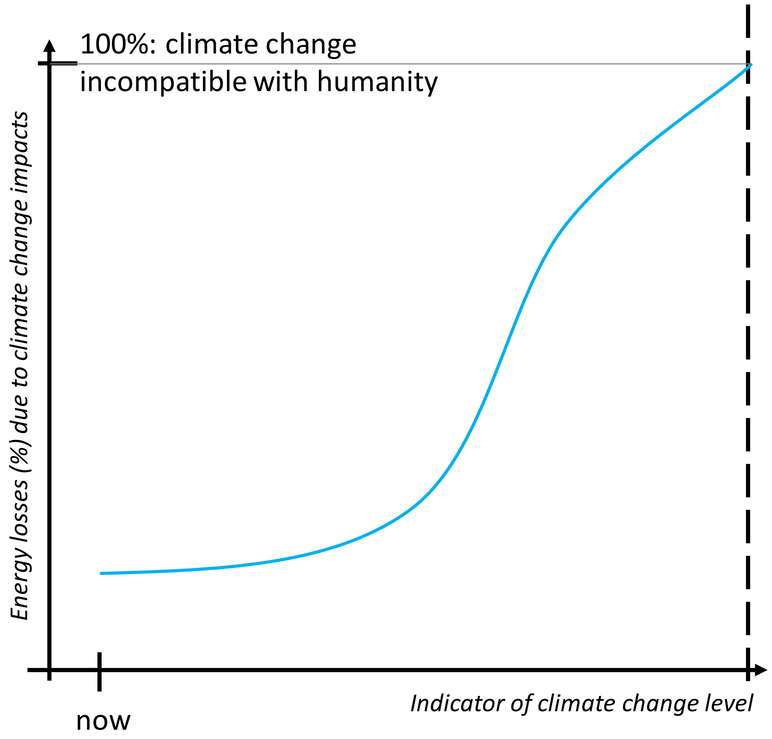

Figure 56: Qualitative representation of the energy loss function (ELF) applied in the MEDEAS framework.

In the standard version of MEDEAS an ELF with a logistic shape that uses CO_2 concentrations from the combustion of fossil fuels and land-use change as climate change indicator is implemented. This function assumes a very low contribution of damages nowadays and takes 1,000 ppm as the threshold of climate change incompatible with humanity:

$$E_{loss}(a;b) = 1 - \frac{1}{a+e^{\frac{ppm-a}{b}}}$$

The parameters a and b are selectable by the user. In the standard version of MEDEAS the following parameters are implemented by default:

- a= 600: 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.

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 57):

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

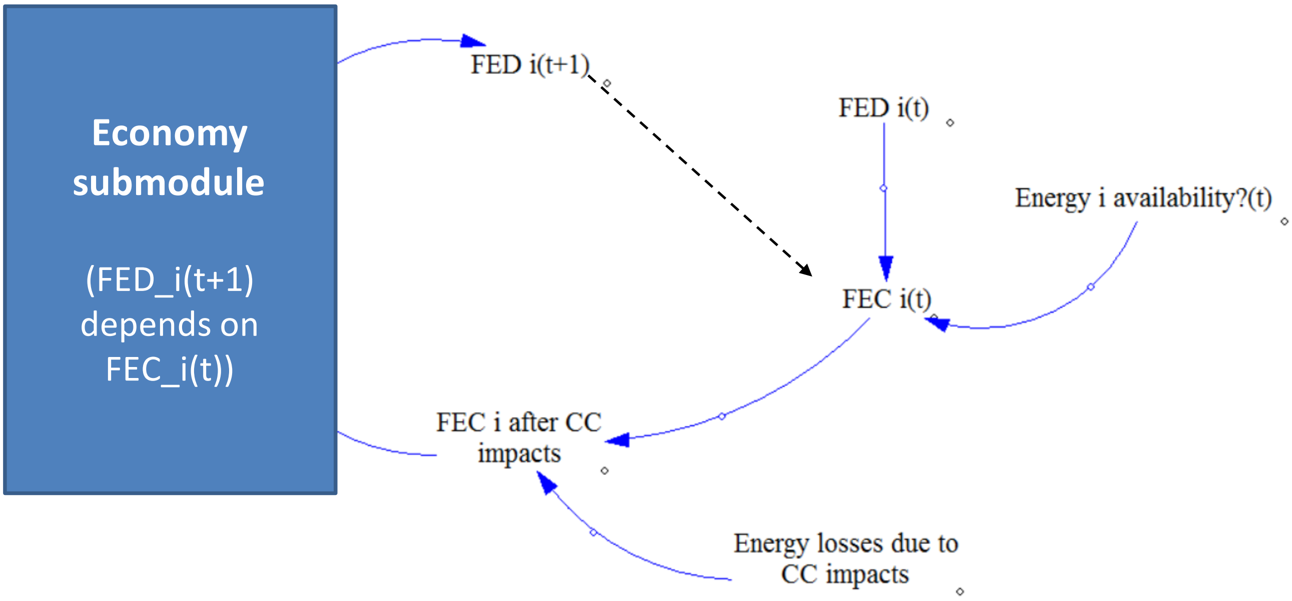

Figure 57: Implementation in MEDEAS framework of the energy losses due to climate change impacts.

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2.6. Land-use module

The land-use module in MEDEAS has two main objectives:

- Estimation of the land-use change GHG emissions: including positive anthropogenic emissions as well as potential ways of capturing carbon,
- Land availability as a potential restriction for RES deployment, with a focus on biomass, solar and hydro.

A simplified model was built in which population, GDP as well as diet patterns conform the non-energy land demand; low carbon policies promote the expansion of RES and climate change impacts tend to decrease the arable model (Figure 71) the module of land-use in the current version of MEDEAS has not been finally integrated in the full MEDEAS framework as initially programmed (see (GEEDS, 2016)), mainly given to the complexity of the design and integration within the rest of the structure of the model.

Thus, in the current version of MEDEAS an effort has been done to implicitly account for the land-use limitations for RES deployment (see for example the section 2.3.4.1 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).

The meaning of “good life” and what is a desirable society has been discussed probably for millennia. In the last decades, several alternative approaches to defining and measuring quality of life were suggested. According to (Diener and Suh, 1997), these are (1) social indicators such as health, education, etc.; (2) subjective well-being measures (assessing people’s evaluative reactions to their lives and societies, such as self-reported happiness); and (3) economic indices. These indicators come from three approaches to well-being that are based, respectively, on normative ideals (the more education we have, the better), subjective experiences, and the ability to produce or purchase goods and services (measuring income or levels of production).

The main aim of this module in MEDEAS framework is to translate the behaviour of each model scenario into a set of variables that provide information about its social dimension. This is a complex and delicate task, since, in fact, social dimensions such as education, health, culture, life expectancy, etc. depend on more dimensions that the ones modelled in MEDEAS, which mainly evolves through energetic and (to a lesser extent) monetary variables. Thus the computation of indicators such as HDI is in principle further the scope of the project (the computing of subjective well-being measures such as “happiness indexes” is obviously discarded). Thus, the followed approach consists on reporting outputs which can be obtained from the current version of the model. MEDEAS does not report “a” variable to measure welfare. We consider that welfare is a multidimensional feature which cannot be reduced to a single variable (UN, 1990). In place, we illustrate the social evolution of each scenario assessing a set of variables. We complete the information with the reporting of key environmental impacts indicators given that well-being is intrinsically linked to a healthy environment, able to provision ecosystem services (Daily, 1997; Levin et al., 2009; Schneider and Morton, 1981). How energy forces and infrastructures interrelate with institutions and ideations of political power are beyond the scope of the project (Boyer, 2014). The construction of this set of indicators was assisted by the D2.2 Task e (MEDEAS, 2016b).

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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 (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 58). Despite its shortcomings (e.g. (Fleurbaey and Blanchet, 2013; Ranis et al., 2006; Sagar and Najam, 1998) the HDI is yet the most accepted indicator to assess the development of a country.

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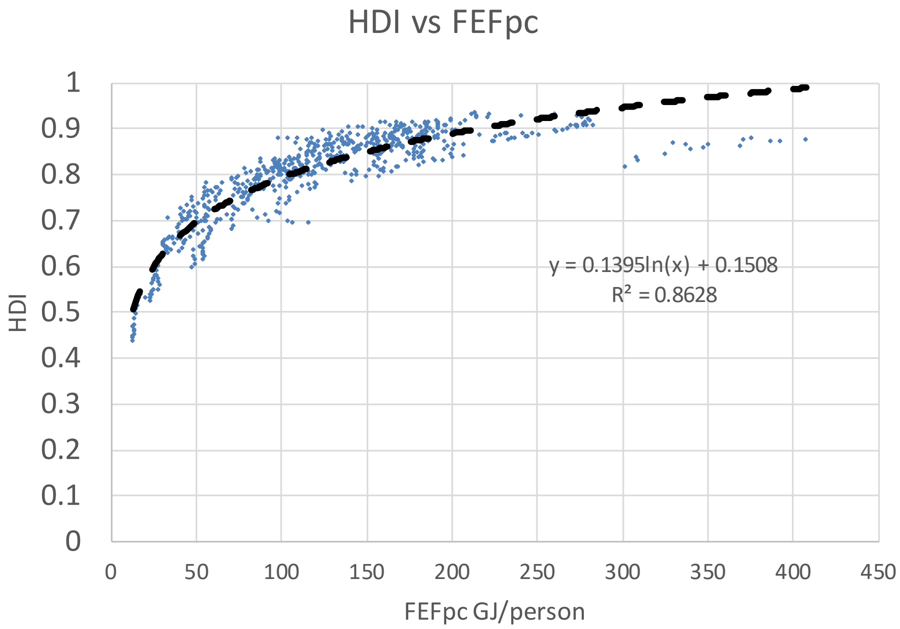

Figure 58: HDI vs Final Energy Footprint per capita (FEFpc) for 40 countries (1995-2009). Source: own work from data from (Arto et al., 2016). Regressions published in the paper refer to primary energy, however from the point of view of the quality of life and in the context of scenarios of penetration 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 2.4.4, the EROI of some of the key RES systems are far from the historical values of fossil fuels, on which our society currently relies. Thus, to assess the feasibility of the scenarios a net energy approach is fundamental (Carbajales-Dale et al., 2014).

We also focus on the potential level of climate change through variables such as GHG emissions per capita and temperature increase levels over pre-industrial levels. Despite MEDEAS explicitly incorporates a feedback to the energy and economic system of the climate change impacts, it is still important to track the evolution of climate change to assess the scale of potential impacts.

