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MEDEAS

MODELING THE RENEWABLE ENERGY TRANSITION IN EUROPE

Project Nr: 691287

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

Deliverable 7(D2.2) Data Analysis

Version 2.0.0

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Document info sheet

Lead Beneficiary: MU – Masaryk University

WP: 2, Data collection

Task: Deliverable 7 (D2.2) Data Analysis: sectors to be analysed evaluating the energy demand for the future scenarios and pathways and future change in energy mixes

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Table of contents

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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Abstract

This document is the second technical deliverable of MEDEAS project and results from WP2 (Data collection) activities carried out from July to December 2016. It constitutes the basis for the development of MEDEAS model, providing the necessary analyses to set-up scenarios and pathways. Deliverable 2.2 describe the sectors to be analysed for evaluating the energy demand for the future scenarios and pathways and future change in energy mixes. These sectors are the following: 1) Electricity sector; 2) Transportation; 3) Total primary energy extraction; 4) Industry, residential and commercial energy requirements; and 5) Social welfare and environmental impacts indicators analysis.

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List of abbreviations and acronyms

450S – 450 Scenario

AFOLU – Agriculture, forestry and other land-use

BEV – Battery electric vehicle

BGS – British Geological Survey

BII – Biodiversity Intactness index

CBG – Compressed biogas

CCS – Carbon Capture and Storage

CF – Carbon Footprint

CHP – Combined heat and power

CNG – Compressed natural gas

CPI – Current Policy Initiatives

CPS – Current Policy Scenario

CSP – Concentrating solar power

DG Directorate General

dwt – ton of dead weight (unit)

EC – European Commission

EDI – Energy Development Index

EEA – European Environmental Agency

EF Ecological footprint

EIA – U.S. Energy Information Administration

EJ – Exajoule

EROI (EROEI) – Energy return on energy invested

EU – European Union

FCV – Fuel cell vehicles

GDP – Gross Domestic Product

GHG – Greenhouse Gases

GIS – Geographic Information System

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GLASOD – Global Assessment of Human-induced Soil Degradation

GNI – Gross National income

GPI – Genuine Progress Indicator

GW Renewable power capacity

HDI – Human Development Index

HDV – Heavy Duty Vehicles

HHV – Higher Heating Value

ICE – Internal combustion engine

IEA – International Energy Agency

IEO – International Energy Outlook

ILUC – Indirect land-use change

IPCC – Intergovernmental Panel for Climate Change

ISEW – Index of Sustainable Economic Welfare

LBG – Liquefied biogas

LCA – Life-cycle analysis

LDV – Light Duty Vehicles

LHV – Low Heating Value

LNG – Liquefied natural gas

Mha – Megahectares

NACE – The Statistical classification of economic activities in the European Community

NPP –Terrestrial net primary (plant) production

NPS – New Policy Scenario

NRE – Non-Renewable Energy

OECD The Organisation for Economic Co-operation and Development

PAVs – Partially Aggregated Variables

PB – Planetary Boundaries

PHEV – Plug-in hybrid electric vehicle

PPP – Purchasing Power Parity

PV – Photovoltaic

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RE – Renewable Energy

RES – Renewable energy sources

RES-e – Electricity from renewable energy sources

RET – Renewable Energy Transition

SDGs – Sustainable Development Goals

SEDI – Sustainable Development Index

TFC –Total Final energy Consumption

TPES – Total Primary Energy Supply

UN – United Nations

UNDP – United Nations Development Programme

UNSD – United Nations Statistical Division

US – United States of America

USGS – United States Geological Survey

WEC – World Energy Council

WEO – World Energy Outlook

WF – Water footprint

WIOD – World Input Output Database

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Glossary

Adaptation to climate change – dealing with impacts of climate change by creating legislations, measures, tools and by taking practical actions to manage risks from climate impacts, protect communities and strengthen the resilience of the economy and sectors producing CO2 emissions

Degree day (Heating degree day; Cooling degree day) – is the most common climatic indicator of the demand for heating and cooling. It is a measure of the average temperature's departure from a certain base temperature. A base temperature is typically set an average indoor temperature.

Easterlin paradox: A concept suggesting that a higher level of a country's per capita gross domestic product (GDP) does not correlate with greater self-reported levels of happiness among citizens of a country.

Ecosystem services: refer to the benefits people obtain from ecosystems (supporting, provisioning, regulating and cultural).

Energy return on energy invested (EROI): is the ratio of the amount of usable energy delivered from a particular energy resource to the amount of energy used to obtain that energy resource.

Genuine Progress Indicator: The GPI is designed to take fuller account of the well-being of a nation by incorporating environmental and social factors which are not measured by GDP.

Gini index: Measure of the deviation of the distribution of income among individuals or households within a country from an equal distribution. A value of 0 represents absolute equality, a value of 1 absolute inequality.

Gross Domestic Product: A monetary measure of the market value of all final goods and services produced in a period (quarterly or yearly). Real GDP estimates are commonly used to determine the economic performance of a whole country or region, and to make international comparisons.

Gross National Happiness Index: The holistic concept of measuring subjective well-being of a country's citizens, developed in Bhutan. GNH has four pillars: good governance, sustainable socio-economic development, cultural preservation, and environmental conservation.

Gross National Income: The total domestic and foreign output claimed by residents of a country, consisting of GDP plus factor incomes earned by foreign residents, minus income earned in the domestic economy by nonresidents.

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Happiness Index: The measure of happiness published by the United Nations Sustainable Development Solutions Network.

Human Development Index: A composite statistic of life expectancy, education, and per capita income indicators, which is used to rank countries according to these four tiers of human development.

Index of Sustainable Economic Welfare: An indicator intended to replace the GDP. Consumer expenditure in ISEW is balanced by factors such as income distribution and cost associated with pollution and other unsustainable costs. Similar to GPI.

Indirect land use change (ILUC): The ILUC impacts of a crops refer to unintended land-use changes in the rest of the world induced by the expansion of croplands production in a given region.

Planetary boundary: refers to a specific point related to a global-scale environmental process beyond which humanity should not go if disastrous consequences are to be prevented.

Power density: is delivered power (energy/time) per unit of area of a given technology.

Purchasing Power Parity: The concept allows to estimate what the exchange rate between two currencies would have been in case if it was at par with the purchasing power of the two countries' currencies. This concept allows to compare what one can buy with the same amount of money in different countries.

Reserves: Part of the reserve base that can be economically extracted in a determined time.

Reserve base: Also called extractable global resource, is that part of an identified resource that meets specific physical and chemical criteria (ore grade, quality, depth, etc).

Resources: Best estimate of the total availability of each commodity in the crust in such form and amount that economic extraction is currently or potentially feasible.

Water consumption coefficients: Water consumed for producing one unit of the sector's output.

Water stress index: An index ranging from 0 (no stress) to 1 (maximum stress) to measure the extent of water withdrawals relative to hydrological availability.

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Executive summary

This document provides the necessary analyses in selected sectors and focus areas that need to be carried out in order to improve the MEDEAS model framework and model relations therein. It answers the following questions: What are the necessary analyses to be carried out? How do these analyses relate to the model needs, and how can they be studied in an integrated point of view? The sectors and focus areas are the (1) **electricity sector,** as an increase in electricity infrastructure and electric energy uses should be considered, (2) **transportation,** taking into account change to a different energy supply, efficiency gains, as well as transport of people and cargo optimization and/or reduction, (3) **total primary energy extraction**, considering production curves of non-renewable resources to frame the transitions' upper limit of available non-renewable energy resources, (4) **industry, residential and commercial energy requirements,** including material requirements (and energy required to extract them and exergy), and (5) **social welfare and environmental impacts indicators**, including relations to energy per capita, impacts of changes of land and water uses, and adaptation to climate change in terms of increase in heating and cooling requirements.

The Results sections of this document are structured according to these five key focus areas, selected for MEDEAS model development. Each of them is divided into three parts, according to the steps that were proposed to contribute in an explicit and structured way to MEDEAS model development. These steps are (1) **ways of model integration**, describing identified drivers in each focus area, (2) **necessary analyses** that are required for corroborating and parameterizing suggested model relations, and (3) **data availability** for the required analyses.

For the **electricity sector**, the increasing role of electricity in industry and transport and related model linkages should be considered, as well as the focus on elecitricity infrastructure requirements for RES, including low and medium voltage grids.

Concerning the **transportation sector,** the model must take into account population growth and resulting transport demand, availability of non-ferrous metals, the interdependencies with the electricity grid, hydrogen technology, substitutions for aviation traffic, as well as potential mode shift shares.

Wirth regards to **total primary energy extraction, t**he main drivers of the primary energy extraction related to mineral commodities are supply and demand, as they are related to availability of mineral resources and to future demand estimations. Additionally, information

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regarding the energy needed to extract, process and recycle those commodities is crucial to have a better understanding of the impact of the mining sector.

Energy efficiency is the main driver to decrease the carbon emissions of **industry, residential and commercial energy requirements**. Technological improvements and their implementation costs are key drivers for the industries. Improvements in building shells are necessary measures in the residential and commercial sectors. In all the sectors the fiscal and corporate governance frameworks and supporting policies can foster these drivers.

GDP is the strongest driver of the Human Development Index, which however is not an optimal proxy for **social welfare**, but could be extended by happiness indices. Inequality is an important, albeit less strongly related, but endogenous variable that should be considered. The energy footprint resulting from indirect **energy demand** is the best explanatory variable to explain social welfare measured with the HDI composite. Modeling education, unemployment, and labor demand could provide important additional drivers and policy variables.

Based on the suitability for modeling and public data availability, four **environmental impacts indicators** have been identified. These include Terrestrial Net Primiary (Plant) Production (NPP) for biological resources, the Global Assessment of human-induced Soil Degradation (GLASOD), the Biodiversity Inactness Index (BII), and the Ecological Footprint (EF).

Concerning **water use**, future residential and energy sector demands have to be considerd, as well as availability, potential, and expected increase in supply at basin and country level, efficiency improvements in the different sectors, and virtual water flows. Population growth and urbanization remain the key drivers of **land use** change, including potential land demand for renewable energies and future demand for carbon storage through afforestation and soil management.

Regarding **adaptation to climate change in heating and cooling sectors**, the following drivers were identified as necessary to be taken into account together with climate change impacts: energy demand, (increasing) income of households, demographic and lifestyle changes, Building regulations, energy efficiency and rising price of energy, regional drivers, energy supply drivers, and climate change adaptation drivers. However, we argue that the impact of CC on the sectors is relatively small in comparison to other drivers. The recommendation for MEDEAS model is to take into account variables such as Heating Degree Days (HDD) or Cooling Degree Days (CDD).

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Introduction

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.

Accordingly, MEDEAS has three specific objectives:

1. Identify the key physical parameters (net energy available to society, amount and cost of necessary materials) and their relationships with economic indicators (e.g. Gross Domestic Product), socio-economic variables (e.g. unemployment rate or Standard of Living), welfare indicators (e.g. Human Development Index), and environmental impacts (e.g. CO2 emissions);

2. Highlight emerging challenges for the implementation of a transition to a low carbon economy, as can be the impact of technological parameters, new concepts in modelling approaches, how to overcome possible drawbacks and provide solutions;

3. Suggest strategies to face such challenges when drafting the roadmap to a European future socio-economic transition to a sustainable energy system.

Deliverable 2.2 specifies which sectors should be analysed to evaluate the energy demand for the future scenarios and pathways and future change in energy mixes. Specifically, Deliverable 2.2 is focused on shedding light on the challenges and opportunities of such analyses, as it tries to identify the drivers of change in each sector, as well as to select proper indicators that are suitable to reflect these changes.

It thus deals with first mentioned objective in the sense that it identifies necessary drivers of the key parameters and suggests necessary analyses in selected sectors that need to be carried out in order to run the model properly. It tries to answer the following questions: What are the necessary analyses to be carried out? How do these analyses relate to the model needs, and how can they be studied in an integrated point of view?

This deliverable covers the following five activities, as specified in the Implementation Document of the Work Package 2:

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- **Electricity sector:** as the future 2050 society requires low-carbon emissions, an increase in electricity infrastructure and electric energy uses should be considered. Rates, improvement and management of the electricity infrastructure should be suggested.

- **Transportation** is currently mainly based on fossil fuels. Here the role of transport in the transition will be analysed, taking into account not only the change to a different energy supply for transport and efficiency gains, but also the role played by transport of people and cargo optimization and/or reduction.

