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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 D2.1

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LIST OF ANNEXES

NOMENCLATURE

a:Si: amorphous silicon
ANFAC: Association of Spanish Automobile Manufacturers
Avg: Average
BAU: Business As Usual
BEV: Battery Electric Vehicle
BGS: British Geological Survey
BOL: Beginning Of Life
BP: British Petroleum
BTL: Biomass to liquid
CAES: Compressed Air Energy Storage
CdTe: Cadmin Telluride
CIGS: Copper Indium Gallium Diselenide
CIPK: Carbon density per kilowatt
CRS: Central Receiver Systems
CSP: Concentrated Solar Power
DST: Domestic Storage
Dv: duplicated variable
EC: European Commission
EIA: Energy Information Administration
EJ: Exajoule
ENTSOE: European Network of Transmission System Operators for Electricity
EOL: End Of Life
EOL-RR: End Of Life Recycling Rates
EPBT: Energy Payback Time
ERC: Exergy Replacement Cost
EROI: Energy Return Of Investment
ETC: Evacuated Tube Collector
ETSAP: Energy Technology Systems Analysis Programme
EV: Electric Vehicle
FAO: Food and Agriculture Organization of the United Nations
FCE: Flash Crowd Effect
FCEV: Fuel Cell Electric Vehicle
FES: Flywheel Energy Storage
FPC: Flat Plate Collector
GA: Grant Agreement
Gb: Giga Barrel
GDP: Gross Domestic Product
GHG: Green House Gas
GJ: Giga Joule
Gt: Giga ton

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GVA: Gross Value Added
HDR: Hot Dry Rock
H2: Hydrogen
HHV: High Heating Value
HDR: Hot Dry Rock
HREE: Heavy Rare Earth Element
HST: Hydro Solar Thermotherapy
ICE: Internal Combustion Engine
ICT: Information and Communications Technology
IEA: International Energy Agency
IPCC: Intergovernmental Panel of Climate Change
IRENA: International Renewable Energy Agency
LDV: Light Duty Vehicle
LEAP: Longrange Energy Alternatives Planning System
LFP: Lithium Iron Phosphate battery
LFR: Linear Fresnel Reflectors
Li/S: lithium sulfur battery
LREE: Light Rare Earth Elements
MROI: Marketing Return on Investment
NBP: No biofuel Policy
NCA: Lithium, Nickel, Cobalt and Aluminium Oxide battery
NMC: Lithium, Nickel, Manganese and Cobalt Oxide battery
NOC: National Oil Company
NPV: Net Present Value
O&M: Operation and Maintenance
OECD: Organization of Economic Cooperation and Development
OPEC: Organization of the Petroleum Exporting Countries
OSR: Old Scrap Ration
PAV: Partially Aggregated Variable
PD: Parabolic Dishes
PGM: Platinum Group Metal
PHEV: Plug Hybrid Electric Vehicle
Ppm: parts per million
PPP: Purchasing Power Parity
PHS: Pumped Hydro Storage
PR: Performance Ratio
PT: Parabolic Trough
PV: Photovoltaic
R&D: Research and Development
RC: Recycling Content
RE: Reference Environment
REE: Rare Earth Elements

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REEV: Range Extended Electric Vehicle
REO: Rare Earth Oxide
RES: Renewable Energy System
RURR: Remaining Ultimately Recoverable Resources
SC: Supercapacitors
SHW: Solar Heat Water
SMES: Superconducting Magnetic Energy Storage
SNG: Synthetic Natural Gas
STC: Standard Test Condition
STP: Solar Thermal Power
TREO: Total Rare Earth Oxide
UNEF: United Nations Emergency Fores
UNEP: United Nations Environment Programme
URR: Ultimately Recoverable Resources
USGS: United States Geological Service
WEO: World Economic Outlook

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ABSTRACT

This document is the first technical deliverable of MEDEAS project and results from WP2 (Data collection) activities carried out from January to June 2016. It constitutes the basis for the development of MEDEAS model, providing the necessary variables to quantitatively set-up scenarios and pathways. It covers the following activities: 1) selection of Partially Aggregated PAVs for MEDEAS model; 2) Preliminary definition of feedback loops between key PAVs and 3) Identification of possible physical constraints and their relationship with the identified PAVs[1]. After a literature review and a comparative analysis with other relevant models, a total of 116 PAVs have been selected and 8 preliminary feedback loops have been proposed. Furthermore, resources constraints regarding availability of fossil fuels, biodiesel and non-energy minerals have been identified. A bibliographic review of EROI[2] values for fossil fuels (conventional and unconventional sources) and for renewables has been carried out. For fossil fuels, a sharp decrease in EROI values associated to deposit exhaustion has been stated. As opposed to fossil fuels, EROI for RES[3] is steadily increasing thanks to technological improvement. Yet such improvements are usually associated to the use of critical raw materials. This is why a thorough exergy analysis (i.e. with a second law of thermodynamics approach) regarding mineral physical limitations for the deployment of green technologies (vehicles, wind, PV, solar thermal power, solar thermal and domestic storage applications) has been performed. It has been stated that In and Te (mainly used in PV) are the minerals with the highest risk of provoking potential bottlenecks. But there are 14 other identified elements with medium to high risks.

[1] Physical Aggregate Variables
[2] Energy return on energy investment
[3] Renewable Energy Systems

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1. 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) and environmental impacts (e.g. CO_2 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.

Specifically, Deliverable 2.1 is focused on shedding light on the first mentioned Objective. It further tries to answer the following questions: What are the main variables and parameters that need to be analyzed? How can these variables be studied in an integrated point of view?

This deliverable covers the following three activities, as specified in the Document of Work of the project:

- A review of Partially Aggregated Variables (PAV) used in currently existing models and first selection of PAVs key for MEDEAS.

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- Possible feedback loops of the variables analyzed as a starting point for the model development.
- Analysis of physical limitations for the expected or desired changes in the transition and their relationship with the selected PAVs.

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 physical constraints of the key PAVs preliminarily identified for MEDEAS. Accordingly, Annex 1 covers socio-economic variables and their link to the environment and carbon sinks; Annex 2 deals with the energy intensity of the different economic sectors; Annex 3 focuses on the amount of reserves and resources of fossil fuels and the Energy Return on Energy Invested (EROI) of fossil fuels – conventional and unconventional – and the different renewable technologies; Annex 4 analyses physical and socioeconomic constraints associated with Biofuels. Annex 5 explains the details of the methodology used to assess the exergy of resources (fuels and non-fuel minerals); Annex 6 presents a bottom-up analysis of the reserves, resources, production and recycling rates of mineral resources; Annex 7 to 12 include top-down analysis of the materials required to deploy different green technologies: Transport (Annex 7); Wind (8); Solar photovoltaics (9); Solar thermal power (10); Solar thermal energy (11) and Storage/Batteries (12).

It should be pointed out that this is a living document and that the selected PAVs will constitute a starting point for MEDEAS Model. Additional PAVs might be added and some might be removed from the list as the project proceeds if new requirements are detected.

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2. METHODOLOGY

2.1. Review of Partially Aggregated Variables (PAV)

The aim of this subtask was to analyze which main PAVs are considered in the key energy models that are currently being used. To this end, a brief summary of the most important ones for MEDEAS will be described next. As there are a good number of energy models, those who have greater international relevance (employed by international bodies) and with greater similarity to the objectives of MEDEAS have been chosen. The selected models to be compared are:

- LEAP
- MARKAL-TIMES
- WoLiM

LEAP (Longrange Energy Alternatives Planning System) is a widely-used software tool for energy policy analysis and climate change mitigation assessment developed at the Stockholm Environment Institute (SEI-US) (Heaps, 2012). The first version was developed in 1980 and has been updated since multiple times. Additionally, it has been adopted by thousands of organizations in more than 190 countries worldwide. It is a medium to long-term modeling tool that can be used to track energy consumption, production and resource extraction in all sectors of an economy. It can be used to account for both energy sector and non-energy sector greenhouse gas (GHG) emission sources and sinks. In addition, LEAP can also be used to analyze emissions of local and regional air pollutants, making it well-suited to studies of the climate co-benefits of local air pollution reduction. LEAP can also be used as a tool for calculating, evaluating and displaying many social, economic, and energy-related development indicators.