Hence, in MEDEAS framework we identify as social indicators the following variables:

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

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

7.3.1 Energy intensity measured in terms of primary energy and gross domestic product (GDP)

8.1.1 Annual growth rate of real GDP per capita

9.4.1. CO2 emission per unit of value added

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Future developments of MEDEAS-World/MEDEAS-EU might expand number of social and environmental impacts indicators, which could in some cases help to endogenize some currently exogenous variables of the model, as well as expand the assessment of other planetary boundaries beyond climate change:

- Equity indicator (monetary and energetic). In fact, equitable resource allocation has been found as a central element of stable and sustainable scenarios (Motesharrei et al., 2014)
- Net employment balance of the transition to RES (i.e. accounting also for the employment loss in NRE technologies)
- Land use by type per capita (Forest, arable, RES production, buffer for biodiversity, etc.), which allow also to compute environmental impacts indicators such as the Global Assessment of Human-induced Soil Degradation (GLASOD)
- Material consumption per capita
- Life expectancy (e.g. through impacts of climate change (Crimmins et al., 2016; WHO, 2014)
- EROI of the whole system (standard, point of use, extended)
- Net primary production (NPP) is the rate of organic matter synthesized by photosynthesis by producers minus the rate of energy rate used for respiration and other damages. NPP integrates aspects of five of the currently defined planetary boundaries (Steffen et al., 2015): land-use change, freshwater use, biodiversity loss, and global nitrogen and phosphorus cycles. It is also influenced directly by two others, climate change and chemical pollution.
- Ecological Footprint

Thus, further developments of the model might allow to estimate the following indicators from the Sustainable Development Goal Indicators (UN, 2015) within MEDEAS framework:

8.4.1 Resource productivity

11.3.1 Ratio of land consumption rate to population growth rate

15.1.1 Forest area as a percentage of total land area

15.3.1 Percentage of land that is degraded over total land area

2.8. Alternative energy technologies considered in MEDEAS

Two criteria have been applied for the choice of the modelling of alternative energy technologies in MEDEAS 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 2.8.1),
- Hydrogen (section 2.8.2),
- Nuclear fast breeders and nuclear fusion (section 2.8.3).

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2.8.1. Carbon capture and storage (CCS) and negative emissions

Carbon capture and storage (CCS) usually refers to the technological process of capturing emitted CO_2 from large point sources, such as fossil fuel power plants, transporting it to a storage site, and depositing it where it will not enter the atmosphere, usually an underground geological formation. Still, power plants combined with CCS are not a free-source of carbon since their GWP can be reduced just by 63–82% and other environmental impacts such as acidification and human toxicity are higher with than without CCS (Cuéllar-Franca and Azapagic, 2015). Despite extensive research and development in the last decades, no large fossil-fuel power plants are currently using CCS at commercial level, and publicly supported demonstration programmes are struggling to deliver actual projects, such as the European NER3000. There is in fact large uncertainty in relation to the future technical and commercial availability of large-scale CCS (Reiner, 2016; Scott et al., 2013).

The rapid application of carbon capture and storage is a much heralded means to tackle emissions from both existing and future sources. The combination of advanced bioenergy and CCS (BECCS) has been assessed in the last IPCC report as the most critical technology in the context of the timing of emission reductions. This is due to the fact that, while GHGs continue to grow globally and we approach the carbon-budget, the possibility to make the transition to low-carbon technologies without removing emissions from the atmosphere fades. As a result, models targetting stabilization scenarios below 2ºC (or 2.6 W/m2, i.e. RCP2.6) include substantial amounts of BECCS to be deployed along the century (Anderson and Peters, 2016; Fuss et al., 2014; IPCC, 2014c; Smith et al., 2016; Vaughan and Gough, 2016).

In relation to the net energy balance and given the lack of estimates in the literature, we have roughly estimated the EROI of energy systems for electricity production burning coal and bioenergy with and without CCS. We have selected coal since it is the fossil fuel with higher EROI and larger estimated resources, and bioenergy since, as aforementioned, most IAMs strongly rely on BECCS to deliver stabilization scenarios. Firstly, it should be highlighted that in the literature about the processes of capture, transport and storage of CO2 from fossil fuel plants (coal and gas mainly) is strongly biased towards techno-optimism. For example, the Cp usually considered in these theoretical studies is 0.9 while data of real power centrals shows Cp values of 0.5-0.6 for coal and 0.6 for natural gas (IEA, 2016a; Shearer et al., 2016). Besides the correction of Cp, the following factors have been taken into account based on literature review:

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- CCS energy penalty, i.e. the operation of CCS incurs in supplementary energy losses to the power plant. The review of LCA studies shows a range of 16-44% for fossil fuels, with a rough average of 30% (Corsten et al., 2013; Haszeldine, 2009; Schreiber et al., 2012; Viebahn et al., 2007). Cormos (2012) found that in the case of coal power plants, the consumption of coal increases +25% with CCS to generate the same electricity output.
- Oversizing of the plant to integrate the CCS mechanism (which also increases the energy requirements for plant dismantling). For example, Hammond and Spargo (2014) estimate that the oversizing of the power plant to integrate the CCS mechanism reduce 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 33)

Table 33 shows the results taking into account the EROIst of each energy source (coal or bioenergy), the additional energy requirements for the CCS process, the energy requirements for plant dismantling and the energy requirements for the operation of the electric network. The following equations shows how the efficiency of each energy system i can be estimated from the EROI (or efficiency) of each phase j accounting for the current quality factor of the electricity (g):

$$\chi^{i} = \prod_{j} \chi_{j}^{i}$$

$$X_{j}^{i} = 1 - \frac{1}{EROI_{j}^{i}}$$

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

For example, the estimation of the EROIst of coal+CCS energy system is obtained as follows (taking into account the factor of Cp correction and the energy requirements for the construction and O&M of the electric network):

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

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

Table 33 reports the estimated EROI_{st} and EROI_{pou} of coal and bioenergy power plants with and without CCS.

Table 33: EROI estimation of coal and bioenergy power plants with and without CCS.

	Coal	Coal+CCS	BioE	BioE+CCS
EROIst of energy source	46 (Hall et al., 2014)		2-3 (de Castro et al., 2014)	
Energy penalty of CCS operation	0	+25% (Cormos, 2012) and literature review (see text)	0	As for coal+CCS
Additional energy requirements for building the CCS infraestructure	0	0.57% (middle of the range from (Schreiber et al., 2012))	0	As for coal+CCS
Energy requirements for plant dismantling	0.2% (Schreiber et al., 2012)	2.62% (middle of the range from (Schreiber et al., 2012))	As for coal	As for coal+CCS
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)			

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EROIst of energy system	14.7	4.6	2.7 – 3.7	1.9 – 2.1
EROIpou of energy system (=EROIst-1)	13.7	3.6	1.7 – 2.7	0.9 – 1.1

In the light of the results presented in Table 33, current coal power plants have an EROI clearly > 10, which allow them to positively contribute to the energy balance of the society. The introduction of the CCS devices implies a drastic reduction of its EROI to below 5:1 level. In particular, the EROIpou of 3.6:1 implies that just to compensate its inherent energy losses, an overcapacity of almost +40% would be required. In the case of BECCS, the results are even worse, given that we find an EROIpou < 1. In the light of these results, the technology BEECS would be an energy drain rather than an energy source. in other words, BECCS technology should be rather considered as a technology to store carbon at an energy cost.

Additionally to the uncertainty in relation to the future technical availability of CCS, its expected high cost and the low energy balance of BECCS, the deployment of large amounts of bioenergy crops faces biophysical constraints due to the requirement of large areas, high fertilizer and water use, and that likely compete with other vital land uses such as agriculture of biodiversity conservation (Anderson and Peters, 2016; Fuss et al., 2014; Kartha and Dooley, 2016; Scott et al., 2013; Smith, 2016) (see also section 2.3.4.1 on land competition).[25] In fact, a recent expert elicitation focusing on the potential of BECCS concluded that assumptions regarding the extent of bioenergy deployment, and development of adequate societal support and governance structures for BECCS are unrealistic (Vaughan and Gough, 2016). Direct air capture has less area and water needs than BECCS and no fertilizer equipment, but it has high energy use, has not been demonstrated at scale, and cost estimates exceed those of BECCS (Hansen et al., 2016b; Smith et al., 2016).

For example, in relation to land occupation, a recent review found that <2ºC stabilization scenarios in IAMs require a range of 380-700 MHa by 2100 for BECCS (considering high-productivity dedicated energy crops), which represents 7–25% of current global agricultural land, and 25–46% of arable plus permanent crop area, a range of land demand which is the magnitude order than land identified

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[25] The logistics of collating and transporting vast quantities of bioenergy globally —equivalent to up to half of the total global primary energy consumption— is also seldom addressed.

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as abandoned or marginal (Smith et al., 2016). These calculations refer to 3.3 Gt Ceq/yr of negative emissions, i.e. just ~25% of the total GHG emissions in 2010 (IPCC, 2014c).

Follows a back-of-envelope calculation considering more realistic/average parameters. For the case of biopower from a short-rotation poplar with clones on degraded lands in Siria and with the use of fertilizants, (Dillen et al., 2013)Dillen et al. found an average gross energy power of 1,1 We/m2 (i.e. > 10x larger than the typical ranges of net power density found in the literature). Applying this density and taking into account the carbon content of dry biomass (47.5% (Schlesinger, 1991)), 6,9TnCO2/Ha·yr would be emitted by the burning of the biomass. Since CCS capture at most 90% of emissions, this system would require 1 Ha to absorb 6Tn of CO2 (without taking into account of the indirect emissions during the process of making available the biomass). Thus, these calculations indicate that to absorb 10% of the current emissions over 650 Mha of fast growing trees should be dedicated to this end.

Thus, it is very likely that the use of bioenergy for negative emissions impacts the amount of land available for food, biodiversity and other human uses if scaled substantially.

Additionally, IAMs and LCAs usually assume bioenergy carbon neutrality, i.e. that the CO2 released from their combustion matches the CO2 uptake during feedstock growth. That convention is premised on globally complete carbon accounting in which biogenic emissions are not counted in energy sectors when carbon stock changes are counted in land-use sectors. However, when accounting for biogenic emissions in soils, real examples show that the extraction of biomass disbalance the soil carbon cycle, provoking unintended additional emissions (or additional supplies such as fertilizers which also imply additional emissions during their life-cycle). For example DeCicco et al., (2016) found for USA that «carbon uptake on cropland was enough to offset only 37% of the biofuel-related biogenic CO2 emssions… [far] from the 100% assumption made by LCA and other GHG accounting methods that asume biofuel carbon neutrality ».

Hence, the dependence of the majority of policy-influential models such as the integrated assessment models participating in the IPCC processes on these speculative technologies affected by such uncertainties, large biophysical requirements and extraordinary costs which may be never available at the timing and scale required, is problematic. Some authors have suggested that the pervasive inclusion of these speculative technologies is a consequence to fine-tune the analyses to conform to dominant political and economic sensibilities rather than to sound scientific modelling (Anderson, 2015; Spash, 2016). Moreover, the expectation that this technology may be available in the future provides a justification for building new fossil fuel power centrals that may be adapted in the future, exacerbating the problem of lock-in infrastructures. Given the risks at play, we judge that

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a precuationary principle approach is more sensitive for policy-advice. Thus, for these reasons, in MEDEAS we do not consider that CCS technology will be available in the future at the (early) timing and (extensive) scale required.

In contrast, we decided to focus on the potential of carbon capture in soils through land management practices and afforestation which are already available, low cost demonstrated technologies (Hansen et al., 2016b; Houghton et al., 2015; IPCC, 2014c).

Recommended Management Practices (RPM) such as crop rotations, low and no-tillage practices, cover crops, holistic management of pastures, agroforestry, use of manure and biosolids and precision irrigation have a great potential to enhance the soil organic carbon (Jarecki and Lal, 2003; Smith et al., 2008). According to FAO (2017), for example, no-till practices have an estimated potential of carbon capture sequestration that ranges from 0 to 150 kgC ha-1/year in warm and dry climates, and to 100 1 000 kgC ha-1/year in humid and cool climates. Although more research in this field is needed, and the actual values of these potential are questioned by same researchers (Baker et al., 2007; Powlson et al., 2011; Sommer and Bossio, 2014), RMP's are technologies interesting by themselves since their adoption increases soil quality and agronomic yield, therefore, they do not necessarily compete with food production and might be profitable for farmers, instead of requiring extra economic investments as BECCS do. In particular, increasing the carbon stock in the soil plays a role in four important ecosystem services: resistance to soil erosion, soil water retention, soil fertility for plants and soil biodiversity; being also a key policy for climate adaptation in many regions of the globe.