- **Total primary energy extraction.** Production curves of non-renewable resources will be analysed to frame the transitions' upper limit of available non-renewable energy resources.

- **Industry, residential and commercial energy requirements.** Energy and material requirements (and energy required to extract them and exergy) in these sectors will be analysed and data will be collected.

- **Social welfare and environmental impacts indicators analysis.** In this subtask, indexes as can be Social Progress Index, Quality of Life, Inequality adjusted Human Development Index and other index data, will be collected, their statistics will be analysed. Through the energy per capita requirements for social welfare, CO2 emissions will be estimated and so it will be impacts of changes of land and water uses due to the transition to a low-carbon economy. Adaptation to climate change in terms of increase social energy requirements (in heating and cooling) will also be evaluated.

The deliverable is a compendium of the current document (executive summary) and a total of 12 thematic independent annexes which include details about the methodology used and information regarding the rationale and necessary analyses of the key sectors identified for MEDEAS.

Accordingly, Annex 1 focuses on electricity sector. Specifically, it analyses the rates of increase of electricity infrastructure and associated energetic costs (Global and European) due to transition to low-carbon economy.

Annex 2 covers the transportation sector. It deals with transportation transition energy costs due to change to a different energy supply; covering transportation transition energy costs per type I

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(Light duty vehicles, Medium freight trucks, Air, Two wheelers) and type II (Buses, Shipping, Heavy freight trucks, rail).

Annexes 3 focus on total primary energy extraction issues. Annex 3 analyses production curves of non-renewable energy resources considering Renewable Energy Transition. Annex 4 provides information on exergy extraction curves considering non-renewable resources and raw materials.

Annexes 5-6 deal with industry, residential and commercial energy requirements. Annex 5 focuses on energy consumption of Industry, residential and commercial sectors; while Annex 6 analyses Exergy Replacement Costs (ERC) for industry, residential and commercial sectors in the Global and European economy.

Annexes 7-12 include possible social welfare and environmental impacts and interlinkages of the transition. In detail, Annex 7 provides an analysis of the interlinkages between Social Progress Index, Quality of Life, Inequality adjusted Human Development Index and other welfare index data. Annex 8 provides environmental impacts indicators analysis. Annex 9 links the current global and European energy per capita consumption with social welfare indicators. Annex 10 describes changes in land uses; and Annex 11 water uses due to the transition to a low-carbon economy. Finally, Annex 12 provides information on adaptation to climate change in terms of increase social energy requirements (in heating and cooling specifically).

It should be noted that this is a living document and that the suggested analyses will constitute a starting point for MEDEAS Model. Additional analyses might be required and some might be abandoned as the project proceeds and if new requirements are detected.

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Methodology

In this section, we describe the methodology used in this deliverable for MEDEAS model development. The methodology provides an overview on how the results of the five activities have been translated into a selection of key insights for further model extension.

The MEDEAS model consists of six key modules, as depicted in Figure 1, including (1) Economy, (2) Energy, (3) Materials, (4) Land use, (5) Climate, and a (6) Social module.

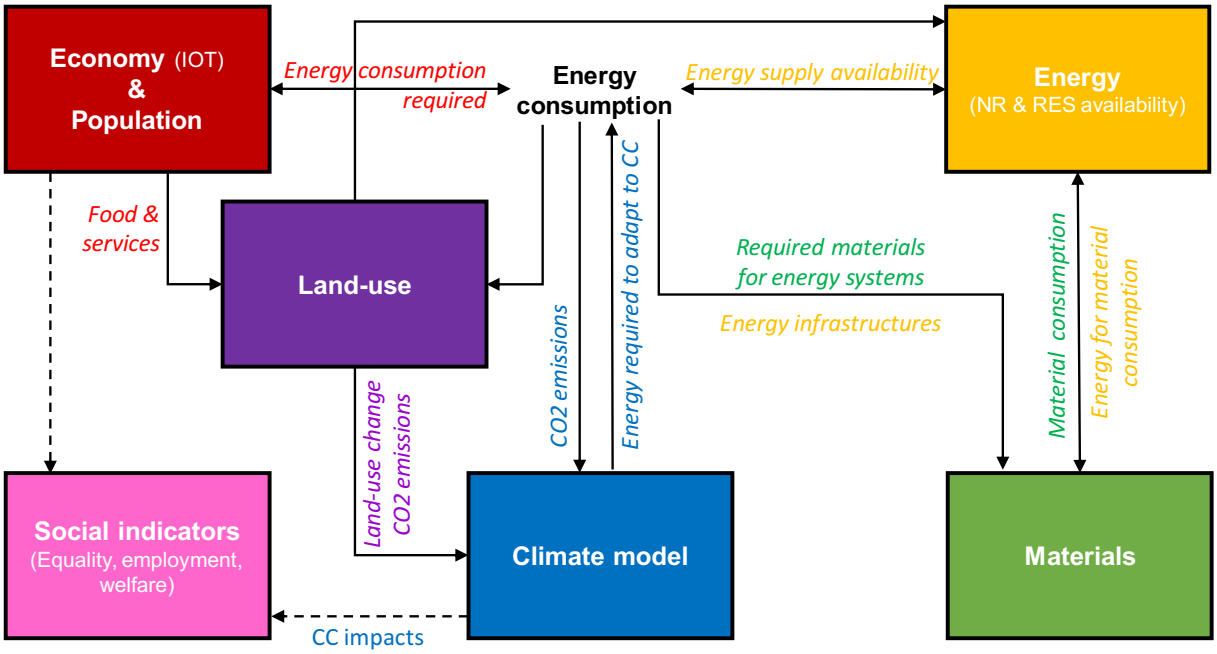

Figure 1: *Schematic interactions between each MEDEAS module*

All modules are interconnected and several connections exist on an industry and sector level. The analyses of this deliverbale have focused on five focus areas, including sectors, and dimensions related to the modules and their interconnections. The following table provides an overview of the connections between focus areas and MEDEAS module connections:

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Table 1: *Contributions of each implementation focus activity to the six MEDEAS Modules*

MEDEAS Module: Implementation focus:	**Economy**	**Energy**	**Materials**	**Land use**	**Climate**	**Social**
Electricity Sector	X	X				
Transportation	X	X	X			
Total primary energy extraction	X	X				
Industry, residential, and commercial energy requirements	X	X				
Social welfare and environmental impacts indicator analysis	X	X		X	X	X

The Results are structured according to these five key focus areas, selected for MEDEAS model development, based on, respectively, 14 reports (originally being subtasks of Task 2.2). Each of them is divided into three parts, according to the steps that were proposed to contribute in an explicit and structured way to MEDEAS model development. These steps are (1) Ways of model integration, (2) Necessary analyses for that, and (3) Data availability for the required analyses:

Ways of model integration aim at identifying the drivers in each thematic focus area that are necessary for a low-carbon transition and should therefore be reflected in MEDEAS model development. This section includes hypothesized and empirically supported relations between variables that are or could be explicitly modeled in MEDEAS.

Drivers for the industrial sectors, for example, could be fiscal frameworks, technology development and adoption curves, profitability and related implementation costs of technologies, institutional set up, corporate governance, including management frameworks.

Necessary analyses constitute of a summary of variables and analyses of interrelations between variables that reflect the drivers identified for model integration.

Analyses for the indutrial sectors could cover the implications of CO2 emission permit costs, emission taxes, energy subsidies, etc., and the interactions of infrastructure with technological

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improvement and diffusion, the effects of implementation costs, and the effects of governance indicators on energy intensities.

The **data availability** section should serve as a basis for further analyses that are necessary to parameterize relations between MEDEAS model variables if their model integration is considered crucial. According to the suggested ways of model integration and the related necessary analyses, a priority for data availability has to be made and potential data constraints have to be considered.

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Results

This section presents the main results associated to the three sub-activities carried out in this Deliverable: a) ways of model integration; b) necessary analyses; c) data availability. Each section should provide an answer to the following questions:

- Ways of model integration: *Which are the main drivers for your sector that are key for transition to low-carbon economy, and should therefore be reflected in the MEDEAS model?*
- Necessary analyses: *Which variables reflect those identified drivers in the industrial sector?*
- Data availability: *Which driver and variables in the industrial sector should receive highest priority, given relevance, required analyses, and potential data constraints?*

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Electricity sector

As the future 2050 society requires low-carbon emissions, an increase in electricity infrastructure and electric energy uses are considered. Rates, improvement and management of the electricity infrastructure are suggested.

Rates of increase of electricity infrastructure and associated energetic cost (Global and European)

Rates of increase of electricity infrastructure and associated energetic cost (Global and European). Management of the electricity infrastructure for the transition: changes to be implemented and associated energetic cost.

Ways of model integration

Power consumption depends to the greatest extent on the economic growth, represented through the GDP, and until recently the curves of their development had been almost parallel. Conversely, the use of electricity is a part of the technological progress. The active policy orientation towards climate protection during the last years, however, has brought to relative decoupling of the intensity of energy consumption in the World and in the EU from the respective GDP.

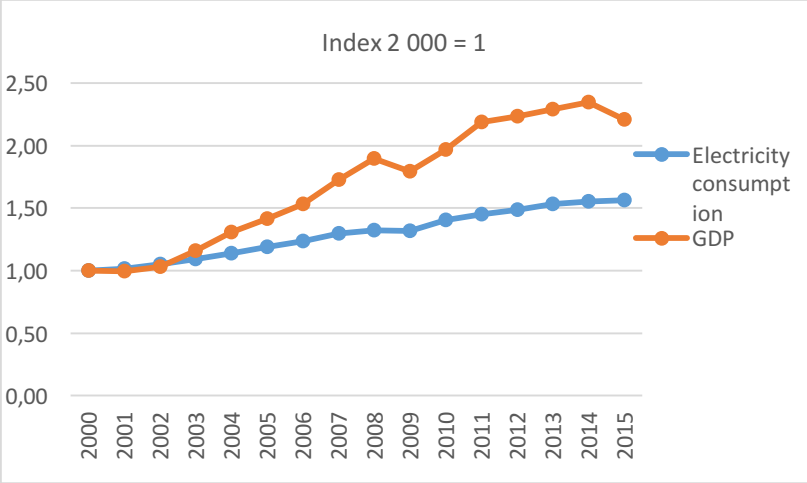

Figure 2: *World electricity consumption versus GDP. Source: World Bank, 2016; Enerdata, 2016*

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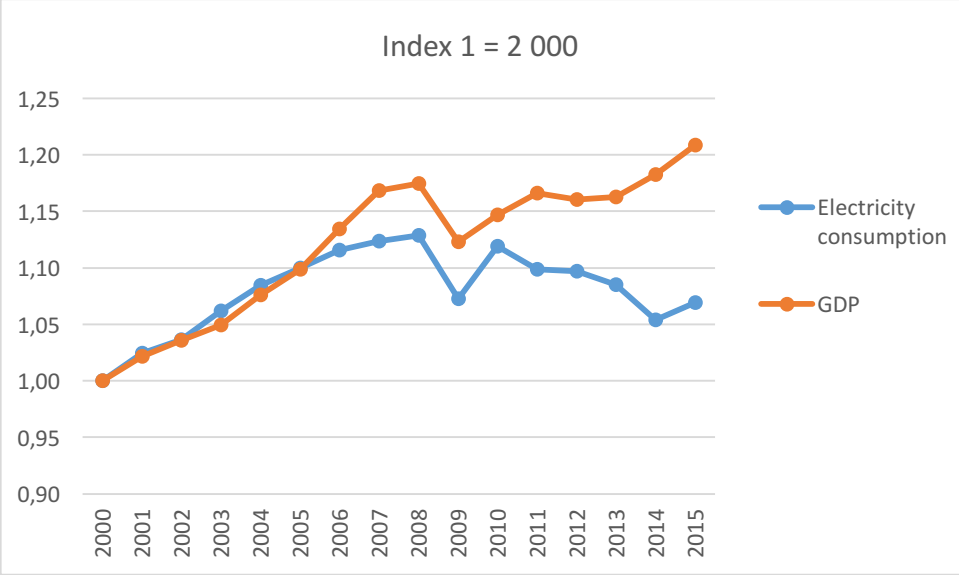

Figure 3: *EU electricity consumption versus GDP. Source: EUROSTAT, 2016, Enerdata, 2016*

This tendency will further continue as a result of the following factors/drivers:

- Improved efficiency of consumption;
- Increasing role of electricity in industry and transport;
- Transition to renewable energy: the ratio RES-e/Electricity Demand;
- Grid technologies development.