MARKAL was developed in a cooperative multinational project over a period of almost two decades by the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency. The basic components of the model are specific types of energy or emission control technology. Both the supply and demand sides are integrated,

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so that one side responds automatically to changes in the other. The model selects that combination of technologies that minimizes total energy system cost (source: IEA-ETSAP website).

TIMES (The Integrated MARKAL-EFOM System) model generator was also developed as part of the IEA-ETSAP (Energy Technology Systems Analysis Program). The TIMES model generator combines two different, but complementary, systematic approaches to modelling energy: a technical engineering approach and an economic approach. TIMES is a technology rich, bottom-up model generator, which uses linear-programming to produce a least-cost energy system, optimized according to a number of user constraints, over medium to long-term time horizons (source: IEA-ETSAP website).

The TIMES and the MARKAL models share the same basic modeling paradigm. Both models are technology explicit, dynamic partial equilibrium models of energy markets. In both cases the equilibrium is obtained by maximizing the total surplus of consumers and suppliers via Linear Programming. The two models also share the multi-regional feature, which allows the modeler to construct geographically integrated (even global) instances. MARKAL has fixed length time periods. However TIMES allows the user to define period lengths in a completely flexible way.

WoLiM is a structurally simple model which compares data from many different sources and helps viewing global panoramas. This model aims to deal with complex and non-linear systems subject to constraints such as human development in natural ecosystems. The WoLiM includes both the energy sources (renewable and non-renewable) and the demand generated by the socio-economic system (Capellán-Pérez et al, 2014).

In Table 1 the different key variables used in each of the previously presented models are compared. Using this information as a first approach, a preliminary list of the variables for the MEDEAS model has been created, taking into account those variables but also considering others that have not yet been used in any of these models.

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Table 1. Variables used in the different models.

Variable	WOLIM	TIMES	LEAP
GDP (Gross Domestic Product)	X	X	X
Population	X	X	X
Electricity Energy consumption	X		X
Electricity Losses	X		X
Capacity factor RES	X		X
Investment cost RES	X		X
RES production	X		X
RES power density	X		
RES lifetime	X		
Capacity factor RES	X		X
Investment cost RES	X		X
RES production for thermal applications	X		X
RES power density for thermal applications	X		
RES lifetime for thermal applications	X		
Investment cost nuclear	X		
Nuclear lifetime	X		X
Nuclear production	X		X
Nuclear CO_2 emissions	X		
Electricity production from oil sources	X		X
Efficiency of oil power station	X		X
Electricity production from gas sources	X		X
Efficiency of gas power station	X		X
Electricity production from coal	X		X
Efficiency of coal power station	X		X
Transport energy consumption	X		X
Gas to transport losses	X		X
Electrical vehicles share	X		X
Electrical vehicles sales	X		
Hybrid vehicles share	X		X
Hybrid vehicles sales	X		
Natural Gas vehicles share	X		X
Natural Gas vehicles sales	X		
Residential energy consumption	X	X	X
Industrial energy consumption	X	X	X
Industrial consumption liquid fuel share	X		X
Industrial consumption gas fuel share	X		X
Industrial consumption coal fuel share	X		X
Industrial consumption RES fuel share	X		
Residential consumption liquid fuel share	X		X
Residential consumption gas fuel share	X		X
Residential consumption coal fuel share	X		X
Residential consumption RES fuel share	X		X
Coal to liquid fuel	X		X
Coal to liquid efficiency	X		X
Gas to liquid fuel	X		X
Gas to liquid efficiency	X		X
Conventional Oil extraction	X		X

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Variable	WOLIM	TIMES	LEAP
Unconventional Oil extraction	X		X
Conventional Gas extraction	X		X
Unconventional Gas extraction	X		X
Service energy consumption		X	X
Agriculture, forestry, fishery energy consumption		X	X
Non-energy use			X
Fuel share in services energy consumption		X	X
Fuel shares in agriculture, forestry and fishery		X	X
Fuel shares in transport			X
Heat losses			X
Heat needs by sector			X
Heat processes efficiency			X
Heat processes share			X
Cost of energy consuming devices by sector			X
O&M fixed cost for each electricity generation process			X
O&M variable cost for each electricity generation process			X
Capital cost for each heat production process			X
Fixed O&M cost for each heat production process			X
Variable O&M cost for each heat production process			X
Primary and secondary energy sources			X
Prices for energy imports		X	X
Limitation for energy imports		X	
Production value		X	
Heating degree days		X	
Floor space per euro gross value added		X	
Demolition rates		X	
Building efficiency of not renovated buildings		X	X
Building efficiency of renovated buildings		X	X
Renovation rates		X	
Share of renovation quality		X	
Share of quality of new build buildings		X	
Share of 13 energy carriers in final energy demand for residential heating 2007		X	X
Demolition rates for heating system		X	
Share of energy carriers in new installed heating systems 2008-2030		X	X
Floor space per person		X	X
Share of existing floor space in single and multi-family houses and in apartments		X	
Demolition rates		X	
Share of new buildings in single and multi-family houses and in apartment blocks		X	X
Building efficiency of not renovated buildings		X	dv
Building efficiency of renovated buildings		X	dv
Renovation rates		X	dv
Share of renovation quality		X	dv
Share of quality of new build buildings		X	dv
Share of 13 energy carriers in final energy demand for residential heating 2007		X	dv
Demolition rates for heating system		X	dv
Share of energy carriers in new installed heating systems 2008-2030		X	dv
Efficiency of heating systems		X	dv
Final energy demand for hot water production per square meter		X	X
Final energy demand for hot water production per person		X	X

Variable	WOLIM	TIMES	LEAP
Share of final energy for hot water production in final energy for residential heating per energy carrier		X	X
Efficiency of hot water production systems		X	X

Once the main PAVs have been chosen, a proposal of feedback loops among the key variables selected is done.

2.2. Physical limitations methodology

A novelty of MEDEAS over other models is that it will consider thermodynamics as an underpinning concept of the energy system. Thus, the market evolution will be constrained by the limitations of the physical system. To link space and time evolution, the model will respond to thermodynamic constraints through the exergy concept. The thermodynamic approach is necessary to eliminate scenarios that are physically impossible. This is essential if a long-term policy approach must be considered as is pointed out in the SET-Plan[4] for 2050.

The unit of measure to assess all limited resources (be fossil fuels or material resources) is property exergy (GJ, ktoe, MWh…). Exergy is a measure of the degree of thermodynamic distinction a system has from the surrounding commonness, and in this sense, it is a measure of an object's rarity. The rarer something is, the greater it stands out. The main advantage of this approach is that we avoid the problem of mixing "apples with oranges" in a conventional analysis based on mass. Through exergy, one considers not only the specific mass of the resource, but also its quality and everything with the same units (energy units).

The exergy of fossil fuels can be approximated with no significant error to their High Heating Value (HHV). Accordingly, 1 kg of oil in exergy terms is more valuable than 1 kg of coal, since the first has a HHV of about 10,000 kcal/kg, whereas the latter around 7,000 kcal/kg. The exergy associated to non-energy mineral resources depends on the concentration of that particular element in the mineral deposits with respect to the concentration it would have in a hypothetical degraded planet where all minerals have

[4] Strategic Energy Technology Plan

been dispersed throughout the crust, and the mining and beneficiating technologies to extract it. The details of the exergy methodology are explained in Annex 5.