In relation to the potential of afforestation and reforestation, Kartha and Dooley (2016) found a potential of 370-480 GtCO2 of negative emissions based in ecosystem restoration and reforestation (0GtC02 for BECCS). However, these options also face land limitations: annual negative emissions of 1.1–3.3 Gt Ceq yr$_{-1}$ would require 320–970 Mha, representing 6–20% of total agricultural land, and 21–64% of arable plus permanent crop area, a range of land demand which corresponds with the magnitude order of land identified as abandoned or marginal (Smith et al., 2016). These negative emissions refer to just to 8-25% of the total GHG emissions in 2010 (IPCC, 2014c).

However, it should be kept in mind that the first step towards a land system which would store carbon would be to reverse the current trends, since currently ~10% of global emissions are from land-use changes. This growing trend endures the last centuries, and its reversal may well imply radical socio-economic changes (Kartha and Dooley, 2016).

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2.8.2. Hydrogen/« Renewable hydrogen economy»

Hydrogen commercialization began in Europe and the US in 1930 for industrial uses. Currently, every year over half a billion cubic metres of hydrogen are produced (mostly from natural gas in industrial processes but mostly as raw material for various other chemicals and not as a fuel (Abbasi and Abbasi, 2011)), i.e. an energy capacity equal to over 10 % of oil consumed. Its applications are expanding towards electrical production associated to a fuel cell with a wide potential range of uses, particularly in transport. Among its advantages: clean fuel if hydrogene generated from RES, high energy capacity (in mass account) in comparison to other storage options (although still 1 kilo of hydrogen equals 3.5 l of oil but 1liter of hydrogen at atmospheric condictions equals to 13KJ – termal-, 5,6MJ at 700bar versus 35,8 MJ of diesel); potential improvement in energy safety if generated by local RES; contributes to mitigate the intermittency of the main RES and has the potential to be used in a wide spectrum of applications. Nevertheless, hydrogen has three serious limitations, i.e. it is a secondary fuel, thus energy must be used to obtain it; it needs to be stored at high pressure (especially in vehicles), since it is the most volatile gas ; and has a relative low efficiency (Bermejo, 2014, chap. 14; Ehteshami and Chan, 2014).

Excepting for solar and biomass, the rest of RES technologies require an electrolyzer to generate H_2, which is a process with an efficiency of around 60-70% (Abbasi and Abbasi, 2011; Levene et al., 2007), while fuel cells operate with efficiencies ranging 40-60% (Bermejo, 2014, chap. 14). This indicates that for most technologies the efficiency of the whole transformation RES electricity-hydrogene-electricity is around 1/3,[26] which is really poor. In terms of net energy analysis, it has been estimated that energy stored on energy invested (ESOI) of RES electricity-hydrogene-electricity is close or even below to 1. In this context, it would be energetically better to curtail than to store as hydrogene.

When the energy source is direct solar, it can be converted to hydrogen via both electrolytic and direct conversion routes. Intensive efforts are also being made to generate hydrogen from anaerobic digestion of biomass and biowastes, but, as of now, success hasn’t been achieved (Abbasi and Abbasi, 2011).

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[26] (Bernal-Agustín and Dufo-López, 2008) also report an efficiency of the whole chain RES electricity-hydrogene-electricity of around 30%.

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In terms of deployment timing, the IPCC reports that "during the second-half of the century, many integrated studies also include substantial shares of electricity and/or hydrogen to fuel electric and fuel-cell light-duty vehicles" (IPCC, 2014c), confirming the current immature state of this technology.

From the point of view of net energy analysis, few estimates of the ESOI of the whole chain exist in the literature, although the high costs of the technology indirectly indicate a low energy return on energy stored. Hacatoglu et al., (2012), for example, find that the EROI of the transformation of electricity from wind and solar to hydrogen would be 1.8 and 0.7 respectively, i.e. an ESOI of the whole chain electricity-hydrogene-electricity clearly < 1 for both RES technologies assuming a fuel cell efficiency of 50%. These results are confirmed by Mori et al., (2014) who also find ESOI levels <<1.

Summarizing, the "renewable hydrogen economy" is estimated to be a marginal option in the MEDEAS timeframe due to its current unfavourable net energy output (ESOI<1), which makes that other alternative technologies for energy storage such as PHS and electric batteries seem better options. For example, in MEDEAS the ESOI of PHS ranges between 12.7 and 5 :1 (see section 2.4.4.2).

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2.8.3. Nuclear fast breeders and nuclear fusion

Breeder reactors refer to plutonium-fueled nuclear power plants that could produce more fuel than consumed. This technology started to be researched as early as during the World War II in the USA by scientists in the atomic bomb program. A recent report from the International Panel of Fissile Materials concluded for the current status of this technology that « such reactors are expensive to build, complex to operate, susceptible to prolonged shutdown as a result of even minor malfunctions, and dificult and time-consuming to repair ». These are the same words than an expert in the field reported in 1956 (Cochran et al., 2010). Thus, despite enormous breeder research funding beetween 1950-2007 (tens of billions of dollars), this technology has still to surmount technical difficulties and is thus far from reaching commercial level. These reactors have failed to be a safe and reliable source of energy; accidents and long shutdowns have characterized fast breeder reactors reseach. For example, during the Superphénix French project life time (the biggest ever made) the Cp was less than 7%). In fact, most experimental reactors in Rusia, USA or France have been suspended. Cochran et al., (2010) conclude: « After 6 decades and tens of billions of dollars, the promise of breeders… remains… unfulfilled and [funding] is cut back [dramatically] in most countries ». Thus, we assume that fast breeders will not be available in the timeframe of MEDEAS.

Nuclear fusion is not considered since the ITER and DEMO projects estimate that the first commercial fusion power would not be available before 2040 (http://www.iter.org), which would prevent this technology to substantially contribute to the mix in the timeline of MEDEAS.

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3. Tested scenarios

MEDEAS model needs assumptions about the world socio-economic evolution (such as expected economic growth, population evolution or technological progress) as external inputs. Running models can be a cumbersome task when the models have several parameters, assumptions and policies that can be varied at the same time. In order to establish those inputs in a coherent and sensible way, scenario methodology is usually applied. The current standard set of scenarios in climate change research are the Shared Socioeconomic Pathways (SSPs). The SSPs are a set of five qualitative descriptions of future changes in demographics, human development, economy and lifestyle, policies and institutions, technology, and environment and natural resources. The narratives are intended as a description of plausible future conditions at the level of large world regions that can serve as a basis for integrated scenarios of emissions and land use, as well as climate impact, adaptation and vulnerability analyses (MEDEAS, 2017a; O'Neill et al., 2017). In this report we apply the SSP2 scenario from the climate change modelling community in the MEDEAS-World framework, which constitutes a scenario similar to a BAU (continuation of current trends). We follow the approach of "adaptative scenarios" presented in Task 3.3.c (MEDEAS, 2017b); i.e. the inclusion of biophysical feedbacks and constraints modifies the exogenous assumptions of the scenario. We call that scenario SSP2-baseline.

Subsequently, we apply a set of policies to try to mitigate GHG emissions to safe levels below the carbon budget. We refer to this scenario as SSP-OLT (optimum level transition, D3.3 (MEDEAS, 2017a)). However, this exercise should be understood as a strategic analysis rather than a planning one, given that world-level policies do not currently exist. For example, in the case of the promotion of the transition to 100% RES, although in regions such as EU, Australia and Oceania a strong support exists, in peripheral countries of the world economy the energy access debate overshadows the 100% RES debate, in others such as USA political and socio-economic barriers to this transition are also important (REN21, 2017).

The section is organized as follows: section 3.1 describes the SSP2 narrative, section 3.2 describes the quantitative drivers and parameters used to run the SSP2.

3.1. SSP2 – Middle of the Road

This scenario is also referred as Dynamics as Usual, or Current Trends Continue, or Continuation, or Muddling Through. In this world, trends typical of recent decades continue, with some progress towards achieving development goals, reductions in resource and energy intensity at historic rates, and slowly decreasing fossil fuel dependency. Development of low-income countries proceeds unevenly, with some countries making relatively good progress while others are left behind. Most economies are politically stable with partially functioning and globally connected markets. A limited number of comparatively weak global institutions exist. Per-capita income levels grow at a medium pace on the global average, with slowly converging income levels between developing and industrialized countries. Intra-regional income distributions improve slightly with increasing national income, but disparities remain high in some regions. Educational investments are not high enough to rapidly slow population growth, particularly in low-income countries. Achievement of the Millennium Development Goals is delayed by several decades, leaving populations without access to safe water, improved sanitation, medical care. Similarly, there is an only intermediate success in addressing air pollution or improving energy access for the poor as well as other factors that reduce vulnerability to climate and other global changes. Literature Context for SSP2 can be found on the D.3.3 (MEDEAS, 2017a).

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3.2. Quantification of the scenarios

For the implementation of SSP2-baseline and SSP2-OLT in MEDEAS the exogenous drivers of population evolution and expected GDP growth from IIASA D3.3 (MEDEAS, 2017a) have been used (see Figure 59).

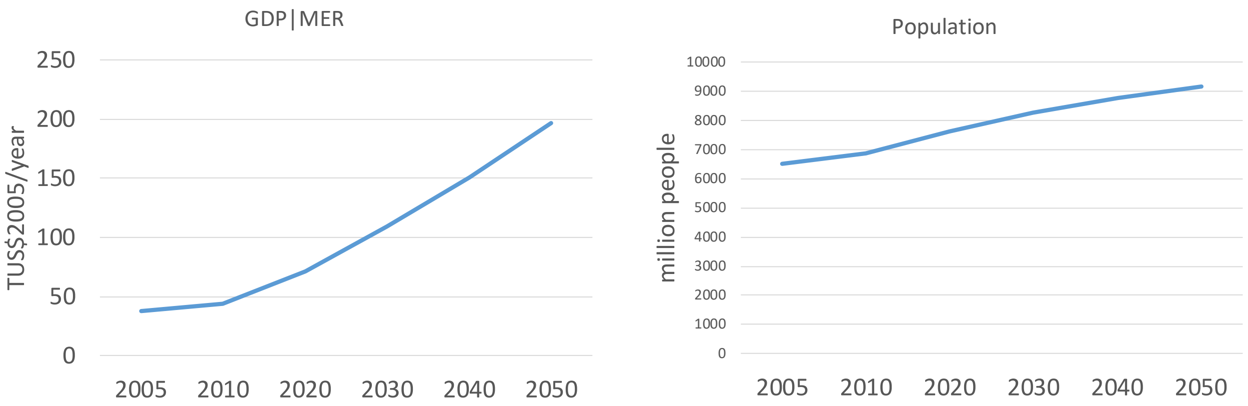

Figure 59: GDP and population growth quantification of the SSP2 from D-3.3 (MEDEAS, 2017a).