The first two factors act in mutually opposite directions and their interrelation determines the course of energy consumption curve. The climate protection strategy will require intensive modifications in power systems' structure, new ways of construction and new forms of control. In other words, sound investments will be needed.

Power grid is infrastructure, which cannot be included in any other way in the economic model, except for the corresponding costs of transformation, storage and transmission of electricity. It is expected that the investments in low and medium voltage grids will increase considerably to the size of several times higher compared to those in transmission grids.

The economic models for energy development are focusing mainly on consumption and production and reflect the technical infrastructure in general, without going into details. This approach is correct as far as these models cannot investigate technical solutions, typical for grids.

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Data availability

World

Several studies present complete projections for the electricity sector development in the world: WEO (IEA, 2016a), IEO (EIA, 2016), WEC. Among them, the first one could be used as a basis for the MEDEAS global projections, although it does not go beyond 2040. WEO study, which is the most appropriate for the aims of the MEDEAS model, proposes three main scenarios: Current Policy Scenario (CPS), New Policy Scenario (NPS) and 450 Scenario (450S), which differ significantly:

- The **Current Policy Scenario** takes into account the policy in the field of climate protection, which has entered into force since the mid of 2015.
- The **New Policies Scenario** is supplementing CPS with new measures, such as "programmes to support renewable energy and improve energy efficiency, to promote alternative fuels and vehicles, carbon pricing, reform of energy subsidies, and the introduction, expansion or phase out of nuclear power".
- The **450 Scenario** supplements NPS with a set of policies to limit the rise in the long-term average global temperature to two degrees Celsius (2°C), compared to the pre-industrial levels, which is expected to stabilise the GHG concentration after 2100 at around 450 parts per million (IEA, 2015).

Costs of network construction

The costs of network development include, among the others, investments in control systems at all levels of voltage grids, especially in relation to the intelligent networks which should be able to operate autonomously, i.e. to undertake all control functions that are common for the existing large systems.

Table 2 illustrates the amount of the necessary investments according to NPS and 450S projections.

Table 2: *Comparison of investment in electrical systems at NPS and 450S projections, 2016-2040, USD2015 trillion. Source: IEA, 2016c*

	Fossil and Nuclear	Renewables	T&D	Total
New Policy Scenario	4,1	7,1	8,1	19,3
450 ppm Scenario	4,2	11,0	7.2	22,4

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As expected, the investments in renewable generation are higher (about 35%) than those in transmission and distribution (about 11%) due, most probably, to the distributed generation and higher efficiency of consumption.

European Union

It is expected that in the next years the main components of the European power system, which operational life is expiring, will be replaced, and by this the costs for the network's rehabilitation will be prevailing in the total power system's investments.

The most comprehensive information regarding the investmets in the European power network is contained in the EU documents and it should be used for the MEDEAS modelling. Such a document is the Roadmap 2050, in which a Reference Scenario and several alternative decarbonisation scenarios are established. These scenarios differ from each other by the way in which the aim of 85% CO_2 emissions reduction could be achieved.

Based on the assumption that the European policy will continue its orientation towards and will follow scenarios for high RES shares, which will require making of more and more investments in the power system, as outlined above, the High RES Scenario is the most likely to be implemented.

Table 3 shows the projections of investments in power system.

Table 3: *Grid investment costs, Bn Euro'95. Source: European Commission, 2011*

Scenario	2011-2020	2021-2030	2031-2050	2011-2050
Reference	292	316	662	1 270
Current Policy Initiatives (CPI)	293	291	774	1 358
Energy Efficiency	305	352	861	1 518
Diversified supply technologies	337	416	959	1 712
High RES	336	536	1 323	2 195
Delayed CCS	336	420	961	1 717
Low nuclear	339	425	1 029	1 793

The publication of the Roadmap 2050 was the beginning of a comprehensive strategy that develops systematically a stream of various regulatory and policy tools – from Directives to Opinions.

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Necessary analyses

Given the different time horizons covered by the various projections (2040 by WEO and EIA, 2050 by the EC Roadmap, 2060 by WEC), various databases used and targets pursued, it becomes evident that there exist serious differences between them, both in scope and in results (e.g. between Europe and EU). The existing information is characterized by certain drawbacks that need to be overcome by extrapolations, indirect comparisons or experts' assessments. This concerns both the World and the EU projections.

- **World:** The information about grid development, and particularly concerning the involved costs, is very limited. There should be followed carefully the appearance of new specialized studies on the expected development of electricity production, similar to the recently published study by the Global Wind Energy Council (GWEC 2016) which covers the period till 2050 and contains detailed information about wind global projections and the corresponding costs for integration.
- **EU:** The Roadmap 2050 (EC 2011c) contains detailed information about grid development in 6 scenarios. The source however is rather old, published in 2011. The new version of the Reference Scenario of Roadmap 2050 (EC 2016) shows an ongoing reappraisal of the 2011 projections. Hopefully new documents devoted to additional projections will be published soon.
- **Necessary updates:** In the course of the project advancement, new studies in the field of power systems are being published. This requires a constant updating of the information, which will be used for the model. Furthermore, with the defining of the model's specific needs, the information will have to be further improved.

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Transportation sector

Transportation is currently mainly based on fossil fuels. Here the role of transport in the transition is analysed, taking into account not only the change to a different energy supply for transport and efficiency gains, but also the role played by transport of people and cargo optimization and/or reduction.

In the due report we examine the current situation and trends within the transportation systems around the world, and draw the prospects for it to enter the post-carbon era, from the technological and scientific viewpoints. The relevant problems, obstacles and possible pathways for this transition are summarized. The research draws attention to the fact that the current state of the transportation system is not sustainable, and can stall within 2-3 decades, if the global, systematic, and drastic measures to promote the transition are not taken. Nowadays, global and European transport still depends heavily on fossil fuels (mostly, oil), that are expected to deplete within a few decades, moreover, it produces a significant fraction of greenhouse gases, pollution in metropolitan areas, and also is a source of millions of accidents every year. The report draws the general structure of world's transportation system with the statistics on agents and consumptions inside every important carrier subsector, that is, cars, ships, aviation, freight, urban transport, and so on. We expect the future transport to be powered mainly by electricity from the (1) onboard batteries, (2) the grid, and (3) hydrogen fuel cells for heavy duty vehicles where the former means are not possible.

Transportation transition energy costs: change to a different energy supply

Ways of model integration

We evaluate the current and perspective costs for these three sources in terms of energetic efficiency, availability of critical resources, and possible technological breakthroughs that may alleviate their flaws.

We identify the following important drivers that must be included in the model:

1. Expected population, affecting the necessary demand for transportation traffic, in terms of people and freight.
2. Availability of non-ferrous metals, critical for the sector: primarily, lithium and platinum.

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3. Structure of future intercontinental marine transportation stemming from the future structure of global economy.
4. Scenario and the scale of deployment of electric grid.
5. Energy that would the future RE economy produce: would there be a surplus to alleviate certain demands (for example, for the deployment of the grid and hydrogen-propelled transport).
6. Conversion scenario of existing fleet (land and marine) to electric analogs.
7. What fraction of aviation traffic can be replaced by the land lines.
8. Introduction of the general strategy of shifting transport 'modes' (from high to low energy intensity).

Necessary analyses

The variables, that would describe those factors, are identified as:

1. Expected GDP, that is translated (coupled with the population numbers) into a prediction for the demand of transportation.
2. Expected extraction volumes and recycling proportion for rare metals.
3. Grid electrification per region; how much copper and energy would be produced
4. Initial estimates of the possible energy deficit (surplus): it is to be taken into the account when designing the future transportation structure.
5. How much of existing fleet (land-based and marine) would be electrified.
6. Minimum necessary numbers and proportion of aviation fleet to satisfy the future demands.

Data availability

We assume that the most crucial are the data related to:

1. The critical resources (rates of extraction, production, recycling).
2. The rate at which the industry is capable to switch to the production of electric vehicles.
3. Energy estimates that would define the scale of the deployment of the grid and hydrogen-propelled transport.
4. Total cost of transition (globally and per region) to estimate the fraction of GDP required.

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Transportation transition energy costs per type (I): Light duty vehicles, Medium freight trucks, Air, Two wheelers

Ways of model integration

The main drivers for transportation transition energy costs for light duty vehicles, medium freight trucks, air, and two wheelers key for transition to low-carbon economy were identified as:

1. Demands for the critical resources (first of all, lithium and platinum) in every subsector.
2. LDV: their role in the future transportation system, firstly, in urban transportation.
3. Realistic expectations on possible replacements of lithium, platinum, copper etc in their respective areas of application.
4. Freight trucks and the possibilities to replace them by trains, or connect them to the grid
5. Minimum necessary levels of aviation fleet
6. Two-wheelers: how much would is expected to be produced
7. Expected policies for urban traffic management

Necessary analyses

Which variables reflect those identified drivers in this sector?

1. Lithium and platinum production and its demand in other sectors
2. Average distances that should an LDV cover, car occupation expectations
3. Deployment of the grid in urban areas: cost, resources
4. Expected numbers for the production of two-wheelers
5. Aviation with numbers per sector (light, heavy, cargo, and similar).

Data availability

We suggest to give the utmost importance to LDV, since nowadays it is one of the major petroleum consumer, growing fast in numbers. We can also notice that a private car had become an almost inevitable companion in rapidly growing middle (and upper) classes. Therefore, we name the following drivers and factors:

1. How much mentioned critical resources can the industry produce and devote to the sector.
2. How many LDVs can be deployed, based on the current data for resources and available technologies; how this number would affect the urban/intercity traffic.

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3. Policies in urban management, changes in public reception required to make the numbers in (1, 2) sustainable and not leading to economic imbalances.
4. What would be the cost, operations and habits of use of a private electric car in the future

Transportation transition energy costs per type (II): Buses, Shipping, Heavy freight trucks, rail

Ways of model integration

The future transportation, especially trains, marine, heavy freight would depend strongly on the scale of the deployed grid, thus the factors that define and put constraints on this are of the major importance.

Which driver and variables in the transportation sector regarding buses, shipping, heavy freight trucks, and rail should receive highest priority, given relevance, required analyses, and potential data constraints?

1. Grid deployment, its degradation/amortization, replacement rates.
2. Resources associated with (1): copper, energy expenditure, possible replacement technologies (this might be included as a probable factor, reducing the requirements by a certain amount).
3. The current fleet of railway, marine transport, heavy trucks might be electrified (at least partially and gradually).
4. What are the realistic constraints that are imposed by the use of fuel cell-based transport? Pt/Pl availability, possible replacement technologies, energetic efficiency, weight.
5. Scenarios for urban and intercity transportation.
6. How to reach a positive public reception of relatively slow railways instead of aviation, intercontinental flights in particular, inefficient high-speed trains (as far as tourism, business trips are concerned); expected numbers of human/freight traffic that might be replaced by railways.

Necessary analyses

Which variables reflect those identified drivers in the transportation sector regarding buses, shipping, heavy freight trucks, and rail?

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1. The cost and resources to deploy the grid (per distance, area) to power railways, bus lines, heavy trucks. The cost to electrify distant regions (agricultural centers, minery, and similar).
2. Numbers of copper availability and demand in other sectors.
3. Expected industrial volumes and its limitations in production of fuel cells.
4. How much of the current fleet of railway, marine transport, heavy trucks is expected to be electrified.
5. Future requirements for heavy transport in extractive industry.
6. Heavy intercontinental and long-range marine transport requirements in future economy, taking into account an optimization of logistics.

Data availability

We identify the major consumers of fossil fuel and producers of CO_2 in this sector being shipping and heavy freight transport. In 100% RE economy of the future the autonomous transport will be propelled by hydrogen, that is currently around 4 times less efficient energetically (compared to the grid), and is also limited by rare materials such as Pt, so this sector must reduce to the minimum necessary levels. Therefore:

1. Defining these levels is of major importance. As a first approximation, this data might be found by considering the current traffic (e.g. in shipping) and identifying its fraction that cannot be replaced by trains, or optimization.
2. Pt and Li reserves, their demands in other sectors affect strongly possible deployed fleet of heavy transport.
3. Conversion proportion and costs, primarily, in marine sector (due to much longer average life cycle)

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Total primary energy extraction

Production curves of non-renewable resources are analysed to frame the transitions' upper limit of available non-renewable energy resources.