With this thermodynamic approach, one can now assess the physical limits of the different green technologies. To this end, a bottom-up with a top-down approach is undertaken. In the bottom-up approach (Annex 6), an assessment of the reserves, resources and estimated production trends (assuming a Hubbert-like production trend) for each resource are assessed on a global basis. In the top-down approach (Annexes 7-12), an analysis of the resources (mainly materials) required for the deployment of different "green technologies" is done. The intersection of both approaches helps to identify possible material bottlenecks, as shown in Figure 1 for Lithium:

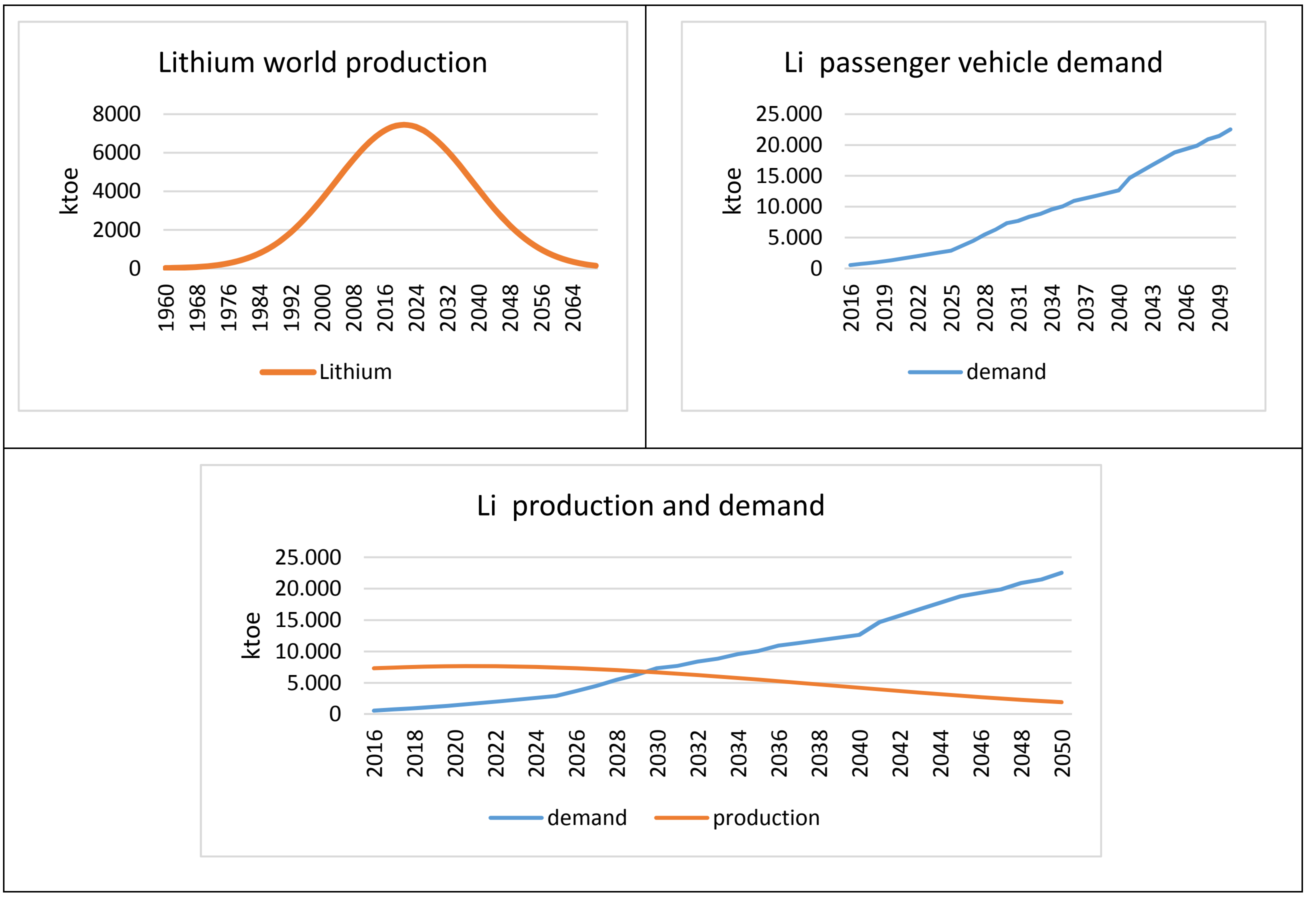

Figure 1: Example of bottom-up and top-down analyses for Li in passenger vehicles

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A key aspect of the deployment of fossil fuels and renewable sources is the concept of Energy Return on Energy Invested (EROI). EROI identifies the efficiency of energy sources as a relation between invested and gained energy.

In other words, it can be described as the net energy remaining after subtracting the amount necessary to explore, extract and refine an energy resource. EROI is obviously constrained by thermodynamic limits, but also by technological and economic aspects. In this sense, Annex 3 of this Deliverable makes a comprehensive review of expected EROIs for fossil fuels (conventional and unconventional) and for renewables.

A complex case is that of biofuels, as they might enter in competition with food production, might have a major influence on land-use change and hence affect climate change, but also the specificities of the crops, the technology and logistics aspects are key issues that might affect their deployment. This is why Annex 4 is specifically devoted to this type of energy source.

3. RESULTS

This section presents the main results associated to the three sub-activities carried out in this Deliverable: a) identification of key PAVs; b) and feedback loops; c) analysis of physical constraints.

3.1. Studied PAVs

This section explains the rationale for choosing specific PAVs for MEDEAS model. The different variables have been classified according to: 1) socioeconomics and efficiency improvement; 2) energy intensity of sectors; 3) transport (as this will be a key sector) and 4) raw materials. The list with the selected variables (a total of 116) can be found fully developed at the end of this document in section 5.

3.1.1. PAV for measuring socioeconomic variables and efficiency improvements

Socioeconomic variables are key determinants for total energy and material use in each sector, including industrial use, household consumption, and demand for transport.

Conversely, the provision of energy and materials is crucial for production and thus also influences socioeconomic activity. Therefore, socioeconomic variables are key mediators in determining the system-dynamic relations between PAVs.

Two variables are central to determine socioeconomic activity: The Gross Domestic Product (PAV 1) and population size (PAV 6). GDP measures total income, which, in turn, determines total demand for goods and services from each sector. GDP measures are readily available on different scales and have been composed accordingly.

Direct demand for thermal and power applications by households (PAV 15, 17, 19, 21), as well as indirect demand of households through consumption of goods and services from industries (PAV 16, 18, 20, 22) is influenced by total income (GDP) used for consumption. Finally, also transport demand is directly influenced by household mobility (PAV 26) and indirectly by mobility necessary for goods and services from industries (PAV 27).

The population size influences the distribution, but also the size of GDP. Because the distribution of income influences consumption also via expenditures on saving and investments, also the median income (PAV 4) is important. Two alternative measures stand out: The Gini coefficient is readily available on national and global levels and could be related to consumption, but also a differentiation of households, splitting them into two or more classes, could be a relatively easily implementable solution to take into account the effects of income distribution on energy and material demand.

In addition, also the unemployment rate has a considerable effect on demand and should be taken into account. Concerning population growth, we had to decide on which growth scenario is most likely. A detailed review and data is available in Annex 1.

The Human Development Index (PAV 5) could be related to GDP as an indicator of genuine progress. Alternative measures of living standards are also possible, but the HDI is the most easily accessible and known indicator. This PAV could serve as an indicator for scenario implications resulting from simulations with MEDEAS and become an important measure to evaluate policies.

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3.1.2.PAVs for measuring energy intensity of sectors

Energy intensity indicators aim to measure the energy efficiency of an economy, explaining how much energy is used to produce one unit of economic output. The energy is simply the energy consumed by the investigated sector (or country), while the economic performance is expressed of GVA[5] , PAV 2, or GDP, PAV 1 at exchange rate and purchasing power parity of a reference year (WorldBank databank and Wordenergy databank)

Global energy intensity in the past decades has declined despite the notable increase in aggregate gross output and energy use (De Cian et al)[6]. This aggregate decline is the result of both changes in the structural composition of the world economy and improvements in the technologies used for production worldwide. Economies have shifted toward less energy-intensive sectors, determining an improvement in energy efficiency. At the same time, energy efficiency within all sectors of the world's economies is likely to increase over time as a result of more efficient production technologies and newer vintages of capital equipment

Usually, energy intensity indicators are based on a hierarchical framework that begins with detailed indexes of energy intensity for various sectors of the economy (PAVs 59, 70, 72, 75), which are ultimately aggregated to an overall energy intensity index for the economy as a whole (PAV 14). Anyway, at an aggregate level, the conventional measures of energy intensity are not all traceable to improvements in energy efficiency.