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

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

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

- Higher deployment of RES for electricity, biofuels and heat,
- (Slight) increase in nuclear power,
- Higher electrification (and shift to hybrid) of transport,
- Higher recycling rates of minerals,
- Activation of a global afforestation programme to capture carbon,
- A lower importance of technologies such as CTL and GTL,
- Reducing the share of oil in electricity and heat consumption.

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

Both scenarios share the same characteristics in terms of required GDPpc required, population evolution and fossil fuel and uranium endowments, among others.

4. Results and discussion

This section reports the main results of MEDEAS-W 1.0 model up to 2050 with the scenarios described in the previous section (SSP2-Baseline and SSP2-OLT). (Note for interpreting the legend of the figures: BAU refers to SSP2-Baseline and SCEN refers to SSP2-OLT).

As expected, population grows following the exogenous path imposed. GDPpc grows for all scenarios until the early 2020s, when they reach a maximum at ~7,500 1995US$ per capita, declining thereafter until < 4,500 1995US$ per capita in 2050 (Figure 60). Total GDP for the SSP2-Baseline reaches a maximum at around the same date and declines thereafter, while the SSP2-OLT manages to maintain a roughly constant level at ~60 T$1995 until the mid-2030s, when it starts to decline. Ultimately both scenarios reach a total GDP by 2050 which are roughly the same than current levels. Thus, as a first result, both scenarios depict a world in clear recession by the mid-century. However, we will see in the next figures that the underlying behaviour of each model differs.

For example, in terms of energy intensity intensity, large differences are appreciated between each scenario (Figure 61). While for the Baseline the total primary energy supply (TPES) intensity as well as the total final energy supply (TFES) maintain, or even slightly improve current levels, the OLT scenario is characterized by increasing energy intensity during the next decades. By sectors, the energy intensity of transport decreases at a rather fast pace in the OLT due to the policy of electrification of the transportation. This can be seen in the energy intensity of electricity, which increases for the OLT scenario while slightly decreasing for the Baseline. There is however another factor influencing the TFES and TPES intensity: the EROI. The massive penetration of RES technologies drives the EROI of the system to low levels, thus increasing the energy invested for obtaining energy in the system (Figure 61)

Figure 63 shows how, excepting for liquids, the consumption of final energy fuels (electricity, heat, gases and solids) increases substantially along the next decades for the OLT scenario. In both scenarios, electricity is projected to cover the greatest share of total final energy consumption by 2050. Figure 6 and Figure 65 show how the contribution of RES in scenario OLT increases substantially along the century. However, in terms of electricity although the potential of RES is not depleted, by 2040s the limitations to the penetration of RES variables in the mix start to be important due to the proximity of the fulfilment of the potential of electric storage (intermittency limit). On the other hand, the potential of RES for heat is depleted by the end of the century for both scenarios.

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Transportation is another key sector. Figure 66 shows the most relevant outputs for both scenarios. For example, the number of electric light duty vehicles in OLT reaches 400 million by 2050, which corresponds with ~1/3 of the total of light duty vehicles in that year. Altogether, electrification policies allow to save around 25% of the final energy dedicated to transport by 2050. These scenarios reveal a paradox: the strong promotion of electrification of transport in OLT scenario would provoke that the system may encounter problems of electricity supply due to the limits of RES intermittency.

Total primary energy supply reaches a plateau for OLT until 2040, while in BAU it starts to decreases already in the 2020s.

In terms of material availability, we recall that the current version of MEDEAS does not constraint the supply of minerals. However, MEDEAS tracks the consumption of a set of minerals key for RES technologies, and compares the cumulated demand with the current estimated level of reserves and resources (Table 34). In terms of resources, in the SSP2-Baseline the only mineral which may suffer supply limitations is the Tellurium. In the OLT, the list includes also Indium and Manganese. From the point of view of reserves, the list enlarges substantially, including in both scenarios elements such as Cadmium, Chromium, Gallium, Lithium, Lead, Silver, Tin or Zinc. Moreover, we observe that there is a trade-off between higher deployment of RES and recycling policies since the SSP2-Baseline scenario includes some elements that may suffer scarcity that are not reported as problematic for the SSP2-OLT (the case of copper o nickel).

Table 34: MEDEAS results. Material availability by 2050 for each scenario. Comparison of the cumulative extraction by 2050 with the level of reserves and resources. “x” indicates that cumulated extraction > reserves/resources.

	SSP2-Baseline		SSP2-OLT	
	reserves	resources	reserves	resources
Aluminium				
Cadmium	x		x	
Chromium	x		x	
Copper	x			
Gallium	x		x	
Indium	x		x	x
Iron				
Lithium			x	
Magnesium				
Manganese	x		x	x
Molybdenum				
Neodymium				
Nickel	x			
Lead	x		x	
Silver	x		x	
Tin	x		x	
Tellurium	x	x	x	x
Titanium				
Vanadium				
Zinc	x		x	

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In terms of land-use, the deployment of RES would substantially increase its land-use requirements. Figure 67 shows that the contribution of crops for biofuels (both in competition and marginal lands), solar PV, solar CSP, hydro and onshore wind would require an amount of ~300 MHa by 2050, i.e. a similar surface to the currently urban land.

Despite the diversity in type and magnitude of the policies applied in OLT, Figure 70 shows that the system still reached dangerous levels of climate change surpassing 450 ppm and the 2°C threshold by 2040 (Figure 70). This causes that climate change impacts become more and more important along the next decades.

MEDEAS also computes a number of energy indicators (Figure 68). The average TPES per capita without accounting for the people relying on traditional biomass is ~100 GJ/pc until 2030 and declining thereafter to 55-65 GJ/pc by 2050 (lower for the SSP2-Baseline). As a reference, we compare with the energy use threshold (in terms of total primary energy footprint) of 106 GJpc found by (Arto et al., 2016) to reach high development (HDI>0.8), and the approximative energy use value to fulfil the acceptable standard of living (in terms of total primary energy use) of 30-40 GJpc (Goldemberg, 2001; Rao et al., 2014; WBGU, 2003). These results indicate that, in the absence of a distribution of the energy supply at global level, most population will remain at low levels of development from the perspective of industrial-consumerist economies. The average FEC and electricity consumption per capita follow similar trends, the latter ranging between 3,500 kWh/person for the OLT and ~2,700 kWh/person for the Baseline by 2050.

Figure 69 shows some of the social and environmental impacts indicators computed by MEDEAS. As previously mentioned, the constraints on economic growth make that since the mid-2020s the annual GDP is 0 or negative both scenarios. The expansion of RES technologies for electricity and heat generation drives an increase in the jobs created by this industry, which could reach 20 million by 2050 in the OLT scenario. For both scenarios, the carbon footprint by 2050 would halve.

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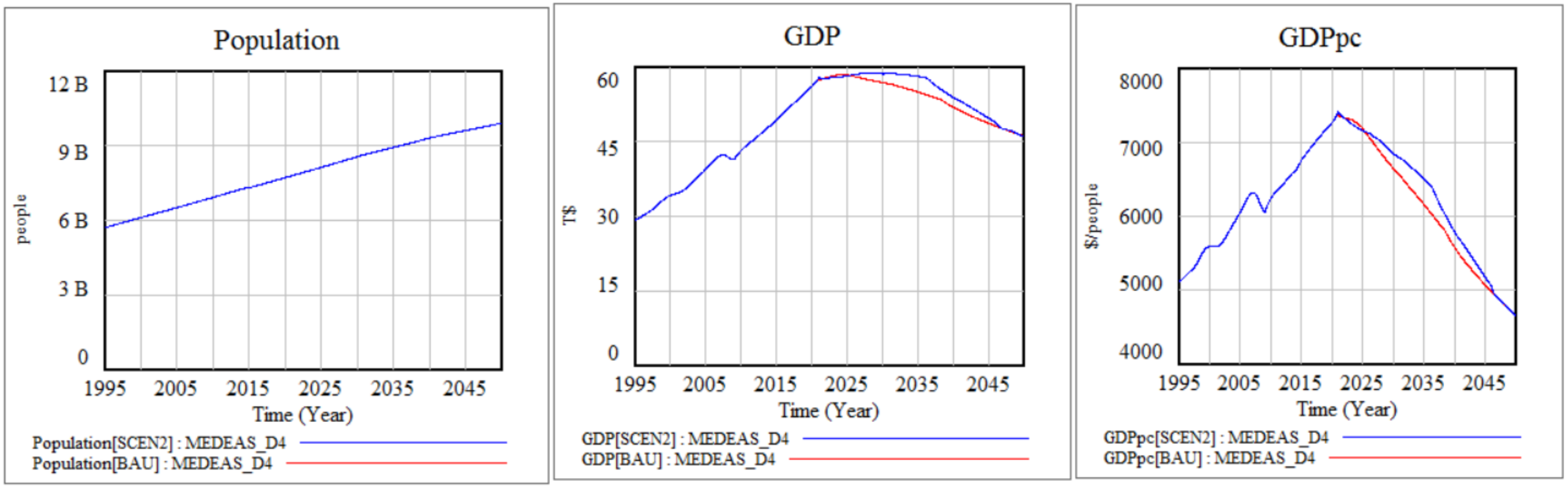

Figure 60: MEDEAS results: GDP and Population. Note to interpret the legend: BAU refers to SSP2-Baseline and SCEN refers to SSP2-OLT.

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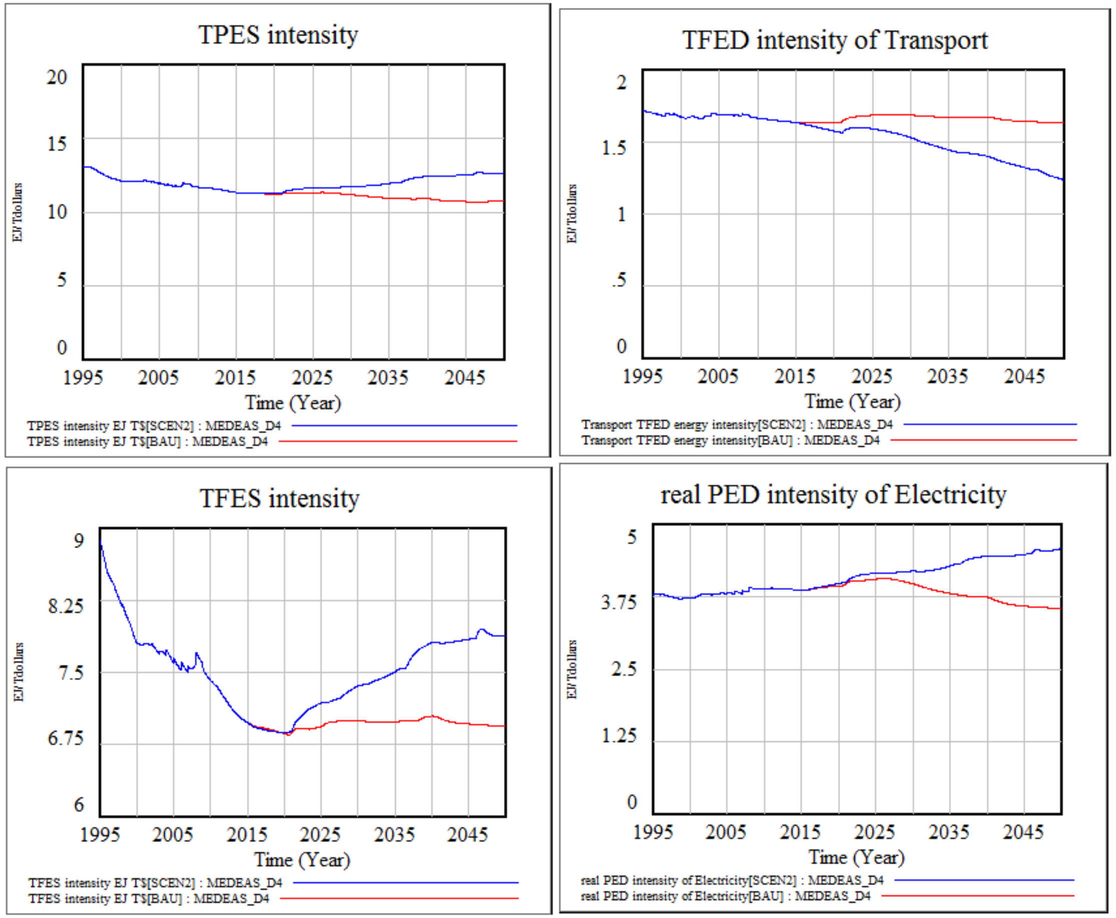

Figure 61: MEDEAS results: Energy demand intensities evolution. Note to interpret the legend: BAU refers to SSP2-Baseline and SCEN refers to SSP2-OLT.