Production curves of non-renewable energy resources considering Renewable Energy Transition

Ways of model integration

Important parameters for modelling extraction and supply of non-renewable resources, including **supply costs**, upstream energy consumption and greenhouse gas emissions etc., are strongly influenced by the type of deposits and according extraction techniques (usually categorized as "conventional" or "unconventional"). With regard to **supply potentials** in the EU and worldwide it is important to distinguish between reserves (volumes that are expected to be produced economically using today's technology) and resources (volumes not yet fully characterized, difficult or costly to extract (IEA, 2013a).

In a model for the EU it is further reasonable to distinguish between the available resources in the EU and global supply. In this context, the very different situations in EU and global oil, gas, coal and uranium supply must be considered. With regard to oil, gas and uranium, EU reserves are moderate in comparison to current and projected future consumption. Even with demand in the EU being largely supplied by imports, scenarios indicate that current reserves of oil and gas will only last for the next 15 years or so. To convert resources to reserves, **advanced technological solutions** and **higher energy prices** are required. Especially unconventional gas is abundant in the EU and could significantly enlarge the EU's fossil resource basis. In contrast to the situation for oil and gas, coal reserves in the EU are large and far from being depleted, even in conservative long-term scenarios.

On a global scale, long-term scenarios until 2040 (IEA, 2016a) indicated that reserves of oil, gas and coal are not expected to be depleted. Current uranium reserves, on the other hand, are projected to suffice until 2040 at the latest.

Another driver for the production of non-renewable energy sources is the deployment of renewable energy technologies. With the current technological approaches, in all stages of the life cycle of renewable technologies, fossil fuels are consumed. These **embedded fossil fuels** impact

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the transition to a low carbon economy in several ways: it might reduce the overall efficiency of the energy sector (thus leading to a larger energy sector for a given energy demand), it reduces the GHG reduction efforts (as renewable energy technologies currently are "low carbon" instead of "zero carbon", and it might limit the potential for renewable energy technologies in total. The materials for these technologies (steel and concrete) and transport requirements are of major importance in this respect, but also the factors determining the energy output, like PV efficiency and average wind speed.

Necessary analyses

In the primary extraction sector, the main drivers are the supply potentials with their respective supply costs, energy prices, technological improvement and the fossil fuels embedded in renewable energy technologies. The variables associated with these drivers are:

- Supply potentials: type and size of deposits (i.e. reserve or resource),
- Supply costs: extraction costs of a deposit
- Energy prices: EU energy imports, market price developments of non-renewable energy sources
- Technological improvement: energetic extraction costs of a deposit
- Fossil fuels embedded in renewable technologies: energy return on energy invested of a renewable technology, share of fossil fuel consumption, material requirements, efficiency and full load hours of renewable technologies

Data availability

For the assessment of the parameters describing the current and future fossil energy embedded in renewable energy technologies, the currently available studies on the sustainable performance of these technologies have to be analysed. Important information for both the current as well as the future development of the variables is the amount of materials necessary for the construction of renewable energy technologies, the processes and energy consumption for the manufacturing, transport and installation of the components, and the share of electricity and fossil energy for this consumption.

Of special importance is the change of the fuel share of the energy consumption of renewable energy technologies. This change can be achieved by a substitution of currently fossil fuelled processes (e.g. the production of steel or the transport of components) by renewable processes (e.g. hydrogen from renewable electricity for steel production or renewable transport

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technologies) and will have a great impact on the overall energetic efficiency and the GHG reduction potential.

Exergy extraction curves considering non-renewable resources and raw materials (Raw materials availability)

Ways of model integration

Going towards a low carbon economy can have a direct influence in the materials that the society demands depending on the evolution of the politic, economic, social and technological situation. In a future scenario where circular economy is promoted, shifting towards more sustainable approaches, secondary raw materials can overcome the demand decreasing the environmental impact associated with raw material extraction. For this scenario, improvements in technology, especially on recycling technologies, must be implemented.

One of the main drivers, or rather, limitations that can have a big influence in the transition to a low carbon economy is the **availability of raw materials**. This availability is driven by:

- **Supply** refers to the amount of raw materials that is made available to the industry and depends mainly on the extraction of minerals from the Earth and the secondary supply coming from recycling.
- **Demand** depends on the extraction, which is in turn limited by the amount of minerals present in the crust, by the total resources, the reserve base and the reserves.

Another limitation can be created by the amount of **energy that is needed to extract the minerals and recycle them**. The drivers that can influence the energy consumption are the following:

- Energy used in the mining sector
- Ore grade (or mineral concentration)
- Recycling

Necessary analyses

The main variables that can provide information about the key aspects identified are:

- Historical data on mineral extraction
- Historical data on mineral reserves
- Historical data on mineral resources

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- Future estimations of mineral production
- Future estimations of demand pear each sector per commodity
- Energy use in the mining sector per commodity
- Average ore grade per commodity
- Current recycling rates per commodity
- Energy used for recycling per commodity

Data availability

In this section the data availability and the source for each of the variables identified as crucial for the MEDEAS model will be mentioned:

- Historical production, reserve, reserve base and resource information can be obtained from United States Geological Service (USGS) from the year 1900 onwards. Yet, the information is sometimes incomplete or inaccurate, and as 2009, the reserve base estimations are no longer provided. Additionally, other sources can be used, as other geological services (British Geological Survey) or even scientific journals, collect and analyze this kind of data.
- It is crucial to compare the extraction information with the mineral trade in each region, to have a better understanding of which regions are mainly mineral producers and exporters and which regions mainly depend on external supply. For this endeavor mineral statistics from the British Geological Survey (BGS) and the United States Geological Survey (USGS) can be consulted, as well as other reports made by the European Commission and national statistics services from European countries. An example can be seen in Figure 2. The information is represented both in mass terms (tons) and in exergy terms (Mtoe) as the physical quality of the minerals can be better represented in the latter case.

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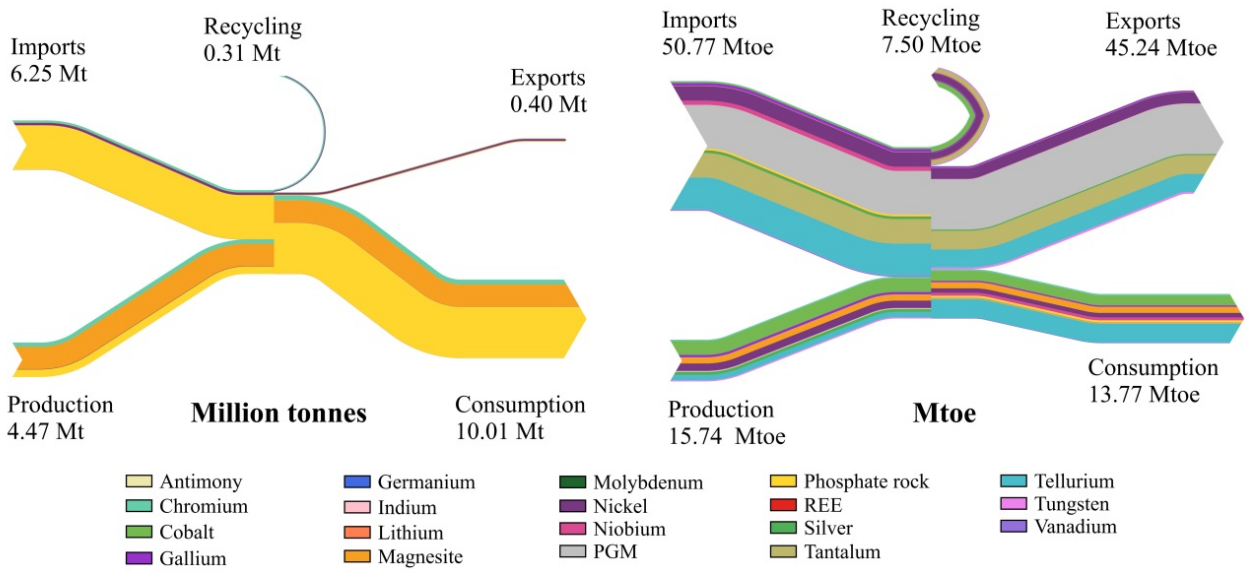

***Figure 4**: Sankey diagram of the flows of the materials selected as critical for the EU-28 for 2014 in million tonnes (left) and in Mtoe (right). Data for imports and exports have been collected from EUROSTAT and BGS statistical services. Source: own elaboration*

- Future production estimations can be made using the Hubbert peak model and have estimations of the maximum production peak for each commodity. The maximum production peak is reached when the higher quality resources (commodities with higher concentrations and easier to extract and process) have been extracted and then the production starts to decrease as the lower quality resources are extracted. For instance, this model has been applied to the minerals that have the highest production rates of all: aluminium, chromium, copper, iron, manganese and zinc, the so-called, "big six" (Figure 5). The Hubbert peak model can help determining which minerals are going to be scarcer in the next decades due to exponential extraction and expected increase in demand in certain sectors. It does not mean that after the maximum production peaks have been reached the Earth is going to run out of minerals, but it can be used as a first approach to put focus on those substances and be used as an early warning indicator.

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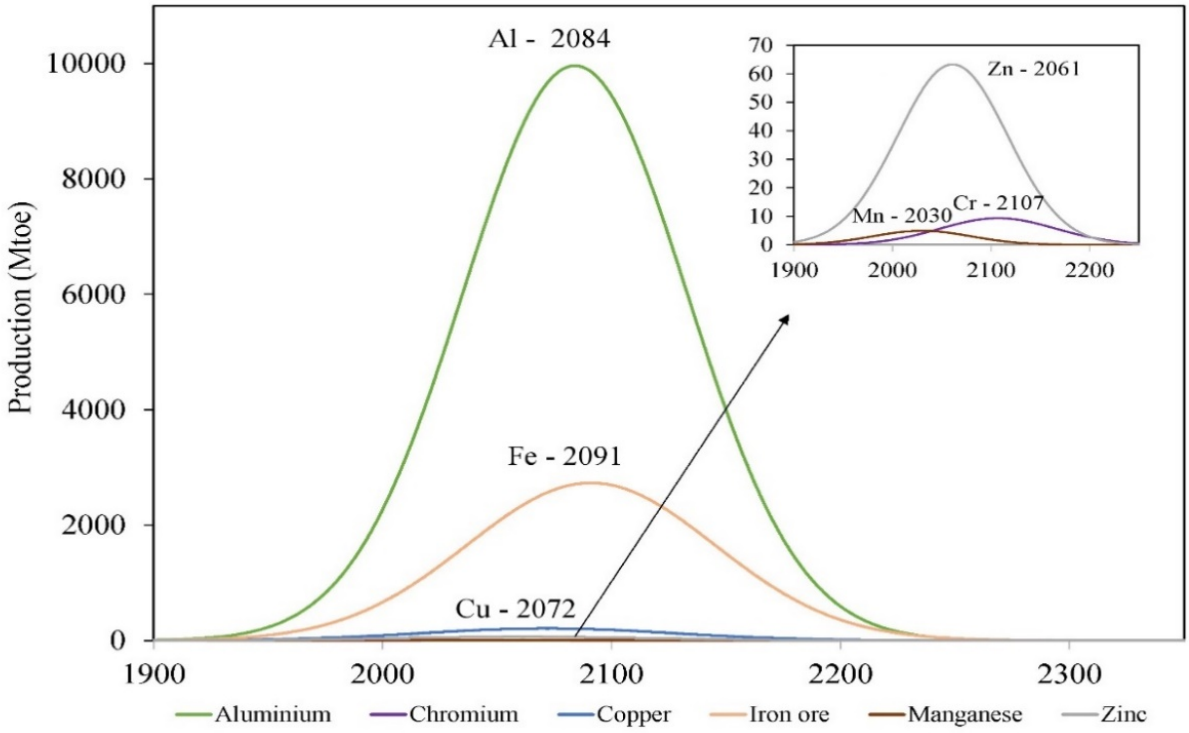

Figure 5: *The Hubbert peak applied to the "big six" resources. Source: own elaboration*

- The mining industry consumes between 8 and 10% of the world total energy therefore, it is fundamental to have a previous knowledge of the mining processes where the energy is used. Many mining companies have started to report annually their sustainability performance along with their financial results. These reports vary substantially from one company to another but they can be used as an approach to have real information on their performance. Using the reported data it is possible to analyze links between different factors, such as energy consumption, ore grade, mineral production, greenhouse gas emissions, and solid wastes, among others.
- Energy needed for recycling, to produce secondary raw materials, is much more difficult to obtain for all the commodities. Additionally, not all the minerals are recycled in the same quantities nor have the same importance for the development of green technologies. Still, as it is possible to obtain data for the "big six" from literature, the energy savings can be quite considerable when compared to the energy to extraction.