In the specific case of MEDEAS Energy intensity is used as a comparative measure between economic sectors: high energy intensities indicate a high price or cost of converting energy into GDP, low energy intensity indicates a lower price or cost of converting energy into GDP.

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[5] Gross Value Added

[6] Energy Intensity Developments, in 40 Major Economies: Structural Change or Technology Improvement? Enrica De Cian, Michael Schymura, Elena Verdolini, and Sebastian Voigt Download this ZEW Discussion Paper, http://ftp.zew.de/pub/zew-docs/dp/dp13052.pdf

Special attention has been paid to the electricity generation sector, as it feeds with electrical energy all economic sectors. To this end, particular PAVS for electricity transformation (28-33), electricity generation with RES (34-41) and with non-RES (42-50) have been selected. Additionally, PAVs 51-58 cover thermal energy generation from RES.

3.1.3.PAVs for measuring transport sector

The transport sector plays a major role as it connects goods, services and markets and is a key driver of growth. It can be divided in different sectors: road, aviation, maritime and train (EUROSTAT, 2014).

A total of 11 PAVs have been selected to analyze this sector, two of them covering the energy requirements through energy intensity and energy consumption by source and transport system using PAVs 59 and 60. The remaining variables correspond to light-duty vehicles, as light-duty vehicles (LDV) demand 47 % of the total energy consumption of the transport sector (IEA, 2009). Furthermore, LDV have excellent opportunities to reduce fossil fuel use and CO2 emissions. Therefore, for these reasons 9 specific PAVs have been chosen to characterize LDV.

First, the total amount of vehicles has been measured (PAV 61), including not only the total fleet but also the type of vehicle, taking into account the share of each vehicle technology (ICE, PHEV and BEV). This has been done by means of PAVs 62, 63 and 64 for ICE, PHEV and BEV respectively. Additionally, market sales evolution is required to quantify the amount of materials demanded yearly. To do so, yearly sales data of ICE, PHEV and BEV respectively have been collected using PAVs 65, 66 and 67.

Finally, the implementation of legislations which limits the amount of GHG emissions of vehicles, can have a severe impact on this sector. In Figure 2 the effect of the EURO legislations in European petrol and diesel vehicles can be seen.

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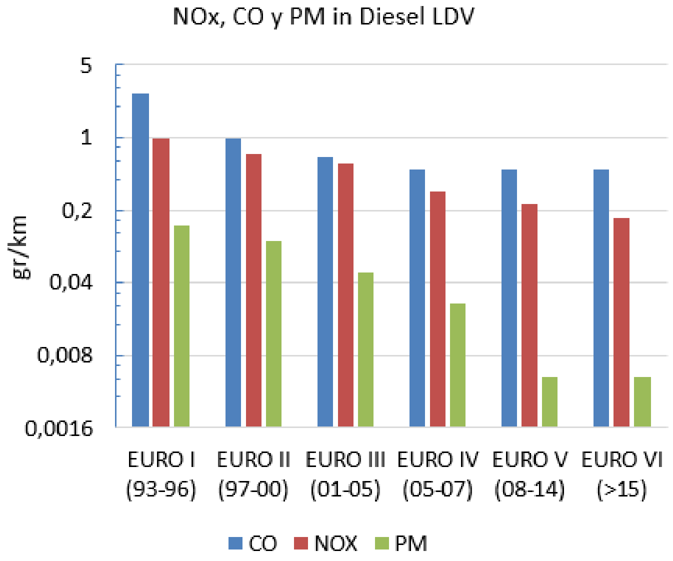

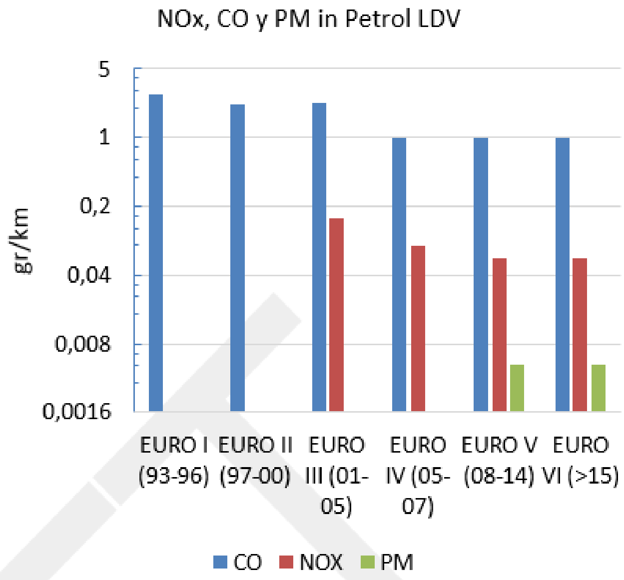

Figure 2: NOx, CO and PM emissions evolution in different EURO legislation for Petrol and Diesel Light Duty Vehicles.

To assess the impact of legislation on vehicles a specific PAV has been defined (PAV 68), which covers NOx, CO, CO_2, PM_{10} and HC emissions. Data sources used are: World Energy Council, International Energy Agency and European Automobile Manufacture´s Association.

Additionally, the impact of biofuels in the sector has been studied, taking into account the share of biofuels in the total transport sector. Biofuels have been steadily penetrating the global energy market for the past 15 years as an alternative transport fuel. Firstly with the scope of supporting the agricultural sector, and later as envisaged by the respective policies for reducing dependency on oil. In parallel decarbonizing the highly energy intensive transport sector. Such policies have boosted the utilization of biofuels in the transport sector, covering around 3% of the global road transport fuels in 2010 (IEA, 2011). In this context, the expected production of biofuels in the future and their contribution in the transport sector are among the most critical parameters for assessing the shift towards a low carbon economy.

Therefore, it was decided to include biofuels production and share of biofuels in transport in the list of key PAVs to be considered for the MEDEAS model implementation.

Since biofuels are directly related to more than one sector, namely energy, climate, agriculture, food, transport, and others, it was important to consider a variety of bibliographical references for estimating the required data. The literature consulted varied from scientific journals related to sustainable energy, biomass, food policy and transport, to policy reports from autonomous world organizations active in the aforementioned fields.

Most of the data collected comes from the International Energy Agency (IEA), as it is one of the most prestigious organizations, with 29 member countries and the mission to contribute to energy security, economic development, environmental awareness and engagement worldwide. Analogously, data were collected from the Food and Agriculture Organization of the United Nations (FAO), which is also considered a highly prominent organization, with recognized research and policy work. Moreover, a number of scientific publications provided data that should act indicatively to the model implementation.

3.1.4. PAVs for measuring domestic storage and distributed generation

A total of 10 PAVs have been defined for measuring the impact of smart grids through the growing of small and medium domestic storage devices.

The growing of domestic storage systems is linked with the batteries evolution used for transport applications, since they will be mainly based on a second life use of transport batteries for stationary applications (Frost and Sullivan, 2010).

PAVs 98 and 99 are defined to assess how the evolution of transport storage is expected to be through energy density and cost evolution parameters. Once a vehicle battery reaches the end of its life, its energy density has decreased with respect to the original value. On the other hand, its cost decreases. For these reasons energy density and cost for domestic applications are monitored through PAVs 100 and 101, respectively.

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Battery lifetime is one key parameter to assess the demand of raw materials to manufacture batteries during the analyzed period (2016-2050). This parameter is measured by means of PAV 102.