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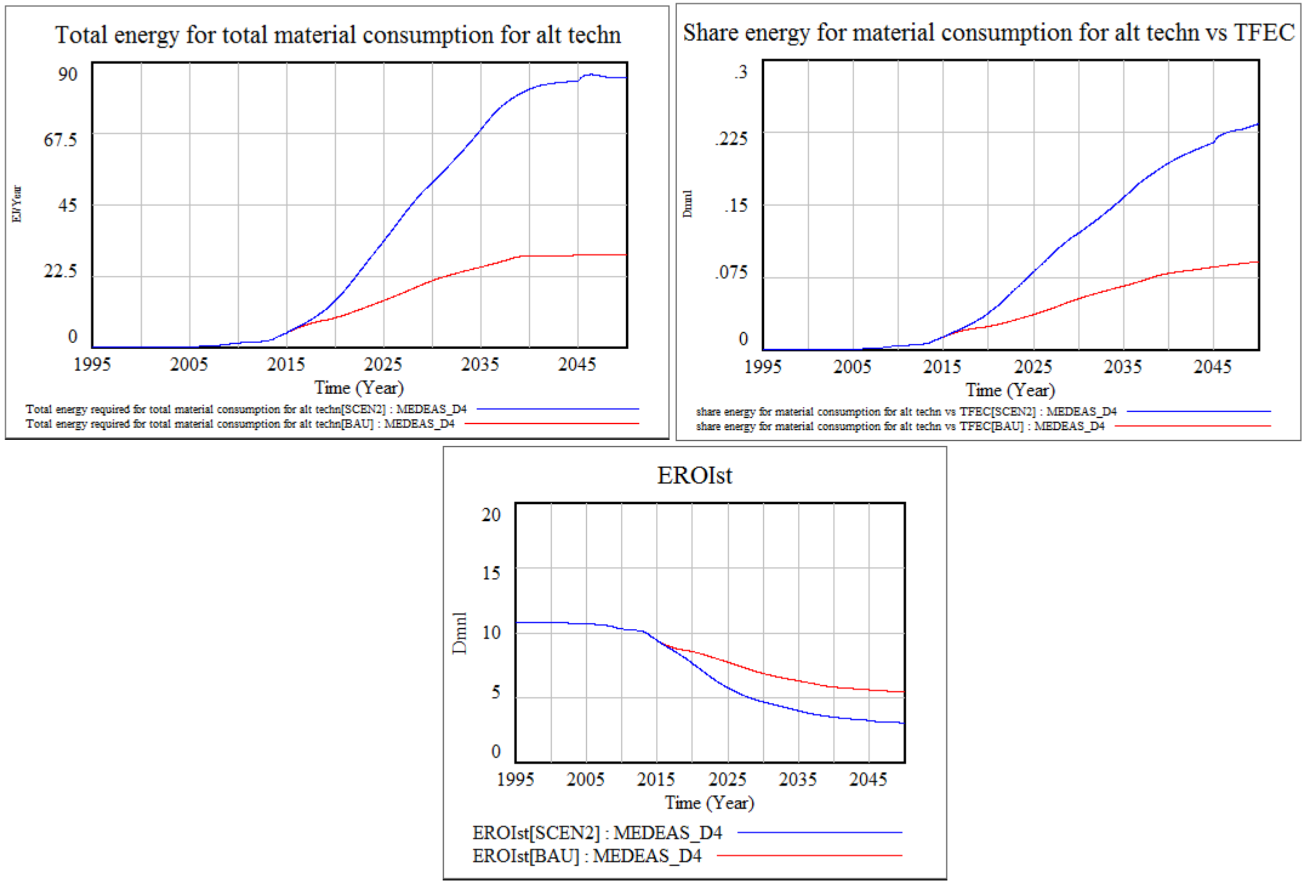

Figure 62: MEDEAS results: Total energy for material consumption for RES technologies for electricity (and its share in relation to TFEC), as well as evolution of the EROI of the system. Note to interpret the legend: BAU refers to SSP2-Baseline and SCEN refers to SSP2-OLT.

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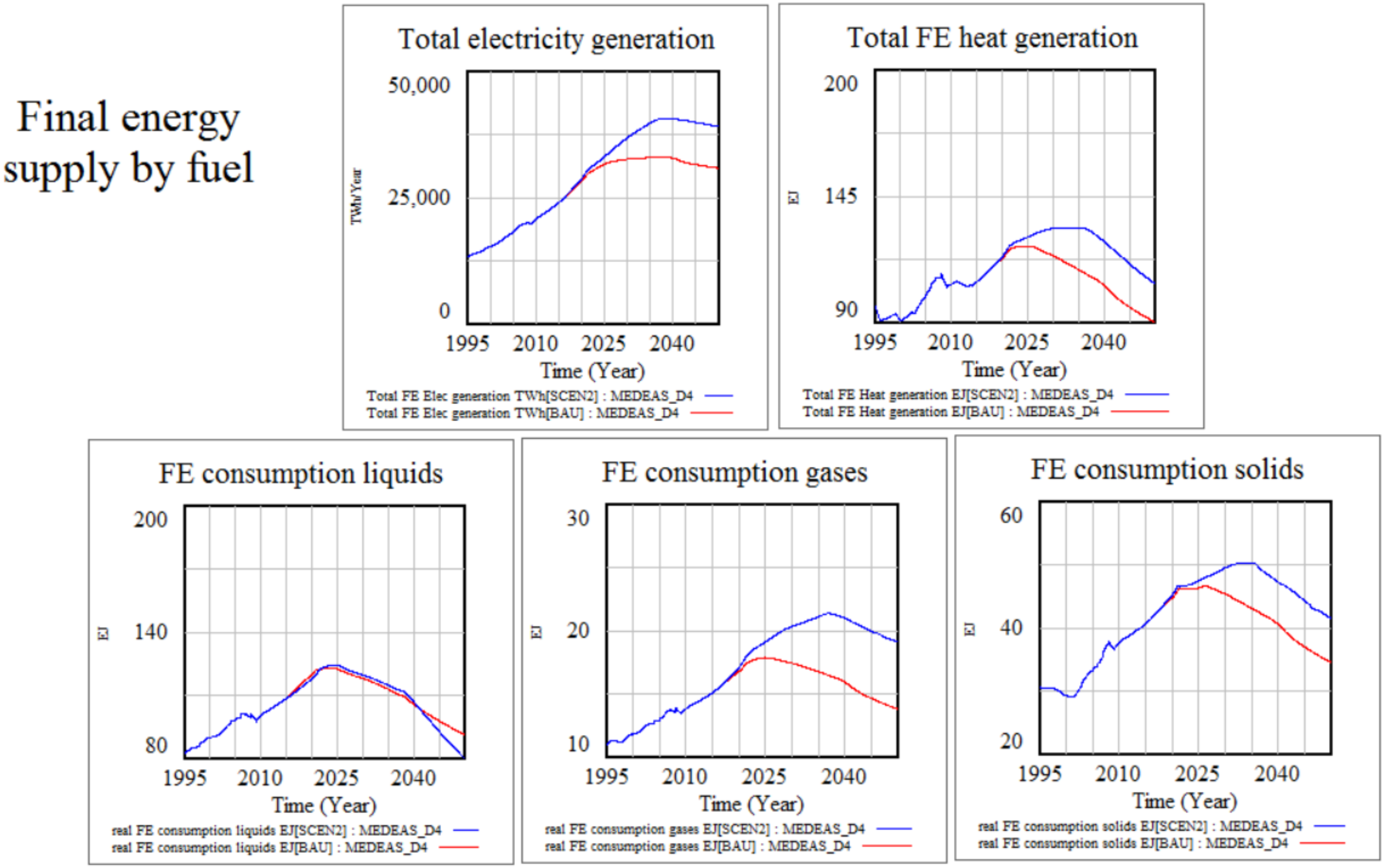

Figure 63: MEDEAS results: Final energy supply by fuel. Note to interpret the legend: BAU refers to SSP2-Baseline and SCEN refers to SSP2-OLT.

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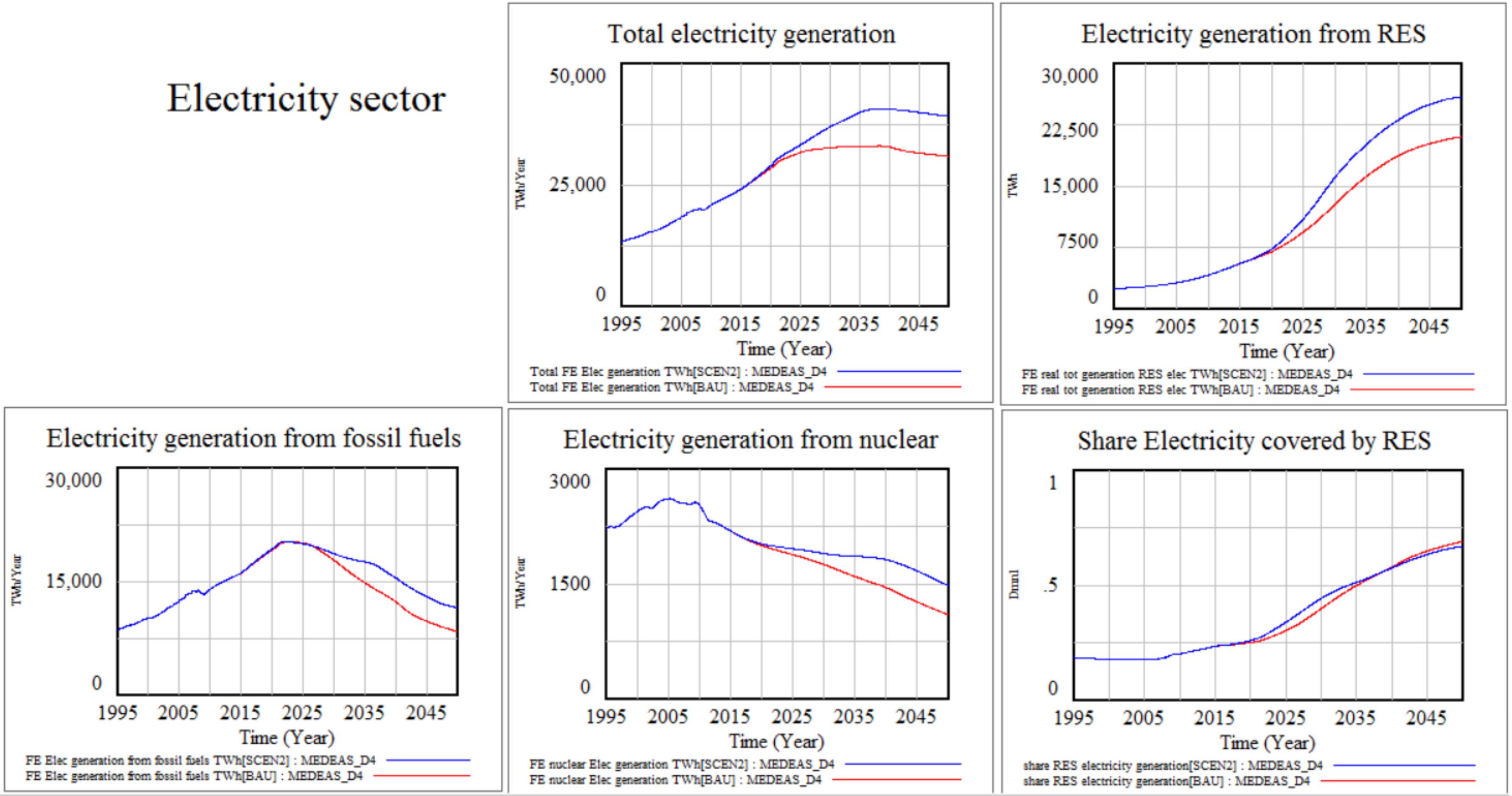