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Industry, residential and commercial energy requirements

Energy and material requirements (and energy required to extract them and exergy) in these sectors are analysed and data are collected.

Energy consumption of industry, residential and commercial sectors

The industry sector accounts for about one-third of total final energy consumption and almost 40% of total energy-related CO2 emissions. Residential and commercial sectors account for approximately 32% of global energy use and almost 10% of total direct energy-related CO2 emissions. These sectors have an undoubted importance in the energy panorama and in the possible future scenarios, therefore the information regarding the energy consumption of these sectors is crucial for the MEDEAS model.

Ways of model integration

In the **industry sector** energy efficiency is an essential driver to decrease the carbon production. It can be accomplished by:

- Technological improvements: applying Best Available Technologies, better system integration or closed-loop processes. Furthermore, renewable energy sources must replace fossil fuels in direct uses.
- Implementation cost: the profitability of the technological improvements is going to be crucial for its deployment.
- Fiscal framework: can foster the efficiency improvements, for example, higher carbon prices can benefit low-carbon technologies but it may increase the risk of carbon leakage (European Commission, 2011).
- The degree of corporate "green" thinking: is going to influence the leaning of the companies to apply measures to improve the energy efficiency.

Projections about the energy consumption in the **residential and commercial sectors** are complex because there are many different factors implied: population, geographic region, climatic conditions, incomes, energy prices, cultural factors and energy efficiency improvements. These

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elements have an impact on the number and size of households, the heating or cooling demand, the quantity and types of appliances existing and their patterns of use (IEA, 2012a).

In order to reduce the CO_2 emission from the residential and commercial sectors the main drivers are:

- Use of more efficient equipment: including lighting, appliances, heating and cooling systems.
- Improve the building shells to reduce energy demand.
- Increase the use of renewable energies.
- Induce changes in energy consumption behaviour.
- Growth in renewable energy: renewables satisfy only 9% of the heat demand in buildings, mainly as bioenergy or solar heating for hot water (IEA, 2016c).
- Fiscal framework and support policies: they can foster the efficiency of the sector influencing standards in new construction and refurbishing of existing buildings.

Necessary analyses

In the **Industrial sector** the drivers identified are: fiscal framework, technological improvements, implementation costs and Degree or corporate thinking. Each of them can be studied using the following variables:

- **Fiscal framework:** CO_2 taxes; renewable incentives; technological improvements incentives.
- **Technological improvements:** energy intensity; available infrastructure; Best Available Technologies implemented; tonnes of fossil fuels replaced by renewable energy sources.
- **Implementation costs:** €/MW of renewables; €/tCO_2 saved; profitability.
- **Degree of corporate "green" thinking:** good governance indicators; voluntary measures tackle by companies to reduce its carbon print.

In the **residential and services sectors** the variables identified are: use of more efficient equipment, improvements in the building shells, and increase in the use of RES and Changes in energy consuming behavior. Each of them can be studied using the following variables:

- **Use of more efficient equipment:** sales of efficient lighting vs. sales of traditional lighting, sales of efficient appliances vs. sales of conventional appliances. Standards and incentives for the use of more efficient equipment. Energy intensity of the residential sector.

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- **Improvements in the building shells:** Standards about construction and remodeling requirements implemented in each country. Support policies and incentives for efficient construction and remodelling.
- **Increase the use of RES:** Residential final energy consumption mandatory share from RES, Renewable energies installed in new or refurbished buildings, Support policies for the use of renewable energies in buildings.
- **Changes in energy consuming behaviour:** this can be study analysing the variable "Residential final energy consumption by type of final energy".

Data availability

Different variables concerning the fiscal framework and policy incentives for the industrial, residential and commercial sector are available and qualitatively measurable, for example: CO_2 taxes, renewable incentives, technological improvements incentives, Standards and incentives for the use of more efficient equipment, standards about construction and refurbishment requirements implemented in each country, support policies and incentives for efficient construction and refurbishment or support policies for the use of renewable energies in buildings. However, a legislation analysis for each country is needed. Furthermore, the comparison among them to obtain a quantitative variable may be complex.

In the industry sector technological improvements are a key factor. They can be directly measured, for instance with data from the Best Available Technologies implemented or using variables such as Energy Intensity. Direct data about the number of Best Available Technologies implemented may be difficult to estimate but data about the energy intensity are available and provided, for example, by the International Energy Agency IEA (IEA, 2016b). By analysing the Industrial final energy consumption by type of final energy it is possible to estimate the amount of fossil fuels replaced by renewable energy sources.

To analyse the profitability of an energy efficiency investment, the implementation cost should be compared with the savings achieved in energy taking into account the electricity average cost for industrial consumers; natural gas average price for industrial consumers; diesel prices for thermal application and industrial consumers and the coal price for heating applications and industrial consumers. All these variables are also considered important for other estimations and have already been included in the model.

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The degree of corporate thinking is difficult to measure but it can be considered high in companies with high technological improvements not supported by a fiscal framework and without a short term profitability.

In the Residential and Services sector legislation and incentives can be analysed calculating the "Residential final energy consumption mandatory share from RES" and also the "Standards about construction and refurbish requirements implemented in each country" and "Support policies and incentives for efficient construction and refurbishment". Due to the difficulty of assigning values to these variables, the "Residential final energy consumption mandatory share from RES", already considered for the model, could be the best indicator.

The use of more efficient equipment can be analysed using the energy intensity of the residential sectors because other data as "sales of efficient lighting vs. sales of traditional lighting" or "sales of efficient appliances vs. sales of conventional appliances" may be difficult to obtain.

Changes in the energy consuming behaviour and the use of RES in the residential sector can be analyse using the "Residential final energy consumption by type of final energy".

Summarising, the variables considered essential are:

- Energy intensity of the industry sector
- Energy intensity of the residential sector
- €/MW of renewables
- Residential final energy consumption by type of final energy

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Social welfare and environmental impacts indicators analysis

In this subtask, social welfare indexes such as Human Development Index and other index data are collected, and their statistics are analysed. Through the energy per capita requirements for social welfare, CO2 emissions are estimated and so are the impacts of changes of land and water uses due to the transition to a low-carbon economy. Adaptation to climate change in terms of increase social energy requirements (in heating and cooling) is also be evaluated.

Social welfare and inequality data analysis

Ways of model integration

Maintaining social welfare is an important aspect of transition to low-carbon economy. Several studies (e.g. Easterlin, 1974, among the most famous ones) argue that human well-being cannot be measured simply by economic indicators such as GDP. Hence, there is a need to identify drivers of human well-being and to find proper indicators that could serve for the assessment of social welfare for the modelling purposes. This section should identify the main drivers of social welfare that are key for transition to low-carbon economy.

There are two ways of addressing life satisfaction – based on "objective" indicators, and, on the other hand, on subjective (i.e. self-reported) level of happiness. We propose to connect social welfare with (in)equality issues, and try to establish link between social welfare and economic production. Specifically, we the MEDEAS Social module should provide answers to the following questions:

- What are the suitable **indicators** to measure social welfare?
- What are the **factors** influencing social welfare, apart from levels of production (and consumption)?
- What role does **(in)equality** in terms of income **distribution** play?
- How much is social welfare linked with **economic production**?
- Up to which levels of consumption does the human well-being rise?

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Necessary analyses

Which indicators reflect drivers identified as key for social welfare and transition to low-carbon economy? In this part we explain and justify our choice of indicators. Then we discuss possible contributions of these indicators to model development. We touch also their criticisms.

By asking the questions raised in the previous part, we have identified four indicators for the purpose of MEDEAS Social module:

- Gross Domestic Product (GDP) – one-dimensional;
- Human Development Index (HDI) – composite;
- Happiness index – composite;
- Gini index – one-dimensional.

GDP is included as probably the most popular socio-economic indcator showing the level of production and consumption of all final goods and services produced in a given period, although we are well aware of its limitations, described systematically e.g. by Van den Bergh (2009).

HDI is a composite indicator, focusing on broader aspects of the socio-economic performance, not just those visible in monetized economy. Except from per capita Gross National Income (GNI), it takes into account life expectancy and education – see Figure 6.

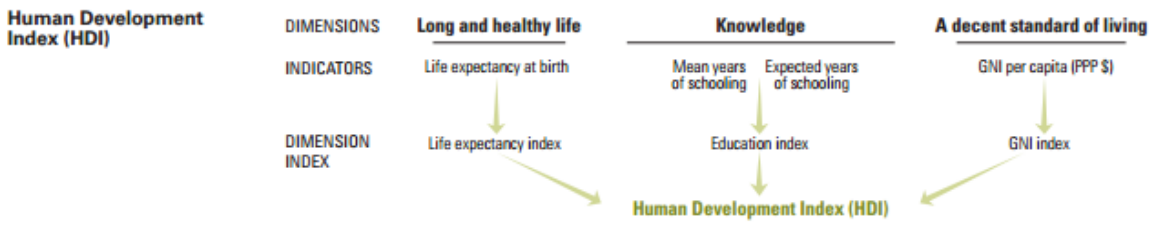

Figure 6: *HDI components. (Source: "Human Development Index (HDI)", 2016). Conceptually similar procedure of merging various variables into one composite indicator is followed by World Happiness Reports. The difference is that the latter are based on subjective self-perception of wellbeing in five categories, rather than data collected by a central authority.*

Happiness index, based on World Happiness Reports, is also a composite indicator, based on ranking answers to life evaluation questions asked in a poll. The respondents are asked to rate their own current lives on 0 to 10 scale, ranking their own self-perceived happiness. The answers are weighted according to six factors: levels of GDP, life expectancy, generosity, social support, freedom, and corruption ("World Happiness Report", 2016).

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Gini index assesses (in)equality in a socio-economic unit, typically a state. Gini index measures deviation of the distribution of income within this socio-economic unit. A value of 0 represents absolute equality, a value of 1 absolute inequality.

These four indicators were selected because of their common use by international organizations, and thus also their relative trustfulness. Pragmatic reasons, i.e. data availability across time, also played a role, because of the need to correlate the datasets.

Pros and cons (regarding their contributions to MEDEAS model) of each of the above suggested indicators are discussed in the respective Annex. Based on evaluation of the suggested indicators, we were trying to investigate their relations. The goal was to suggest possible links and interdependencies for the MEDEAS model structure. We analysed correlations on the global aggregate level between:

1. **HDI and GDP** to see their mutual position (and, regarding the report about energy, emissions and social welfare, to see which of them should be linked with energy consumption per capita);
2. **HDI and Gini index** to see links between composite social welfare indicator and (in)equality;
3. **GDP and Gini index** to see the relation between economic production/consumption levels and (in)equality;
4. **GDP and Happiness index** to see the contribution of purely economic indicator to self-reported level of life-satisfaction;
5. **HDI and Happiness index** to see the link between broader "developmental" composite indicator and happiness perception;
6. **Happiness index and Gini index** to see the relation between (in)equality and self-reported level of life-satisfaction.

It should be noted that our datasets were (in case of Gini index and HDI) composed out of country level data. Hence, the correlations on a global level have been derived from weighted aggregates, and should therefore be taken with caution. The correlations only provide an indication. Further analyses can (and should) be made accordingly, depending on the MEDEAS model demand. Panel regressions for all countries will provide much stronger evidence, depending on the needs of MEDEAS model.

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Data availability

To answer which drivers and variables concerning social welfare should receive highest priority, given relevance, required analyses, and potential data constraints, we discuss the results of our analysis.

- The strongest link has proved to be between GDP and HDI.
- The model should therefore take into account GDP as having impact on social welfare measured by HDI.
- However, GDP can contribute to, not explain social welfare.
- Even composite indicators such as HDI cannot themselves be seen as drivers of human well-being or social welfare.
- Happiness is probably a suitable complement to HDI or even GDP. These two or three (happiness and HDI/GDP) can provide a relatively good notion of social welfare within a given socio-economic unit.