Chemical storage applications based on lithium seems to be the most feasible technology to be installed at large scale in a short to medium time. However, other storage applications based on Hydrogen could also become prominent. For this reason, the evolution of storage systems based on Hydrogen is covered through PAVs 103, 104 and 105, which measure energy density, cost and EROI, respectively.

Domestic storage systems are linked with the promoting of smart grids in combination with renewable technologies to produce electricity. For this reason, the link between RES power capacity in small applications and storage systems is measured through PAV 106.

Finally the promotion of smart grids will require an increase of material demand to build more distributed electricity infrastructure. For this aim PAV 107 measures the impact of smart grids on material demand.

3.1.5. PAVs for measuring raw materials

A total of 7 PAVs have been selected for measuring raw materials in this project. When talking about raw materials, the most obvious and more direct information is the world production for each substance. For the most extracted commodities, the so-called "big six" (Aluminum, Chromium, Copper, Iron, Manganese and Zinc), the available information is very reliable and the main source that has been used to compile information on global extraction is the United States Geological Service (USGS). In the case of other minerals, such as rare earth elements (REE), gallium, germanium or indium, where the leading producing countries are China, Republic of Korea or other Asian countries, and as the vast majority of these elements are usually byproducts, the information might be less accurate but still the USGS remains the best available source.

Another important issue when talking about raw materials is the extractable amount that is still available on the Earth's crust. For this endeavor, the two most used indicators have been implemented: total reserves and total resources (Figure 3).

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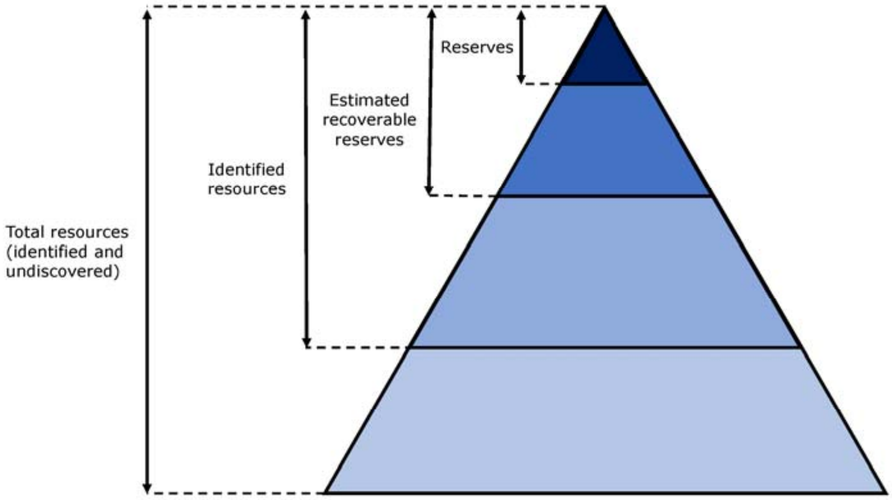

Figure 3. Mineral resource classification.

The total resources is the best estimate of the total availability of each commodity in the crust, included identified resources and undiscovered. Total reserves are that part of the estimated recoverable reserves which can be economically extracted or produced in a determined time. Therefore, as the technology and commodities prices change, the reserves varies as well. If new production technologies are developed, unattainable resources can be reachable or profitable. Both reserves and resources are dynamic data. They may be reduced as ore is mined, as the extraction feasibility diminishes or increase as additional deposits are discovered or are more thoroughly explored.

The estimations usually come from inventories of mining companies as well as from national geological services, and they are limited by many factors, such as price of the commodities, lack of exploration, geologic limitations and demand.

In this case, the information has been compiled from different sources, according to the type of commodity.

For the vast majority of the raw materials the source used has been the United States Geological Survey and they have been completed with information in Emsley (2001), Frenzel et al. (2014; 2016) and Sverdrup and Ragnarsdottir (2014).

Even if raw material extraction is very important at world level to provide the materials that the society demands, another secondary source for materials is recycling. In this case, the information regarding recycling rates of the commodities has been extracted from UNEP (2011). As there are different types of recycling rates, the selected one for this study is Recycled content (RC) that is calculated as follows, according to the different paths shown in Figure 4:

$$RC = \frac{b+c}{a+b+c}$$

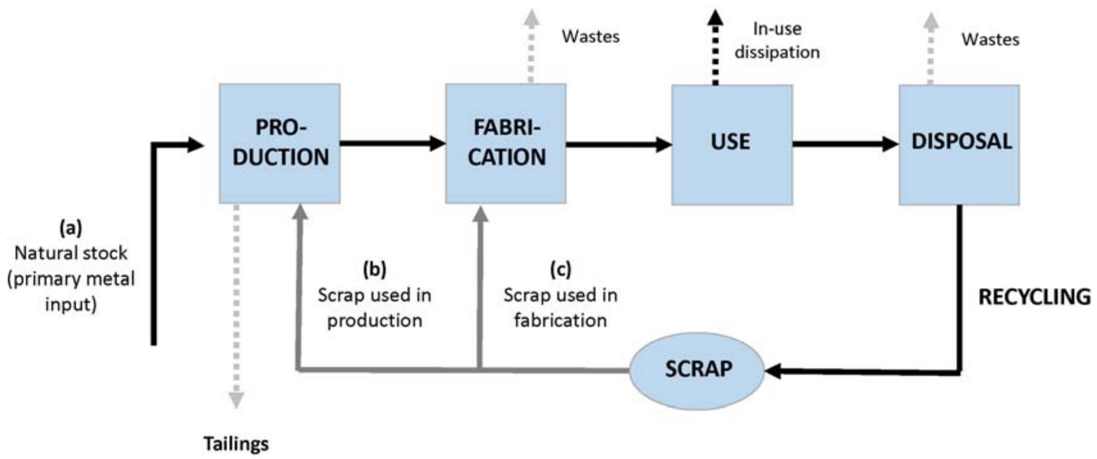

Figure 4. Simplified metal life cycle (modified from UNEP, 2011).

Recycled content has been selected as it is an absolute indicator that measures the actual amount of metal that enters into the industrial lifecycle of an element.

Associated to recycling, the information related to the energy needed for the recycling process is also a factor that must be taken into account as to compare the energy needed for primary and secondary production.

The energy needed for primary production, meaning extraction, and the associated emissions, has been extracted from Valero and Valero (2014). The energy needed for secondary production is more difficult to obtain and only the information available comprises the most extracted commodities, such is the case of aluminium, copper, nickel, tin and zinc (Grimes et al, 2008; 2016).

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3.2. Possible feedback loops

This section shows preliminarily identified feedback loops between key variables selected (tagged with the number of the given PAV – see list in section 5) and a brief explanation of the rationale for the loops. Such loops should serve as a first approximation to develop MEDEAS model tool.

3.2.1. Feedback loops between materials and energy with socioeconomic variables

Socioeconomic activity is related to population via per capita productivity. Although economic growth is more volatile than population growth, and both indicators grow at vastly different rates, populations and economic output tend to grow in tandem, albeit at different rates. Per capita productivity increases. As a key relation, the function relating GDP to population should take into account variables that influence per capita productivity, including capital and energy inputs, and the potential negative effects of climate emissions on productivity.

There is a link between emissions production and GDP growth, albeit the ratio is far from fixed. Emission intensity is – in this case – the amount of greenhouse gas (respectively CO_2) emissions produced per unit of gross domestic product (GDP). The ratio between CO_2 emissions and GDP is declining, i.e. lesser CO_2 emissions are needed to produce one unit of GDP. However, there is still a well-documented positive correlation between these two variables. The possibility of (absolutely) delinking the amount of CO_2 emissions produced from GDP growth is being discussed and confirmed by some studies, though not generally accepted.

Materials use also requires energy input, which is related to emissions production and emissions intensity, respectively. Admitting that materials use is a core feature of growing economies that produce emissions, economic development and technology advancement significantly influence CO_2 emissions.