Figure 64: MEDEAS results: Electricity sector. Note to interpret the legend: BAU refers to SSP2-Baseline and SCEN refers to SSP2-OLT.

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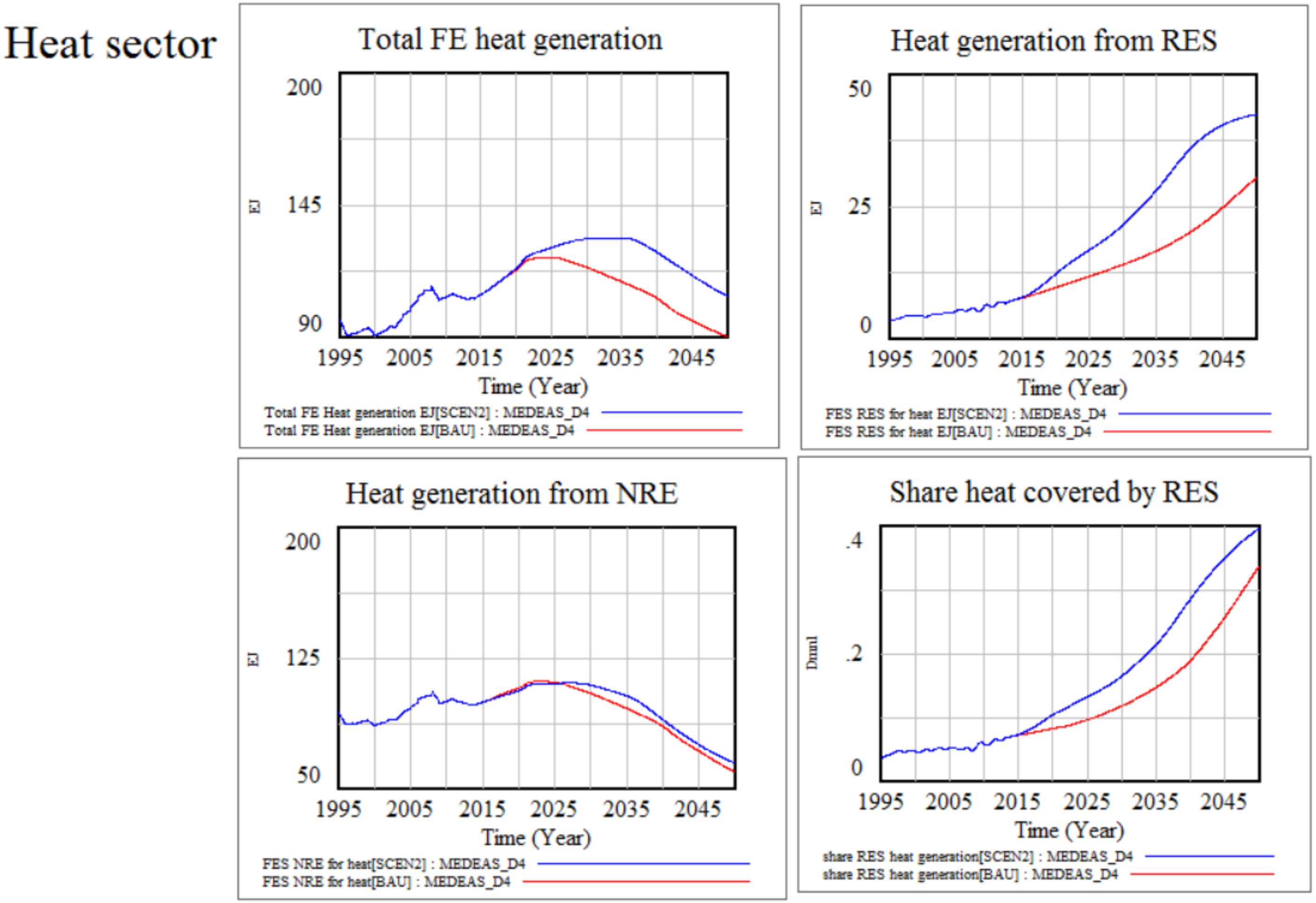

Figure 65: MEDEAS results: Heat sector. Note to interpret the legend: BAU refers to SSP2-Baseline and SCEN refers to SSP2-OLT.

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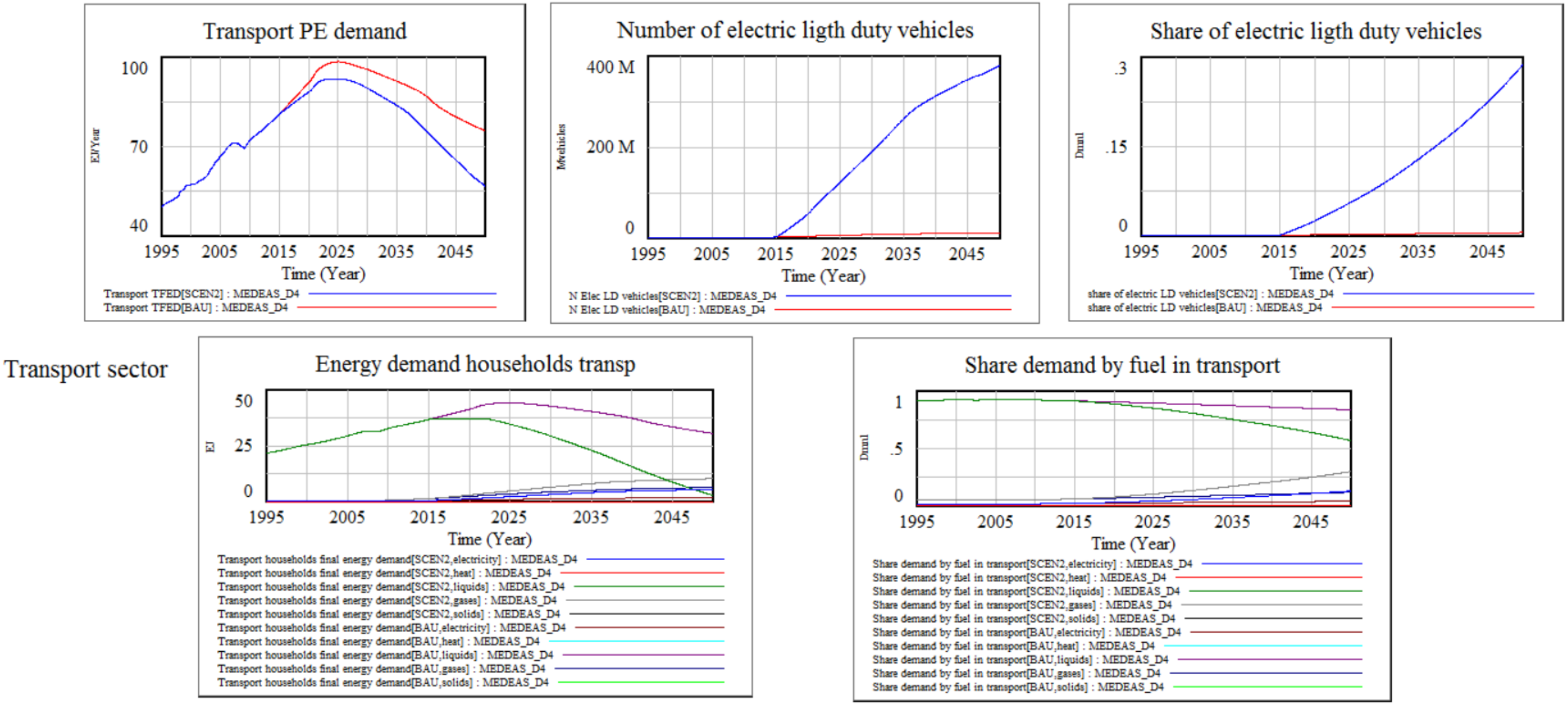

Figure 66: MEDEAS results: Transportation sector. Note to interpret the legend: BAU refers to SSP2-Baseline and SCEN refers to SSP2-OLT.

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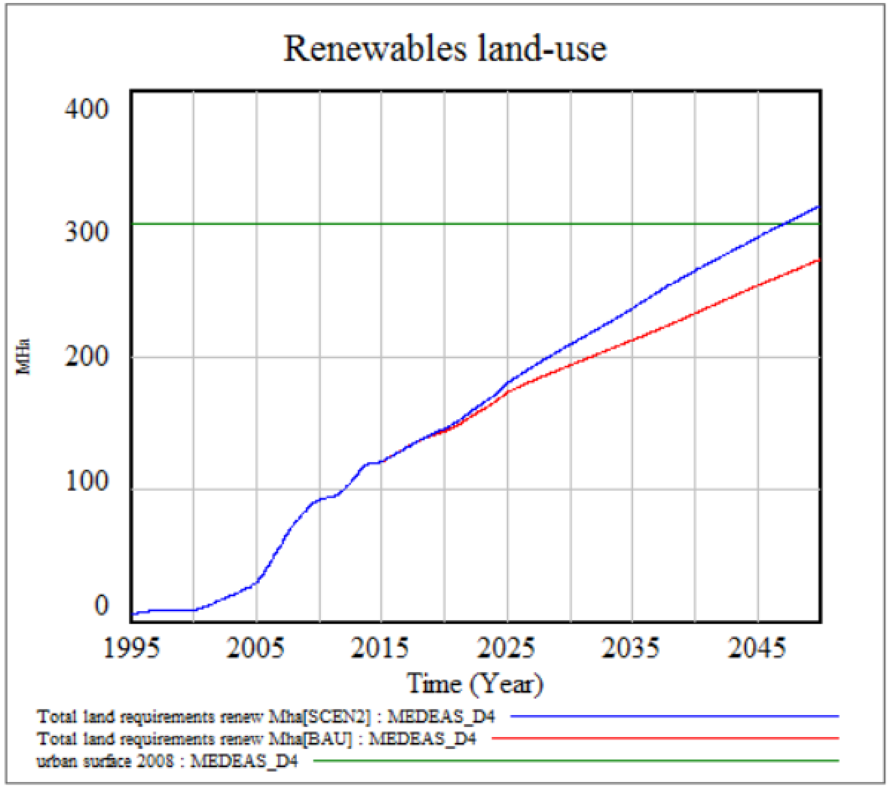

Figure 67: MEDEAS results: Land-use dedicated to RES. Note to interpret the legend: BAU refers to SSP2-Baseline and SCEN refers to SSP2-OLT.