To strengthen this basis of social welfare describing indicators, MEDEAS model should take into account (in)equality in terms of income (measured by Gini index). Albeit Gini index seems to be only relatively weakly linked with happiness, this might very likely be due to poor data basis, and the link between (in)equality and hapiness/human development should be further studied and elaborated, e.g. with panel data for particular countries.

Environmental impacts indicators analysis

Ways of model integration

To select the best suitable indicators for an impact assessment of the RET we used as a framework the main developed modules within the MEDEAS model. Such model modules are: Economy, Energy, Materials, Land, Climate and Social. Here, due to the main objective of this subtask (environmental indicators), we will focus on Energy, Climate and Land. However, we also report some indicators regarding Ecosystem and Water. Ecosystems are a key player in food security, which affects both, Economy and Social issues. Biosphere and the so-called ecosystem services directly affect atmospheric and ocean GHG (which, in turn, impact Earth's climate).

- **Ecosystem:** Considering Planetary Boundaries as a framework, we selected 4 indicators to cover the main ecosystem aspects, that to date, better capture and summarize information and with open data sources.

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- **Climate:** We selected indicators selected in the AR5 IPCC reports to track Climate Change impacts.
- **Water:** Water is a key factor of interaction between human activities, ecosystems and natural resources. One of the main issues to consider is the water cycle as a whole and its role in the availability of freshwater for human uses.
- **Energy:** In this area there were two main sets of indicators that can be analysed: energy environmental impacts (mainly emissions) and energy efficiency indicators. We have selected three indicators that can give information of the ratio of electricity produced by renewables, the energy consumption per capita, and the amount of energy produced by RES.

Necessary analyses

A total of 120 indices have been explored under the ecosystem, climate, water, and energy areas. For each area we selected 14 key indicators reported bellow.

- **Terrestrial net primary (plant) 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. It refers to measurements of biomass and estimated NPP for terrestrial sites worldwide. NPP provides a measurable boundary for human consumption of Earth's biological resources.
- **Global Assessment of Human-induced Soil Degradation (GLASOD):** world map of human-induced soil degradation, using a expert-based approach. The status of soil degradation is presented in detail: extent, degree, rate and main causes of degradation.
- **Biodiversity Intactness index (BII):** gives the average richnessin a specific area impacted by a set of anthropogenic activities relative to their abundance in an intact ecosystem. See also Local Biodiversity Intactness Index-LBII (under construction: http://www.predicts.org.uk/)
- **Ecological footprint (EF):** is a measure of human impact on earth's ecosystems (of resource use). It is the amount of environment required to produce the goods and services to support our lifestyles. EF is a "measure of how much area of biologically productive land and water an individual, population or activity requires to produce all the resources it consumes and to absorb the waste it generates, using prevailing technology and resource management practices."
- **GHG emission levels** amount of Greehouse Gas released to the atmosphere per year. It is measured in million of metric tons of carbon dioxide equivalent.

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- **Atmospheric GHG concentration levels:** concentration of GHG at a certain time. It is measured in parts per million (ppm).
- **Changes in global temperature and sea-level rise:** refers to the changes in the global mean surface temperature (Celsius degree per year) and mean sea level rise (Global Mean Sea Level in mm per year).
- **Changes in regional climate variables:** they are related to changes in regional temperature, precipitation, solar radiation, relative humidity and air speed.
- **Changes in the intensity or frequency of extreme events:** they can include heat waves, droughts, heavy downpours, floods, hurricanes and changes in other storms.
- **Carbon Footprint (CF):** The concept originates from the ecological footprint indicator (see above). CF is the amount of all GHGs (including Carbon) produced to directly and indirectly support human activities, usually expressed in equivalent tons of carbon dioxide (CO2). It is an indicator of unsustainable energy use.
- **Water Footprint (WF):** measures the amount of freshwater resources are used and polluted. Is an indicator of freshwater use, of direct water of a consumer or producer and the indirect water use.
- **Share of renewable energy:** is the amount of renewable energy consumed for electricity, heating and cooling, and transport in the EU member states with actual and normalised hydro- and wind-power generation, and expressed as share against gross final energy consumption. The units of this indicator are ktoe. This indicator is developed to track the evolution of the Europe 2020 strategy for renewable energy in the EU.
- **Energy use (kg of oil equivalent per capita):** refers to use of primary energy before transformation to other end-use fuels, which is equal to indigenous production plus imports and stock changes, minus exports and fuels supplied to ships and aircraft engaged in international transport (IEA, 2016b).
- **Renewable power capacity (GW):** is the maximum net generating capacity of power plants and other installations that use renewable energy sources to produce electricity. For most countries and technologies, the data reflects the capacity installed and connected (IRENA, 2016).

Data availability

For each indicator we report the data availability, data sources and, if possible, type and quality of the data.

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- **Terrestrial net primary (plant) production (NPP):** 82 NPP data sets are available online, covering the major world ecosystem types. Used to validate models of vegetation-soil-atmosphere interactions within the global carbon cycle and to calibrate remote sensing of vegetation worldwide.
- **Global Assessment of Human-induced Soil Degradation (GLASOD):** The type, extent, degree, rate and main causes of degradation are documented and can be downloaded.
- **Biodiversity Intactness index (BII):** Under construction: National Biodiversity indicators are under development after the Aichi Biodiversity Targets: https://www.bipindicators.net/
- **Ecological footprint (EF):** The Ecological Footprint measures for a particular population or activity how fast we consume resources and generate waste compared to how fast nature can absorb our waste and generate new resources. Two types of data: Biocapacity (biologically productive area available) and Ecological Footprint.
- For GHG emission levels, Atmospheric GHG concentration levels, Changes in global temperature and sea-level rise, Changes in regional climate variables, Changes in the intensity or frequency of extreme events, Carbon Footprint (CF), different International organisms provide information about the cited climate indicators but IPCC collects and has a database where the historical and forecasts data can be downloaded.
- **Water Footprint (WF):** Data can be measured in cubic metres per tonne of production, per hectare of cropland, per unit of currency and in other functional units. Five datasets are included in the WF database: product water, national water, international virtual water flow, water scarcity and water pollution level.
- For all the energy indicators (**Share of renewable energy, Energy use, Renewable power capacity**) there are two main source of data for the two geographical levels required. For global data it can be used the World Bank database or the IEA database. For EU there are Eurostat and the European Environment Agency databases.

Current global and European energy per capita and link with social welfare

Ways of model integration

Energy is an important requisite for human development. The relation between energy consumption and social indicators has been analyzed extensively (see, e.g. Steinberger and Roberts, 2010). Many studies demonstrate strong correlations between energy consumption and living standards at lower levels of “development”, but this relation weakens with increasing stages

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of "development". Most frequently, the relation of the Human Development Index (HDI) with primary energy demand has been studied.

Recently, also the indirect energy footprint has been analyzed. Arto and colleagues (Arto et al., 2016) show that the relation is considerably stronger when the HDI is related to the energy footprint. This has important consequences for model development: If the **HDI** is taken as a key indicator of model outcomes, then the link may be preferrably made with the **energy footprint**. Alternatively, combinations of GDP and energy consumption could be tested as explanatory variables for the HDI composite.

The link of **energy consumption** to the **education** level, unemployment, and working hours and labor sharing may have to be considered in the model framework. The first dimension, namely education and training, may be a key parameter for some policy makers and stakeholders more generally. We show that education has an effect on energy intensity and could therefore be an important policy parameter.

Second, the effects of the scenarios and pathways of low-carbon energy transition may result in different levels of **labor demand** and resulting **unemployment**. In addition, some stakeholders may consider reduced work time and would be interested in its effects on the future economy. Therefore, we analyze relations between working hours, Gross Domestic Product, and the energy intensity of an economy.

Necessary analyses

The hypotheses described above provide an indication of the analyses required to test potential and establish and parameterize relevant model relationships:

1. **Household energy demand and GDP** to model the direct energy consumption demand of households,
2. **Household energy demand and HDI,** and
3. **Energy footprint (indirect energy demand) and HDI** to test which relation is most important to establish a feedback relationship in the model, in addition to the currently suggested link between GDP and HDI;
4. **Education and energy intensity,** as education may be a potentially crucial policy variable for several stakeholders;
5. **Unemployment, labor sharing, and GDP,** as labor sharing is frequently discussed as a policy measure for sustainability transitions;

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We provide preliminary descriptive analyses and results on these relations. The following figure depicts the relation between final per capita energy demand of households, as provided in the WIOD database, and constant GDP per capita (constant 2010 USD).

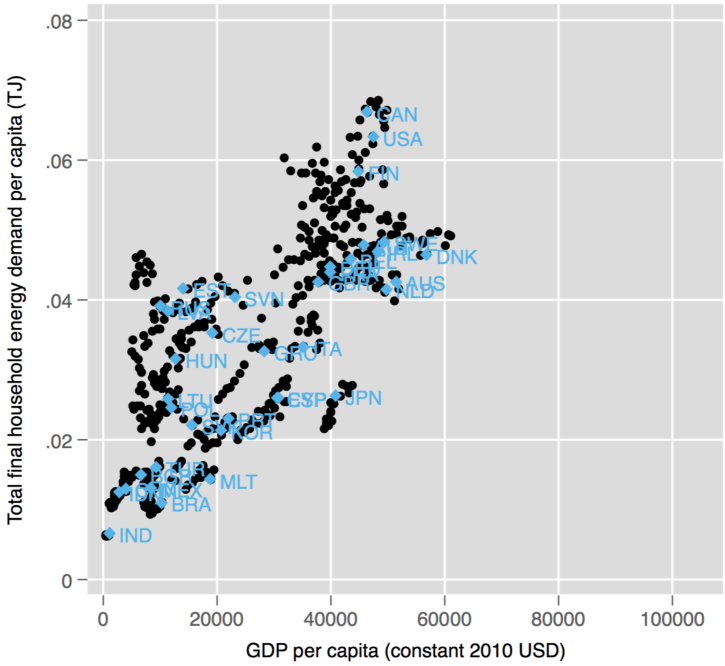

Figure 7: *Relation between final per capita energy demand of households and GDP per capita. Source: own calculations based on WIOD, IEA and World Bank data*

While the relation between income and energy consumption has been extensively studied, the country level variables and properties have received less attention. This could have important consequences for model development, also when focusing on a global scale. The influence of climate change on heating and cooling, e.g., could influence this relation. A random effects panel regression could reveal such country-level differences.

Naturally, the composite index is supposedly most strongly related to its component elementary indices and proxies. Inequality and education are two key components of the HDI. Inequality, as studied in task 2.2.e.1., is both an important result and a potential driver of aggregate income (GDP) and consequently also energy consumption. Similarly, also education has an influence on other model parameters. Therefore, a decomposotion or **step-wise partial aggregation** should be considered in model development to take into account the **endogeneity** of some of the variables included in the HDI. The following to relations make this clear:

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First, energy consumption and education are related in multiple ways. Higher education may lead to a reduced energy intensity in production, as shown in the report.

Second, equality is related to higher GDP levels, but also to higher energy demand. A careful specification could therefore increase the model precision considerably.

A low-carbon energy transition may effect labor demand and therefore result in different levels of unemployment, as shown by some indicative analyses. Finally, we find relations between working hours and GDP that could be considered to take into account policy measures related to labor sharing, which is considered crucial by some authors concerning a general sustainability transition.

Data availability

We use the WIOD database for sector-specific gross output, value added, energy use, skill of labor, and hours worked. Therefore, we draw from the main WIOT structure (Dietzenbacher et al., 2013) and from the environmental and socio-economic satellite accounts:

- The environmental accounts include data on energy flows in each of the NACE entities. WIOD uses the international energy balances provided by the IEA based on a joint annual survey by IEA/OECD/ESTAT/UNECE with harmonised methodologies and definitions, and derives sector-level energy accounts. The correspondence key is easily established for some of the NACE entities, but in some cases, the energy balance needs to be related to more than one industry. This is the case for “road transport”, which is distributed to all industries and households, and “commerce and public services” (Genty et al., 2012).
- Another problem occurs due to the differences between national accounting frameworks and national inventory balances due to the residence principle used in the former, and the territorial principle used in the latter. This is especially critical in the case of all transport sectors, for which a bridging framework is necessary (Genty et al., 2012, p. 8). Any analyses related to territories and transport should therefore be done with caution, considering the implications of the data bridge.
- Data on employment by skill levels, wages, and total hours worked have been collected from different sources, in most cases from the labor force survey (LFS). For most OECD countries, labor data from the EU KLEMS database is used. One caveat emerges concerning the underrepresentation of self-employed labor, which leads to imputation difficulties especially for less advanced economies and the agricultural, trade, business, and personal services sectors (Erumban et al., 2012).
- For skill levels, the 1997 International Standard Classification of Education (ISCED) is used to categorize low, medium, and high skill labor. Low skills include basic education, including lower secondary, medium skills include secondary and post-secondary, but non-tertiary

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education, and high skills include first and second stages of tertiary education (Erumban et al., 2012, p. 4). Caveats of imputations for wage data are not relevant here, because no analyses are based on this data.