There is a positive relationship between energy consumption, per capita GDP and CO_2 emissions. The relationship between GDP and emissions production is leveraged

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through energy use (GDP is positively associated with energy use, which is positively linked to growing emissions production). Total energy consumption from fossil fuels (producing CO_2 emissions) should be analysed according to the needs of the model.

Carbon sinks are natural or artificial reservoirs that accumulate and store carbon-containing chemical compounds for an indefinite period. Carbon sinks remove Carbon dioxide (CO_2) from the atmosphere by carbon sequestration. Knowing the carbon sinks capacity (globally), we are informed about the external limits of the socioeconomic activity. For example, if we want to keep some amount of emissions fixed (in order not to destroy ecosystems etc.), we should count with some "safe" amount of emissions, i.e. not exceeding the capacity of carbon sinks, for example.

Figure 5 represents the feedback loops between socioeconomic and energy variables. An increasing population (PAV 6) will increase socioeconomic activity, measured as GDP (PAV 1). Vice versa, also an increasing GDP will influence population growth. Increasing socioeconomic activity requires an increasing demand for electricity and leads to increasing primary consumption and resulting emissions (PAV 28-33). Conversely, also an increasing electricity supply can positively influence socioeconomic activity. In addition, an increase in emissions due to fossil fuel consumption leads to climate change that negatively influences socioeconomic activity via damages. Therefore, both positive and negative feedbacks go from PAV 28-33 to PAV 1. The relation between GDP, electricity demand, and emissions is influenced by power and thermal density of renewable energies (PAV 38/39 and 55/56).

Technically, power and thermal density also influence each other. Electricity demand will also depend on electricity generation efficiency from non-RES (PAV 46/48/50) and the energy return on investment (EROI) of fossil sources (PAV 86-90).

The EROI influences actual fossil fuel production (PAV 81-85), but an increase in fossil fuel production also reduces the EROI.

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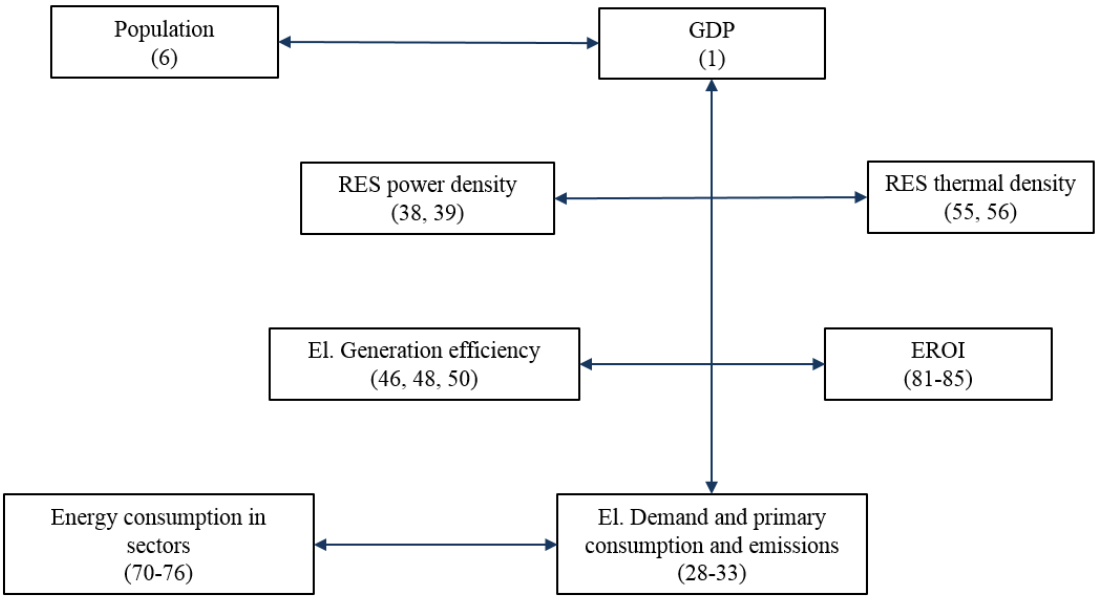

Figure 5. Feedback loop - Socioeconomic and energy variables.

Figure 6 represents the feedback loops between material demand and socioeconomic variables. The material consumption per capita (PAV 13) is directly linked to the material extracted (PAV 108), which in turn requires a certain amount of energy for the extraction process (PAV 115). This energy demand for material extraction (PAV 115) will therefore generate emissions (PAV 116) which will trigger changes in the CO_2 emissions and specially in certification prices CO_2 (PAV 25) moving towards a low carbon economy.

This can additionally affect the GDP (PAV 1), which is also depending on the energy imports (PAV 10) on which an economy relies in order to meet its energy needs. The final energy consumption (PAV 11) depends on the energy that the material extraction sector requires (PAV 115) and establishes the energy intensity (PAV 14), meaning the primary energy needed to produce a money unit. If the energy intensity changes (PAV 14), the energy imports (PAV 10) can be affected too to meet the total demand.

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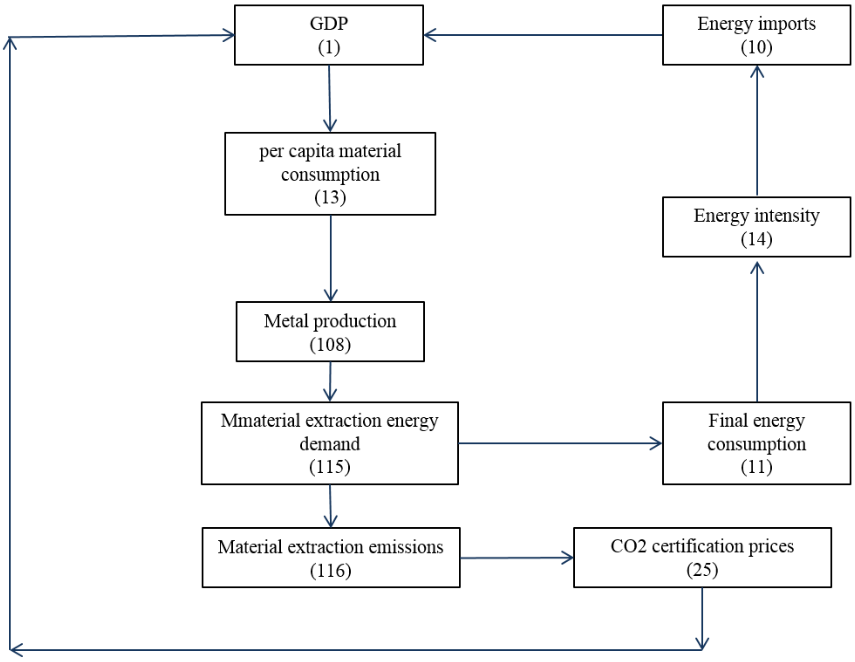

Figure 6. Feedback loop - Material demand and socioeconomic variables.

3.2.2. Feedback loops between Green technologies and material demand

Figure 7 represents the feedback loops between green technologies and material demand. Green technologies such as Renewables (PAV 37) or new designs of Vehicles (PAVs 63, 65 and 67) will demand materials for their manufacture (PAVs 109 and 110, respectively). Such materials will come either from primary ores (PAV 108) or from recycled materials (PAV 113).

Primary material production (PAV 108) induces a reduction of mineral reserves (PAV 111) and in turn mineral resources (PAV 112) and require not insignificant amounts of extraction energy (PAV 115), provoking associated GHG emissions (PAV 116). The recycled material (PAV 113) comes, among others, from the recovering of vehicle scrap originated from the passenger vehicle fleet (PAV 61) or from the same RES technologies (PAV 37), which are affected by a certain RES lifetime (PAV 40). Recycling technologies consume equally a certain amount of energy reflected in PAV 114.