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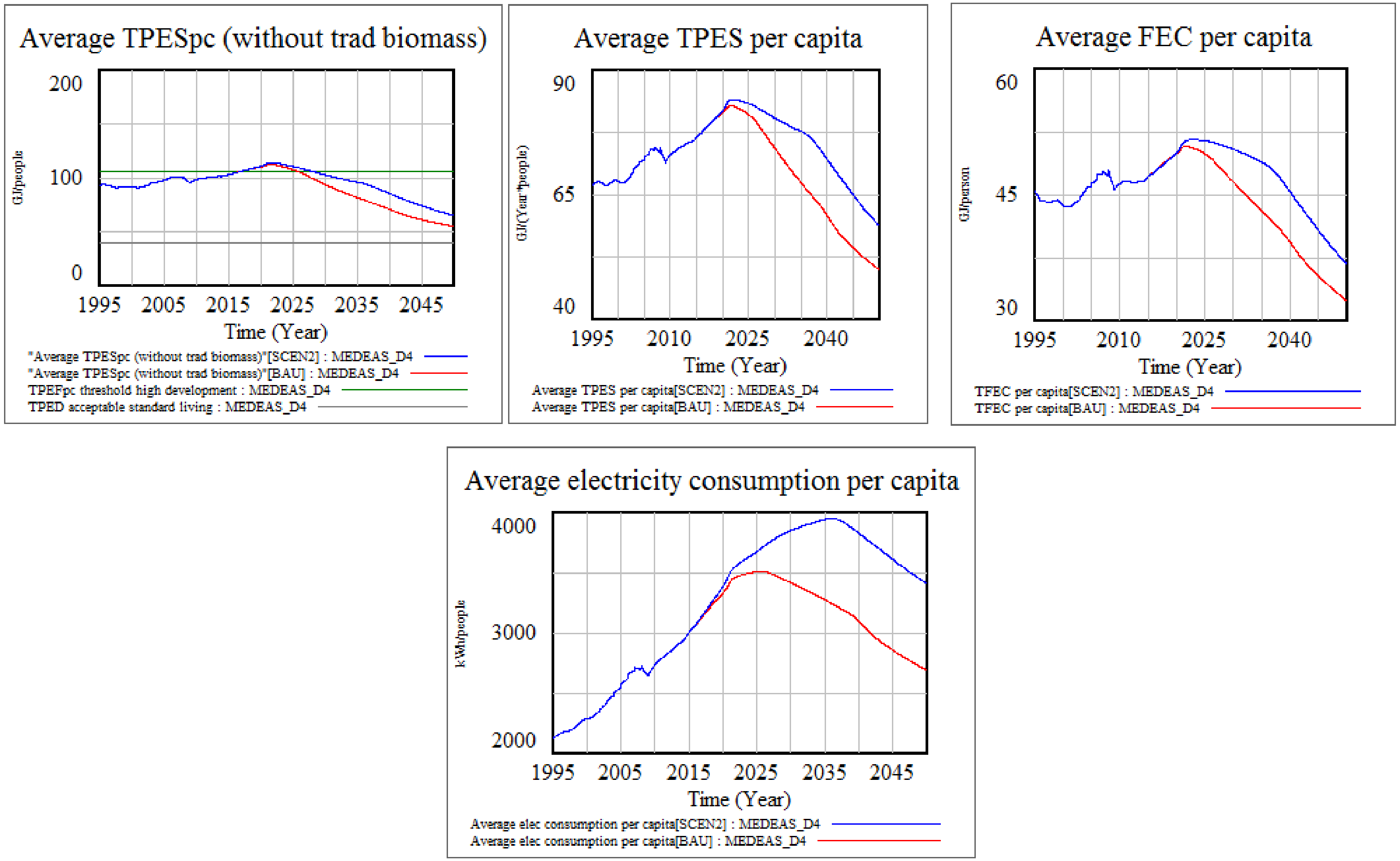

Figure 68: MEDEAS results: Energy indicators. Note to interpret the legend: BAU refers to SSP2-Baseline and SCEN refers to SSP2-OLT.

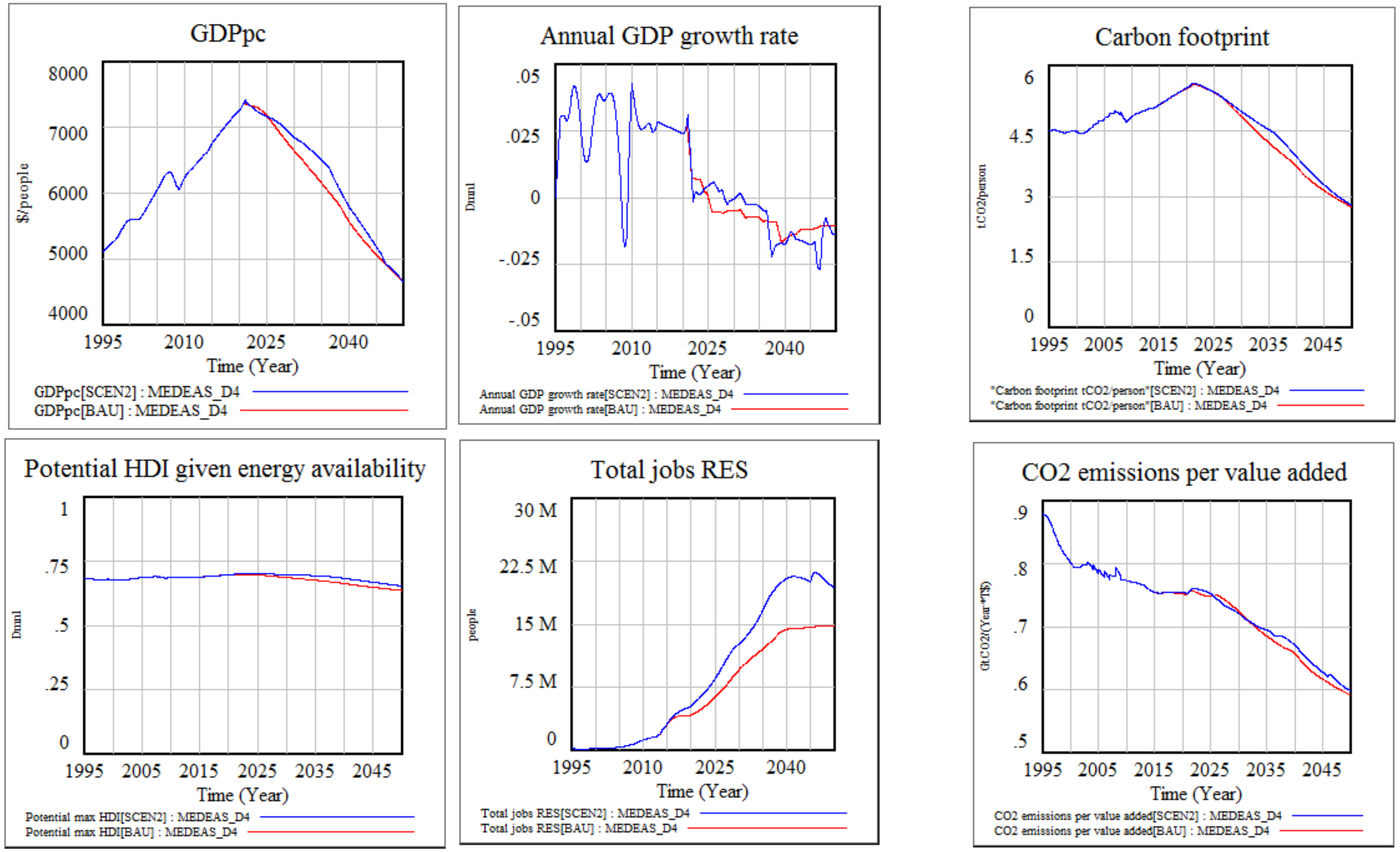

Figure 69: MEDEAS results: Social and environmental indicators. Note to interpret the legend: BAU refers to SSP2-Baseline and SCEN refers to SSP2-OLT.

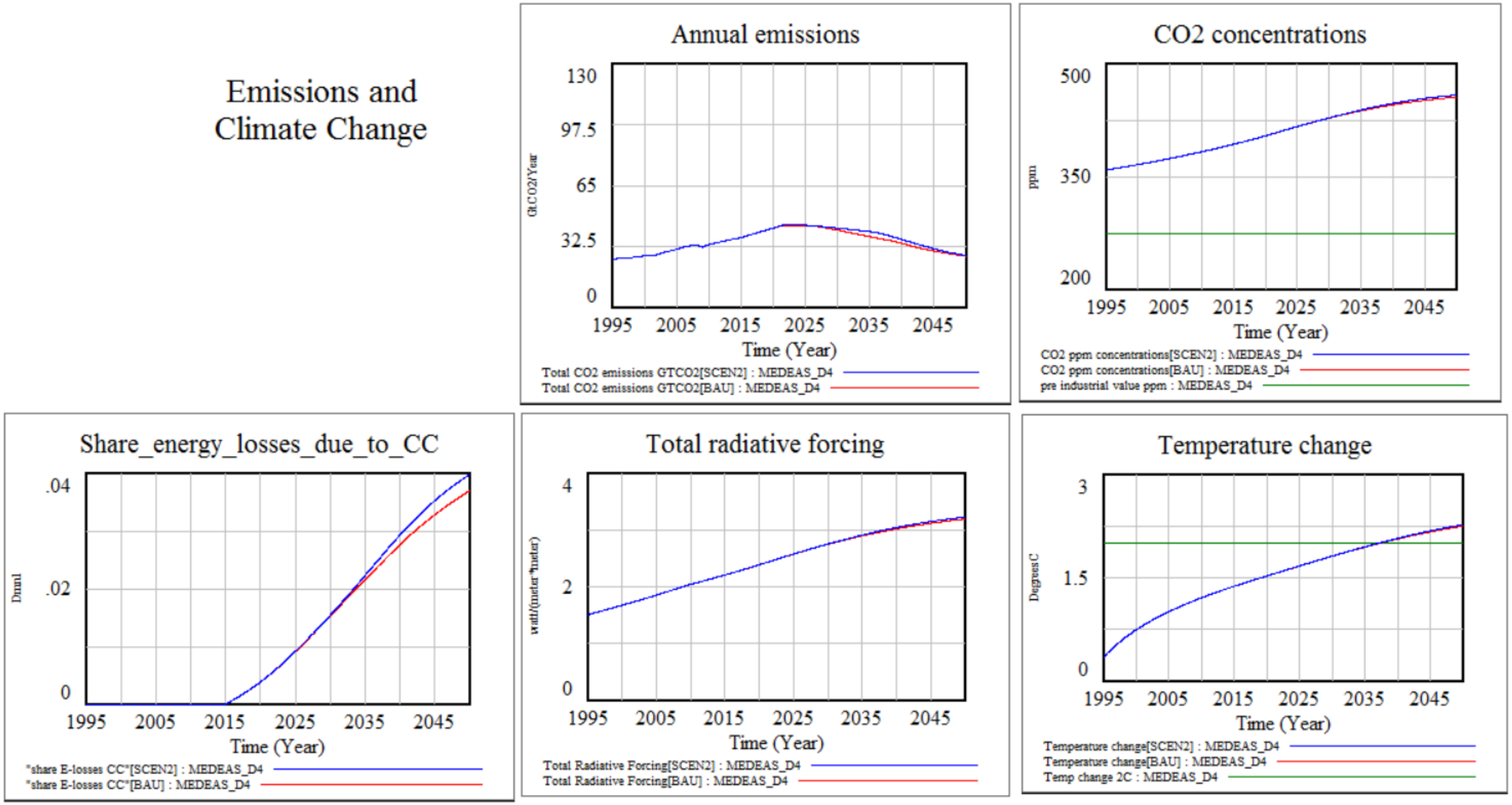

Figure 70: MEDEAS results: Emissions and climate change. Note to interpret the legend: BAU refers to SSP2-Baseline and SCEN refers to SSP2-OLT.