Land uses due to the transition to a low-carbon economy

Ways of model integration

Land is one of the main modules of MEDEAS together with Economy and Population, Energy, Climate, Materials and Social. This module will cover two main objectives: (1) assess the potential restrictions that land availability might impose to RES deployment (mainly bioenergy, solar and pumped hydro), and (2) estimate the land-use change GHG emissions to feed the climate model.

We identify the following important drivers that must be included in the model (Smith et al, 2010):

1. Population growth and urbanization trends, which drive the urban land requirements,
2. Diets and incrase in food demand, which drive the land-uses for agriculture and livestock (Kastner et al., 2012),
3. Energy policy, since transition to RES will intensify the competition for land due to the lower density of RES in relation to fossil fuels (Scheider and Sorman, 2012) (see Figure 7),
4. Climate policy, given that the future availability of technological ways to sequestrate carbon (such as carbon capture and storage CCS) may even not be available at the large scale required, afforestation and soil-management emerge as key strategies to store carbon (Hansen et al., 2016).
5. Land-use practices and management.
6. Global environmental change/climate change impacts and biodiversity loss drive soil degradation, soil erosion and deforestation.

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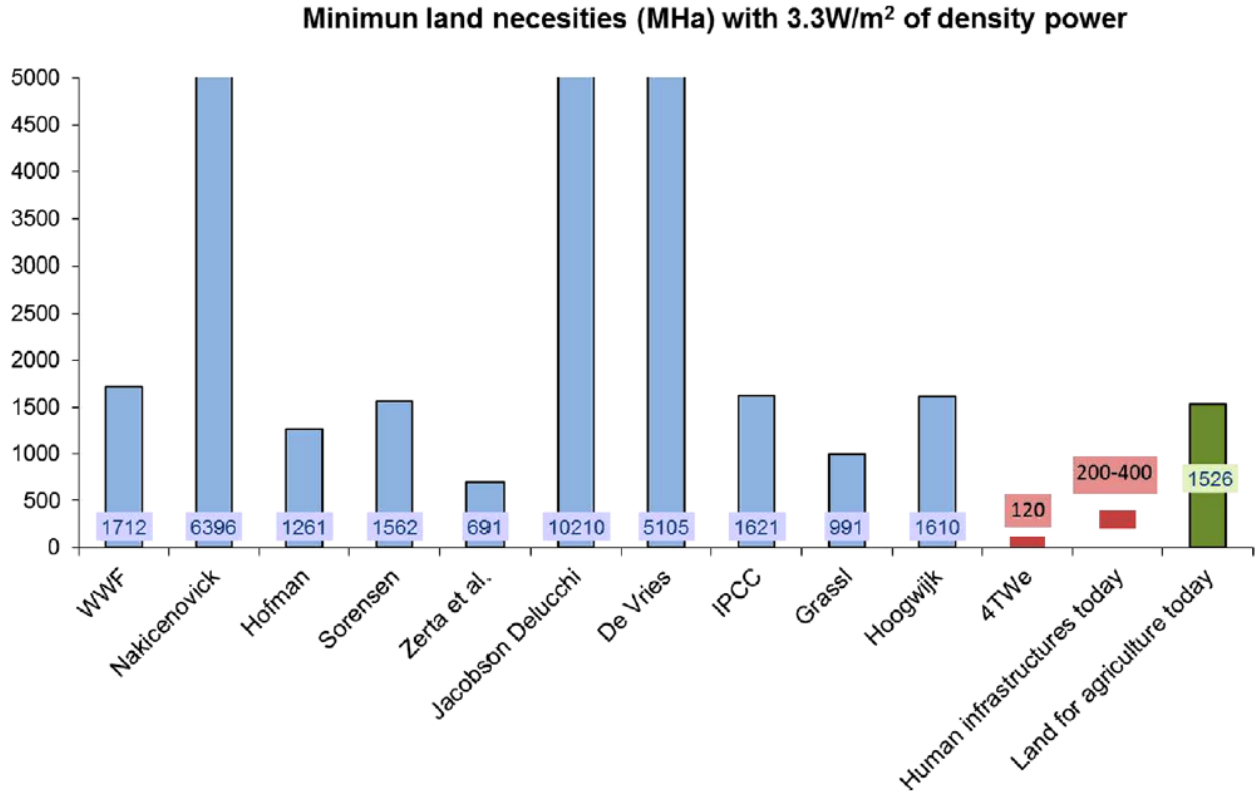

Figure 8: *Minimum land requirements with the estimated power density. Source: de Castro et al., 2013. Minimum land requirements with the estimated power density 3.3We/m2 to reach the technical potentials in the literature (blue columns). For comparison, the land requirements for a net power production of 4TWe (red column), the approximate current area occupied by human settlements and infrastructures (red bar) and the land currently dedicated to agriculture (green column), are also represented.*

Necessary analyses

We assume that the most crucial are the data related to:

1. Land for covering human needs (food, fiber, shelter and infrastructure)
2. Land for bioenergy and RES generation technologies,
3. Land for capturing CO2,
4. Land to assure biodiversity conservation,
5. Useful land lost due to soil degradation and erosion.
6. Water availability.

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These variables are affected by other modules of MEDEAS. For example, degraded land and biodiversity conservation trends will be critically affected in the future by the level of global environmental change. The energy mix will drive the land requirements for energy production. Assumptions about energy and food security for the regional modeling of Europe should be made given that substantial levels of both food and energy (mainly in the form of biomass) can be imported (Johansson, 2013).

Data availability

The variables, that would describe those factors, are identified as:

1. Demand of food, fiber, shelter, settlement and infrastructures,
2. Future yields of crops,
3. Surface power densities of energy crops and technologies,
4. Energy demand (and mix),
5. Land availability for human uses compatible with biodiversity conservation,
6. Climate policies for storing carbon in land (afforestation, soil management, etc.), inverting historical trends (see Figure 8)
7. Climate change impact on land degradation

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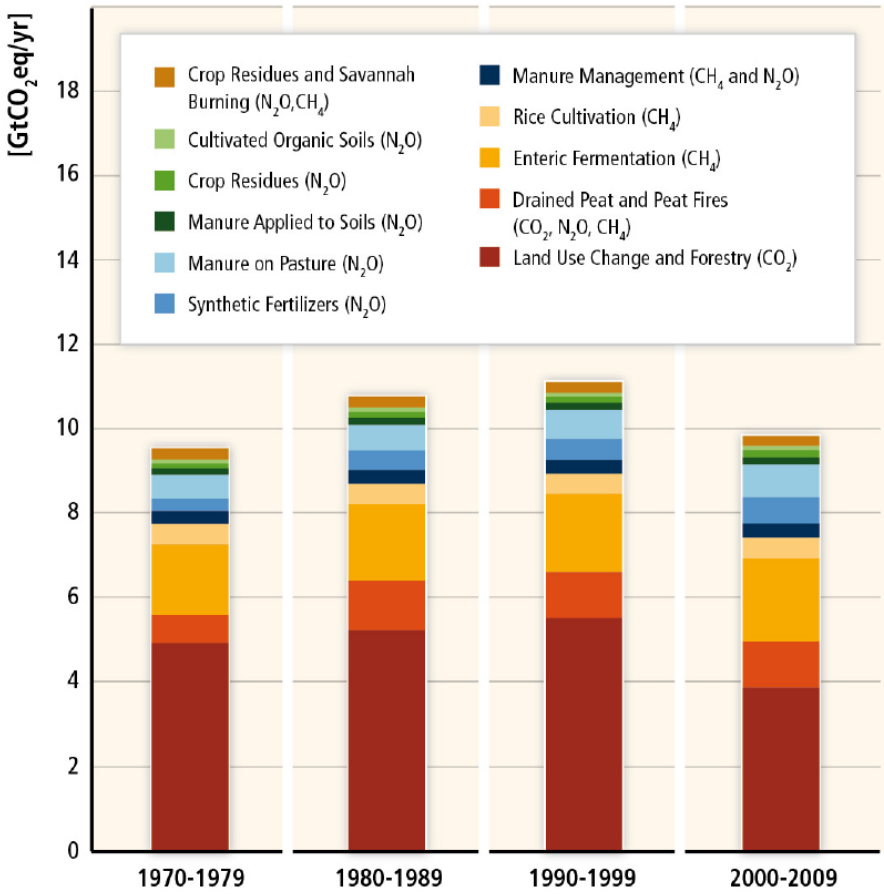

Figure 9: *AFOLU emissions for the last four decades. For the agricultural sub-sectors emissions are shown for separate categories, based on FAOSTAT. Source: IPCC, 2014a*

Water uses due to the transition to a low-carbon economy

Ways of model integration

Water is an important input for nearly all forms of energy production, from fossil-fuel extraction, transport and processing, to power production and irrigation of feedstock for biofuels. In the transition to a low-carbon economy, the constraints from water availability, withdraw, and effective supply should be taken into consideration in the MEDEAS modeling simulation.

The following forces need to be considered in specifying the water constraints:

- Future population and their life-style in relationship with water consumption and energy use. Residential water use is an important force competing with the energy sector for water.

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- Water availability, withdrawing potential, and expected increase in supply capability at the scale of country and river basin.
- Historical patterns (at the levels of country and river basin) on water use across the sectors of agriculture, manufacturing, energy, and residence; and the expected water-use efficiency gains in each of the above sectors in the future.
- Development scenarios of agriculture, manufacturing, and services, consistent with the current Sustainable Socioeconomic Pathway (SSP) implementations.
- Virtual water flows embodied in trade in general and transboundary electricity supply in particular.

Necessary analyses

Although at the EU aggregation, water shortage is not a concern, it is well-known that water resources are unevenly distributed across countries and regions of Europe. The same amount of water consumption in a water scarce region may lead to severe environmental impacts compared with the impacts in a water-rich region. Thus, **it is crucial to take water scarcity into account when assess the water impacts of low carbon pathway**.

Data availability

For historical water use in EU countries, the group for Ecological Systems Design at the Institute of Environmental Engineering, ETH Zurich (http://archive.baug.ethz.ch/www.ifu.ethz.ch/ESD/downloads/WATER_DATA.html) provides water consumption coefficients for agriculture, manufacturing, residence, and electric power generation. ETH's water consumption coefficient for electricity power generation in different countries is based on individual country's energy mix (Pfister et al., 2011).

ETH team also provides data on water stress measure (water stress index; Pfister et al., 2009). The aggregation of this index is freely downloadable from the above web-site. The maps of the index across 50x50km grid-cells are accessible based on signing a collaboration agreement.

For introducing future water constraints into the MEDEAS model, a short-cut is to establish scenarios on water-use efficiency gains for individual water-use sectors (higher water-productivity or lower water use coefficients), and adopt water supply scenarios from IIASA's Water Programme.

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Adaptation to climate change in terms of increase social energy requirements (in heating and cooling)

Ways of model integration

The results of the Work Package 4 conceptual overview of the MEDEAS model assume that additional energy investments will be required for adaptation to climate change (CC), reducing the Net energy supply availability. We analized two of the key sectors that are directly influenced by climate change – heating and cooling:

- Based on projections overviewed by (IPCC, 2014b), it is highly agreed that **CC will globally reduce energy demand for heating and increase energy demand for cooling in the residential and commercial sectors.**
- Heating and cooling in the **industrial sector** lacks attention in most of studies, although the share of demand of heating for industry in cold and temperate countries is almost as significant as in residential and commercial buildings sector and in warmer countries even higher (IEA, 2016d). Therefore the industrial sector is also taken into account in this report.
- The balance of the energy demand for heating/cooling influenced by CC depends on the **geographic (regional), socioeconomic and technological drivers** of the CC adaptations, so we explore the issue from these perspectives and also add the **aspect of adaptation policies**.
- We concentrate also on the supply side of the energy sector, looking at the impact of CC on different energy sources, particularly on the water-energy nexus of cooling in thermal and nuclear power plants, in which decreasing efficiency has been projected.
- We also present the potential of renewable energies in heating/cooling adaptation. Studies also indicate that there are important interactions between adaptation and mitigation practices with both potential synergies and trade-offs.