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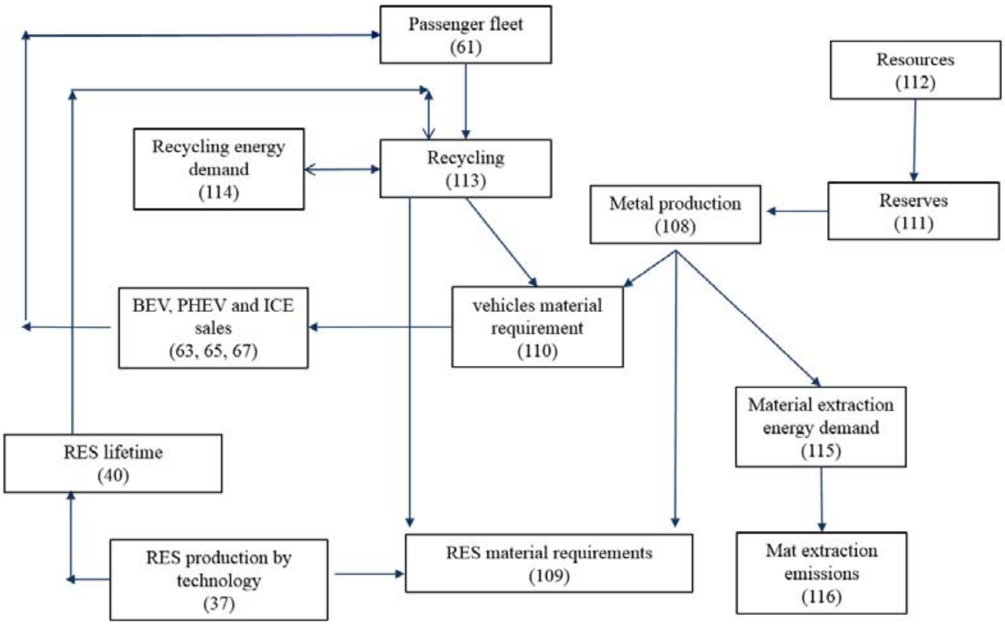

Figure 7. Feedback loop – Green technologies and material demand

3.2.3. Feedback loops between socioeconomic and energy variables in the different economic sectors

Electric sector

The Electric power production is supposed to be the sum of RES and Non-RES, minus the energy lost by supply losses. The available energy is coupled to the demand that, in turn, is proportional to the GDP.

Energy consumption is in a positive feedback loop with GDP: more GDP creates more demand, more demand creates more GDP. The model also assumes that the EROI of renewables is affected by R&D which, in turn, requires financing from GDP. The same is true for NON-RES, although the EROI should be affected also by depletion (not included in the scheme for simplicity). Figure 8 shows the corresponding feedback loop proposed for this sector.

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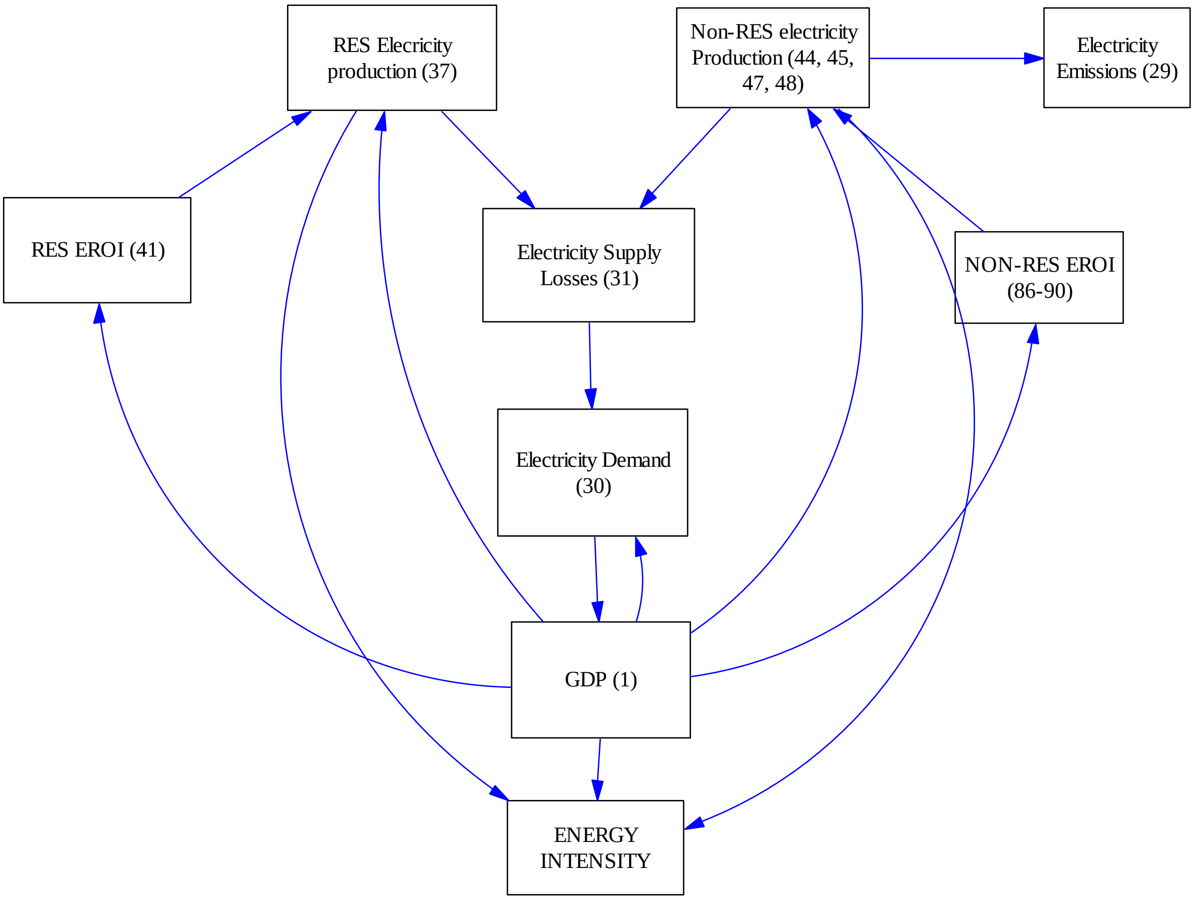

Figure 8: Feedback loop – The Electric sector (which is equated to the INDUSTRIAL SECTOR) supposed to be powered mainly by electric energy

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Transport sector

Here, it is assumed that vehicles are powered by two different kinds of energies, electrical energy and liquid fuels. There follows the cascade that goes, on one side, from RES electricity to the Transportation final energy consumption. On the other side, both biofuels and conventional fuels can power ICE vehicles. GDP is again in a positive feedback with transportation energy consumption; the higher the GDP the more energy for transportation is consumed. This determines the "people and freight mobility. Here, as in the case of the electric/industrial sector, part of the GDP can be allocated to R&D to improve the EROI of the production of both RES and NON-RES energy sources.