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5. 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 MEDEAS-EU.

5.1. Structure of the model

By submodules, we identify the most significant potential developments:

Economy module

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

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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,
- Estimation of EROIst, EROIpou and EROIext 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.

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

Materials

- Consider better estimates (e.g. RURR) of 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 fonction 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 71). The integration of such a module would allow to consistently integrate the different uses of land (food, biocrops, biodiversity conservation, afforestation, etc.) and assist in the assessment of sustainable potentials for biocrops and other land-intensive RES technologies. The modelling of agriculture and food production would also be required.

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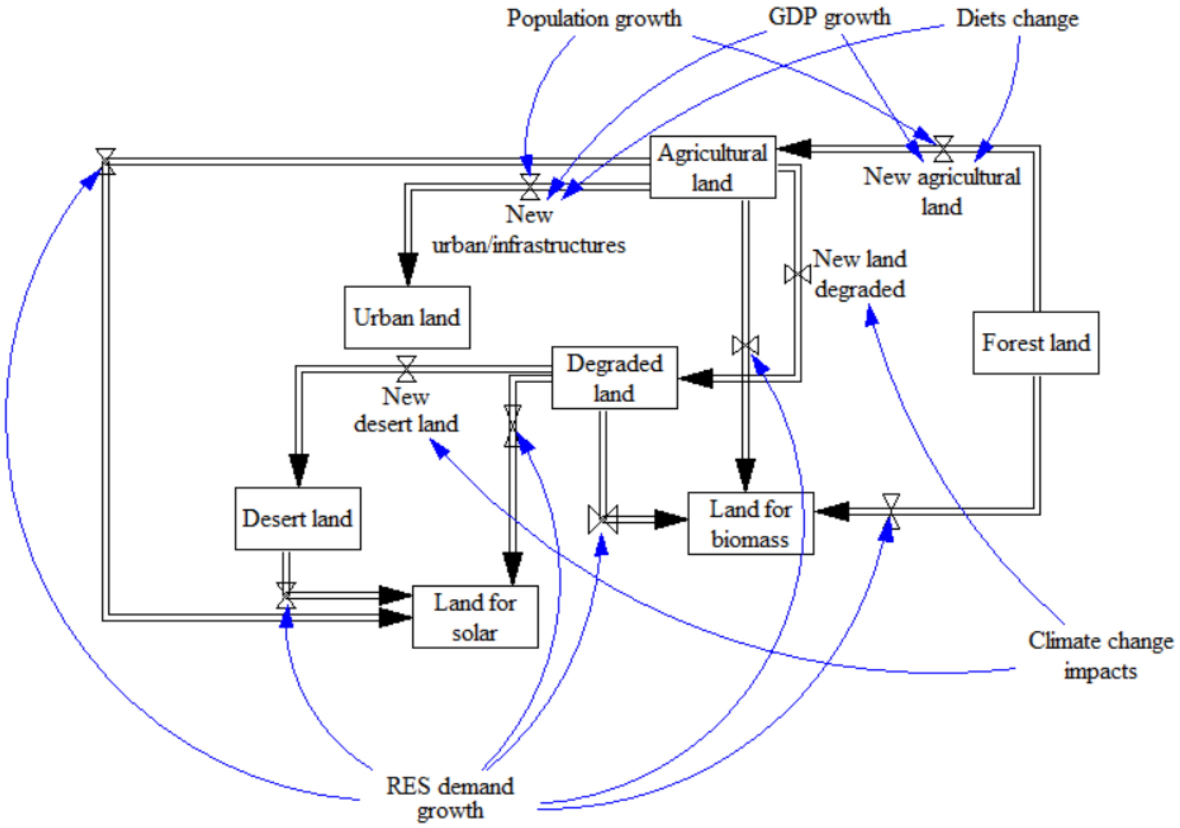

Figure 71: Modelling approach of the land-use module in MEDEAS framework. However this structure has not been finally included in the current version of the model.

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),
- Include all sources of GHG,
- Replace the current simplified climate module by a more complete, complex and accurate representation. A literature review was performed in order to select a model which would fulfil the following conditions:
  - Relatively fast solving/simple model (far from the long simulations from global circulation models),
  - Open-source to be compatible with MEDEAS licence.

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The reviewed models were the following: DICE-2013R (Nordhaus and Sztorc, 2013), FREE (Fiddaman, 2002, 1997), C-ROADS (Fiddaman et al., 2016; Sterman et al., 2012), MAGICC (Meinshausen et al., 2011) and ESCIMO (Randers et al., 2016). The best candidate was found to be C-Roads, which presents the additional advantage to be already designed in SD.

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 72 by dashed arrows.

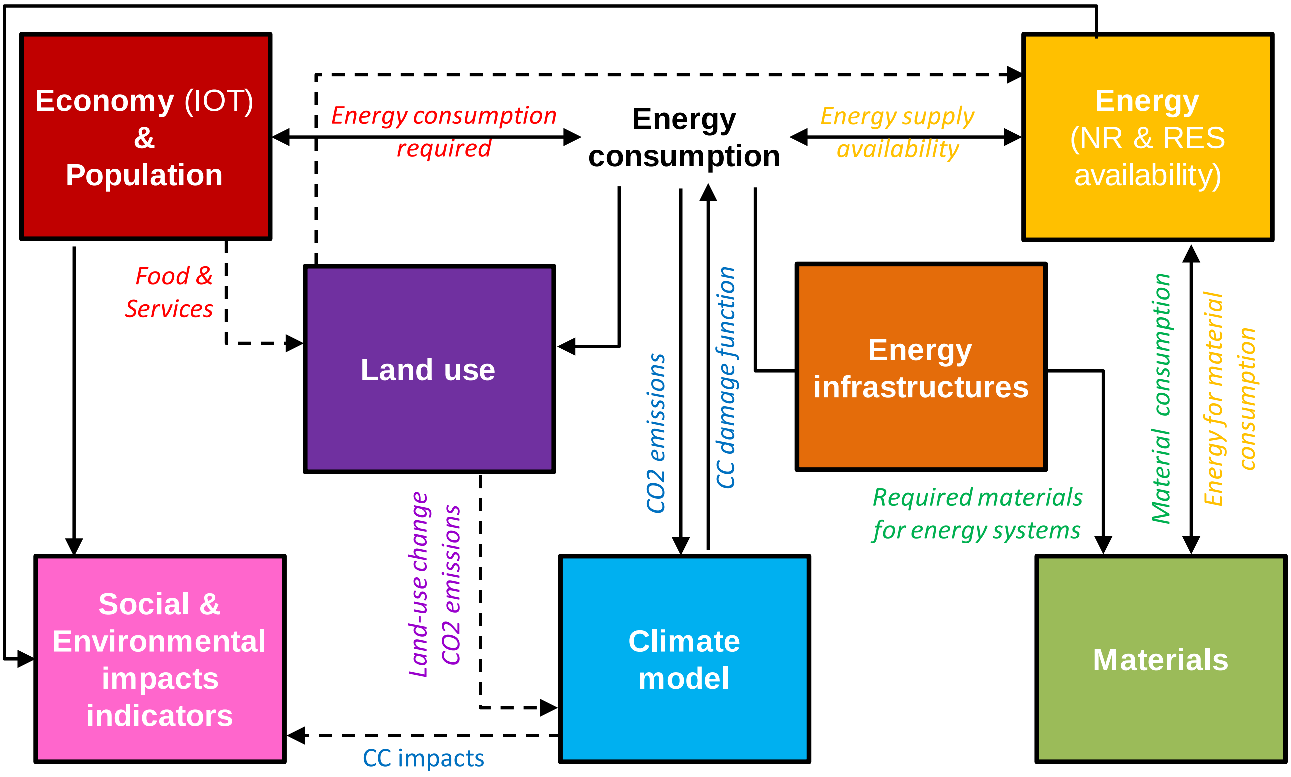

Figure 72: Overview of MEDEAS-World by modules. Straight lines represent relationships currently modelled, while dashed lines represent future potential developments.

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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 focus on the consistent integration of feedbacks that may start to operate in situations of continued GDP reductions (e.g. affecting investments, demand, etc.). These feedbacks will likely be very different depending on the societal approach to deal with this situation, e.g. maintain of the “growth paradigm” or shift to alternative “no-growth” approaches (Capellán-Pérez et al., 2015). Non-linear effects such as the so-called “Seneca effect” (i.e. when the decline is faster than growth) might also be expected.[27]

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

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5.2. Policies

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

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

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6. 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, 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 literature:

- 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 more potential.
- Estimations of the potential mineral scarcity,
- EROI estimation and feedback.
- The effects of climate change are feedback into energy consumption.
- Socio-economic indicators model implementation.

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

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.

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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.

The results presented in this report illustrate the potentiality of the model: the consideration of feedbacks and interrelations between submodules lead to the conclusion that current Green Growth scenarios, often promoted by institutions as the way to going forward to achieve a sustainable energy transition, may have serious drawbacks. Our results show that the solution of individual problems could lead to the creation of others. These dynamics cannot be revealed in the common models characterized by sequential structures.

Despite the challenges encountered with the model, there are still many limitations and uncertainties. In particular, further developments should address the inclusion of more dynamics in the economy module. Concretely, it is important to make A matrix evolve under scenarios, but endogenously as well. More dynamization would help to better model the allocation between different energy fuels and technologies. Moreover, the modelling of the interaction between energy supply and demand in cases of energy scarcity should be improved. The portfolio of policies should be expanded to include more non-technological options. For these and other reasons detailed in the previous section, the interpretation of the results must be done with caution. MEDEAS is not intended to predict the future, but rather to guide qualitatively the best options for the energy transition towards a low carbon economy. It is a tool to explore strategies, not specific policies, since the latter are applied at a different (reduced) political scale.

The MEDEAS model will be publicly available in open software Python as from February 2018 on the project website (http://www.medeas.eu/model/medeas-model).

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

Acknowledgements

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

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

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

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