Necessary analyses

First, we suggest understanding CC impacts, respectively energy requirements for adaptations, as influencing both demand and supply of energy. Second, we suggest discussing impacts of CC on energy consumption attitudes of individuals and also impacts of policy implementations. Third, we suggest including also CC mitigation practices in the further development of the model.

- The heating and cooling sectors are considered to be the most influenced by CC temperature changes, often considered the only or primary impact of CC.

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- However, it has to be understood, that the impact of CC on the sectors is relatively small in comparison to other drivers, such as **demographic changes**, **technology**, **lifestyle**, **regulation** and **governance**.
- We understand these drivers as wider **trends**. Their relative importance incl. relative importance of the CC will differ regionally as well as over time. For each of these trends, we suggest to take into account the following variables.
- **Energy demand:** Millions of tons of oil equivalent (Mtoe) per resource type
- **Increasing income:** Income per capita, Gini Index
- **Demographic and lifestyle changes:** Floor area per capita, Household size, Population growth rate
- **Building regulations, energy efficiency and rising price of energy:** Average cost of energy (by source) for household consumers, Average cost of energy (by source) for industrial consumer, Energy productivity by source, Building regulations variables
- **Regional drivers** (in urban regions – such as urban heat island effects, climatic regions): Heating Degree Days (HDD), Cooling Degree Days (CDD) (Isaac and van Vuuren, 2009); Air temperature, Days with reduced energy production
- **Energy supply drivers** regarding water-energy nexus: Days with reduced useable capacity, Annual/Seasonal streamflow changes and shifts
- **Climate change adaptation drivers:** Days with reduced useable capacity, RES energy production by technology, Investment in RES capacity, Renewable energy consumption by source and sector, Qualitative and quantitative survey energy consumption attitudes by sector, Heat (Cold) related mortality; Demographic variables; Biophysical variables, Costs of concrete policies (investment costs, operation costs, but also CBA and SWOT analyses

Globally, (IEA, 2013b) expects that by 2050 **energy demand for space heating will increase by 12% from the 2010 level, compared with 28% in the absence of climate change. In the same scenario, global space cooling demand is projected to rise by 220%, compared with 175%.** The solely CC impact is projected to decrease the global energy demand in 2050 due to higher decrease of heating, than increase of cooling. However, a reverse pattern is expected in the second half of the century with a global energy increase from CC impact (Isaac and van Vuuren, 2009). **For Europe, by considering both heating and cooling, total energy demand during 2000-2100 is estimated to decrease** (Isaac and van Vuuren, 2009)**.**

Data availability

Energy requirements resulting from the adaptation to CC are generally difficult to project due to:

- Uncertain predictions of wider trends (GDP, population, technological progress, industrial performance, etc.)

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- Various CC scenarios, whose relevance is fundamentally connected to the economy-energy nexus and performance resulting in CO2 emissions
- Need for availability of various datasets– climatic indicators, demographic indicators, technological indicators, macroeconomic indicators, biophysical indicators and behavioral surveys

Under these conditions, the suggestion to the MEDEAS consortium for the further development of the model would be to focus mainly on variables that enable model calculations of energy required for residential heating and cooling, such as HDD, CDD. Analyses focusing on energy effectiveness of the energy sector and of new technologies and buildings are available and adjustable. Analysis of the industrial sector is however limited due to constraints of industry performance in the future globally as well as in concrete regions. It is suggested to project the industrial sector in a shorter scale.

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Conclusions

Electricity sector

An overview of the various projections of the **electricity grid** to 2040-2050 and their comparison from different perspectives was presented.

- Given the different times they were developed in, various data-bases used and targets pursued, it becomes evident that there exist serious differences between them, both in scope and in results.
- In order to enable the comparisons, it became necessary to make extrapolations for some of them.

As a result of the analysis and comparisons, two projections are proposed for consideration within the MEDEAS project:

- WEO projections for the World (IEA, 2016), and EU Roadmap2050 for the European Union (EC 2011a).
- The current level of information requires further checks and supplementation with a combination of different sources.
- It is expected that after the approaching WEC's Congress in Istanbul, a new version of the projections will be released.
- Especially useful will be the information from the ongoing development of the Energy Roadmap 2050.

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Transportation sector

In the due report we draw the **general monetary and energetic estimates to perform the transition in every transportation sector**, including the change in fleet and infrastructure.

The report also states the fact that the analysis conducted has limitations, including:

- introduction of technologies that might replace the critical resources or alleviate the energetic deficit
- population growth and distribution
- scenarios of conversion of the current fossil fuel transport to electric transport
- economic growth
- readiness and global states' consensus on deployment of decarbonized economy, that can translate in different scenarios of how the transition is financed and fostered.

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Total primary energy extraction

Concerning **production curves of non-renewable energy resources considering Renewable Energy Transition**, the main drivers are:

- Supply potentials with their respective supply costs;
- Energy prices;
- Technological improvement;
- Fossil fuels embedded in renewable energy technologies.

The variables associated are:

- Supply potentials: type and size of deposits (i.e. reserve or resource),
- Supply costs: extraction costs of a deposit
- Energy prices: EU energy imports, market price developments of non-renewable energy sources
- Technological improvement: energetic extraction costs of a deposit
- Fossil fuels embedded in renewable technologies: energy return on energy invested of a renewable technology, share of fossil fuel consumption, material requirements, efficiency and full load hours of renewable technologies

The main drivers of the **primary energy extraction related to mineral commodities** are:

- Supply and demand, as they are related to availability of mineral resources and to future demand estimations.
- Additionally, information regarding the energy needed to extract, process and recycle those commodities is crucial to have a better understanding of the impact of the mining sector.

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Industry, residential and commercial energy requirements

- Energy efficiency is the main driver to decrease the carbon production in the industry residential and commercial sectors.
- Technological improvements and its implementation cost are key for the industry.
- The use of more efficient equipment and the improvements in the building shells are necessary measures in the residential and commercial sectors.
- In all the sectors the fiscal framework and support policies can foster these drivers. Furthermore, the corporate and individual willing is another necessary promoter.
- The variables considered essential are the energy intensity of the industry sector, the energy intensity of the residential sector, €/MW of renewables and the Residential final energy consumption by type of final energy.

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Social welfare and environmental impacts indicators analysis

SOCIAL WELFARE:

- The strongest link has proved to be between GDP and HDI, thus the model should take into account GDP as having impact on social welfare measured by HDI.
- However, GDP can contribute to, not explain social welfare.
- Even composite indicators such as HDI cannot themselves be seen as drivers of human well-being or social welfare.
- Happiness issues instead of HDI or even GDP are a better driver of the social welfare itself, even though happiness seems not to be so strongly linked to the economic variables, here represented by GDP.
- This is probably because of the self-reporting nature of happiness reports that were used in the analysis.
- Thus, happiness together with HDI and GDP provide a broad enough basis to define the level of social welfare. Other new indicators such as Gross National Happiness Index could also be taken into account, once they dispose longer time series.
- The MEDEAS model should thus take into account inequality in terms of consumption issues (provided by Gini index data). Albeit Gini index seems to be only relatively weakly linked with happiness, it provides an interesting third dimension to the social welfare assessment, which impact on happiness is not included in any of the other composite indicators.
- The link between inequality and hapiness/human development should be further studied and elaborated, e.g. with panel data for particular countries.

ENVIRONMENTAL INDICATORS:

- A total of 120 indicators was explored.
- Based on the MEDEAS model, we have selected four areas to classify the environmental indicators.
- The selected areas are: Ecosystem, Climate, Water and Energy. For each area of study a set of indicators has been chosen.

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- The indicators selected have the common characteristics of having public available historical data, which can be found in international environmental organizations such as Eurostat, World Bank or European Environmental Agency.
- The main conclusion regarding environmental indicators is that, despite the amount of available indicators and their popularity for management purposes, there is a lack of agreement within the scientific community about the usefulness of some indicators (or sets of them) to capture the complexity of the phenomena they aim to represent.
- Besides, here we suggest the most representative in the areas selected, compatible with the modelling purposes, as a first step to consider for inclusion within the MEDEAS model.

Social welfare and energy use:

- A replacement of the HDI by its constituent variables should be considered, because some of the constituent variables are endogenous.
- Specifically, we suggest to consider effects of inequality on GDP and energy consumption
- Education level, another constituent of HDI, has effects on energy intensity
- Labor unemployment and renewables
- Labor sharing and working hours – GDP link
- While the relation between income and energy consumption has been extensively studied, the country level variables and properties have received less attention. This could have important consequences for model development, also when focusing on a global scale. The influence of climate change on heating and cooling, e.g., could influence this relation. A random effects panel regression could reveal such country-level differences.

Water:

- Water resources are unevenly distributed across countries and regions of Europe.
- The same amount of water consumption in a water scarce region may lead to severe environmental impacts compared with the impacts in a water-rich region. Thus, it is crucial to take water scarcity into account when assess the impacts of low carbon pathway on water.
- The estimation of water consumption coefficients for electric power generation in each EU countries has been provided by the group for Ecological Systems Design at the Institute of Environmental Engineering, ETH Zurich (http://archive.baug.ethz.ch/www.ifu.ethz.ch/ESD/downloads/WATER_DATA.html).

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- However, the corresponding coefficients for other energy sectors in each EU countries have been missing.
- For assess the impacts of future low carbon pathway on water, we would have to use water consumption coefficients of individual energy sectors at the EU level, with the assumption that energy supply in general and electricity supply in particular would become more and more integrated.

LAND:

- **Land** is a critical component of any analysis focusing on sustainability:
- Without correcting actions, the main drivers of land-use will continue to operate in the next decades: population growth, urbanization trends and shift to more land-intensive diets.
- Additional factors may arise in the next decades as a result of the promotion of renewable energies and climate policies.
- The EU is especially vulnerable to future developments given its current high dependence on foreign land, mainly from Latin America and Africa.
- The Land module in MEDEAS will be directly linked with -at least- three other modules: Economy and Population (e.g. through food and services demand), Energy (e.g. through energy policies, i.e. land requirements of different energy mixes) and Climate (e.g. through land-use change CO2 emissions).
- An analysis of the historical data of land use categories and the drivers of land-use change at both global and European level should be done in order to establish the relationship between the variables of the model.
- Projections of future food requirements (including diets), urbanization and infrastructures expansion, degraded land, required land for preserving biodiversity should be built in a scenario methodology framework.

ADAPTATION TO CLIMATE CHANGE IN HEATING AND COOLING:

- Climate change is projected to increase global energy demand in 2100, with a downward shift until 2050, when the global energy demand resulting from CC adaptations actually decrease:
- In Europe, a total CC related energy decrease is estimated until 2050, with decreasing requirements for heating, but increasing requirements for cooling.

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- Adaptations are fundamentally influenced by regional aspect, but they will vary among sectors (residential, commercial, industrial) and they will have important technological and political implications over time.

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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

List of Tables

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

List of Figures

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

List of Annexes

Annex 1: Task 2.2.a Rates of increase of electricity infrastructure and associated energetic cost (Global and European).

Annex 2: Task 2.2.b Transportation transition energy costs: change to a different energy supply.

Annex 3: Task 2.2.c.1 Production curves of non-renewable energy resources considering Renewable Energy Transition.

Annex 4: Task 2.2.c.2 Exergy extraction curves considering non-renewable resources and raw materials.

Annex 5: Task 2.2.d.1 Energy consumption of industry, residential and commercial sectors.

Annex 6: Task 2.2.d.2 Exergy replacement costs for the materials used in the European economy.

Annex 7: Task 2.2.e.1 Social welfare and inequality data analysis.

Annex 8: Task 2.2.e.2 Environmental impacts indicators analysis.

Annex 9: Task 2.2.e.3 Current global and European energy per capita and link with social welfare.

Annex 10: Task 2.2.e.4 Land uses due to the transition to a low-carbon economy.

Annex 11: Task 2.2.e.5 Water uses due to the transition to a low-carbon economy.

Annex 12: Task 2.2.e.6 Adaptation to climate change in terms of increase social energy requirements (in heating and cooling).

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