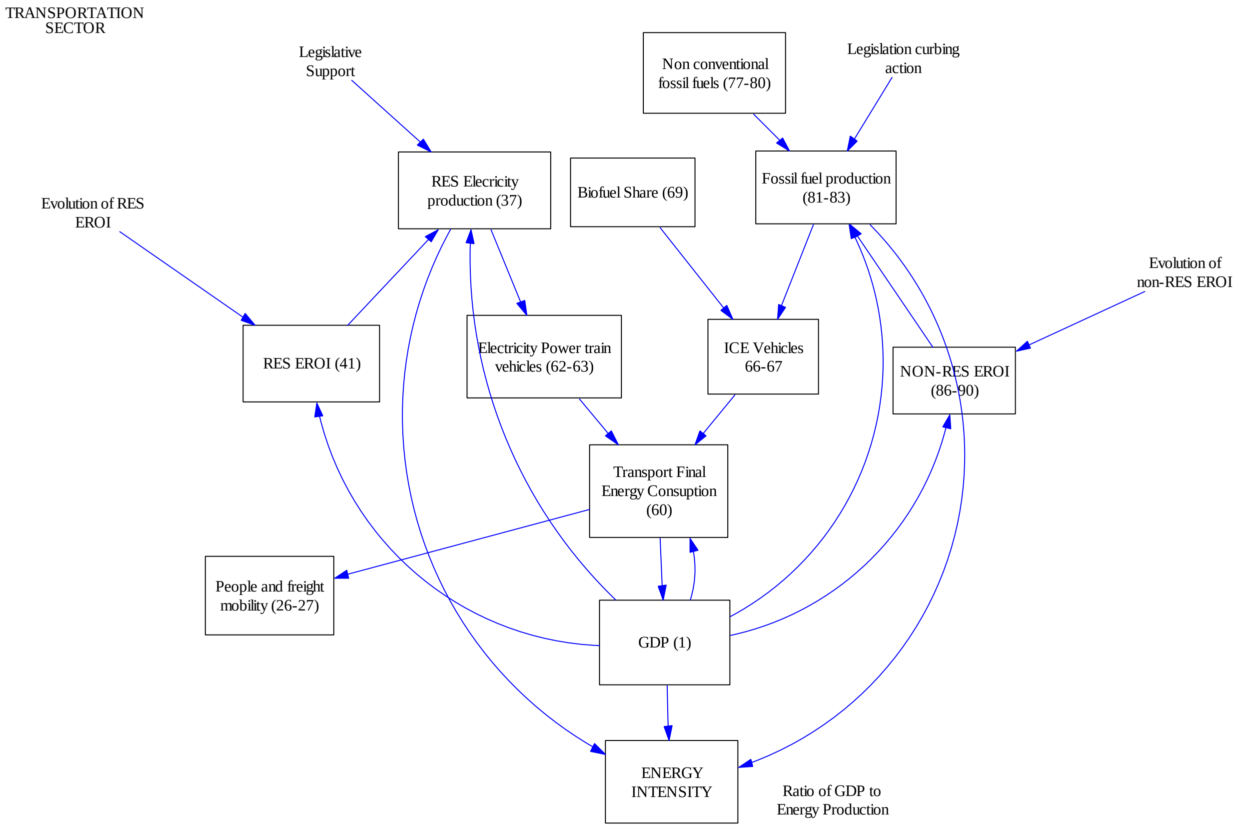

Figure 9: Feedback loop – Transportation feedback loop between energy e socioeconomic variables

Residential sector

Energy intensity represents the energy necessary to contribute in GVA of a sector. In particular possible loopbacks that RES transition leads in Energy and Economy of the Residential Sector are examined, describing possible cause loops that affect the PAV 72 (Energy intensity of residential sector)

Residential energy intensity depends directly on energy production form electricity sectors, both from RES (PAV 37) and NO-RES (PAVs 44, 45, 47 and 48). In particular RES production is driven by RES EROI (PAV 41). On the other end, NO-RES production affect directly EROI of NO-RES electricity productions variables (PAVs 86 and 90). The production curves of NO-RES show logistic behaviors; such tendency imply also a decrease in their EROI due to the increasing difficult in the resource extraction that will be reflect in PAV 72.

Because of heating represents around 25% of world energy consumption, RES production also drives RES heating sectors (PAVs 52) in particular if it is assisted by subsidy from government (PAV 74).

The evolution of RES heating obviously has reflections on the actual heating supply mix (PAV 73) and then on prices of fuels of the mix (PAVs 17, 19, 21). Energy import (PAV. 10) can also change (.e. at European level) due to the electrical demand for heating in residential. Finally emissions from electricity and heating interact with GVA (2) and GDP

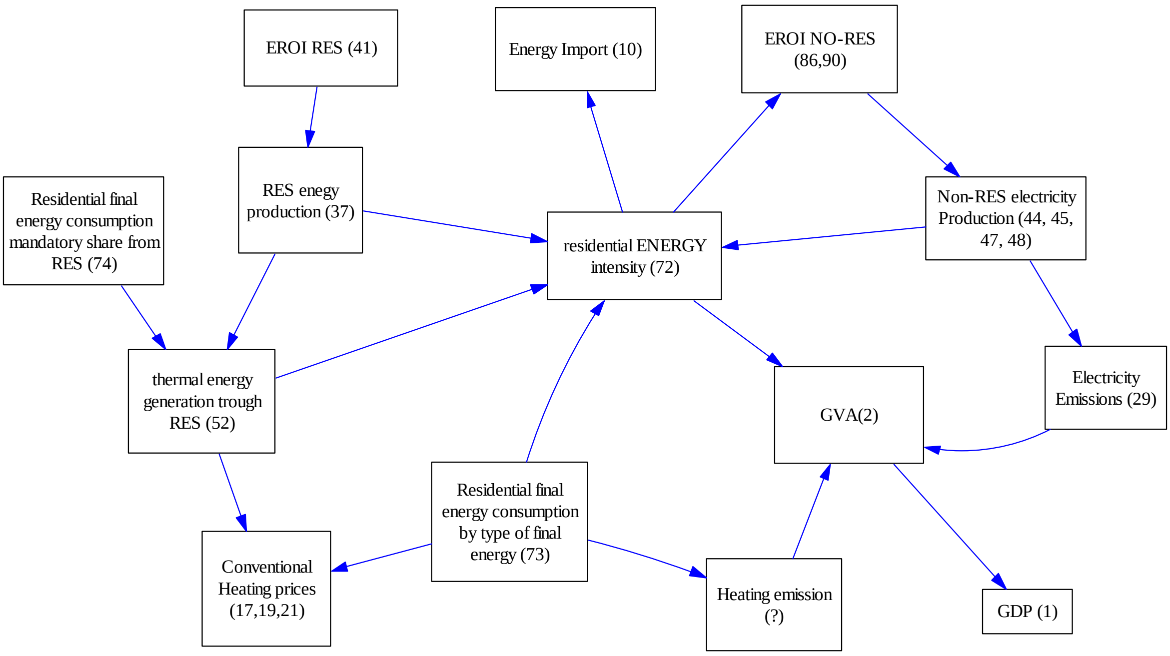

Figure 10: Feedback loop – Energy intensity of Residential Sector and Residential heating energy variables.

Other Sectors- Services

For Other Sector, the expected dynamic is mainly due as a mixed contribution from both transportation sector and residential sector. Looking at the diagram loop, the right side is likely the same of Residential Sector feedback loop.

Nevertheless there is another emerging Service sector that has a growing impact on energy demand, economy and society: this is the ICT sector which energy demand represents now about 2%[7] of the global demand. This sector drives global communication services, requiring H24 stable electricity supply. The energy intensity of this sector is going to increase, as the velocity of ICT installation and consumption as raised by 10 from 2007 to 2012[8].

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[7] Trends in worldwide ICT electricity consumption from 2007 to 2012. Ward Van Heddeghem⁎ , Sofie Lambert, Bart Lannoo, Didier Colle, Mario Pickavet, Piet Demeester Department of Information Technology (INTEC) of Ghent University - iMinds, Gaston Crommenlaan 8, B-9050 Gent, Belgium, tel: +32(0)9 33 14 977, fax: +32(0)9 33 14 899330; 330 TWh/19000TWh

[8] Same above as ref (1) 340 TWh ICT/19000 TWh GLOBAL

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The importance of this sector is related directly to the ability making circulates information, that is a fundamental key of global development (PAV 5). ICT has completely change our society in the last 30 years, becoming one of the most important service industries on which economy and social welfare is based. Even if PAV 76 is expected to increase, it could have also positive effect on the decreasing of energy intensity of other sectors, i.e. transport consumption (digital conferences). Obviously the impact of this tertiary sector, is great also on the industry of materials, metals (Lithium) and rare metals in particular (108), necessary to develop storage (PAVs 106,107) technologies and end-uses devices (mobile phone, pc and so on). Also, the boosting of recycling industry of such materials (PAVs 113,114) is expected to occur.

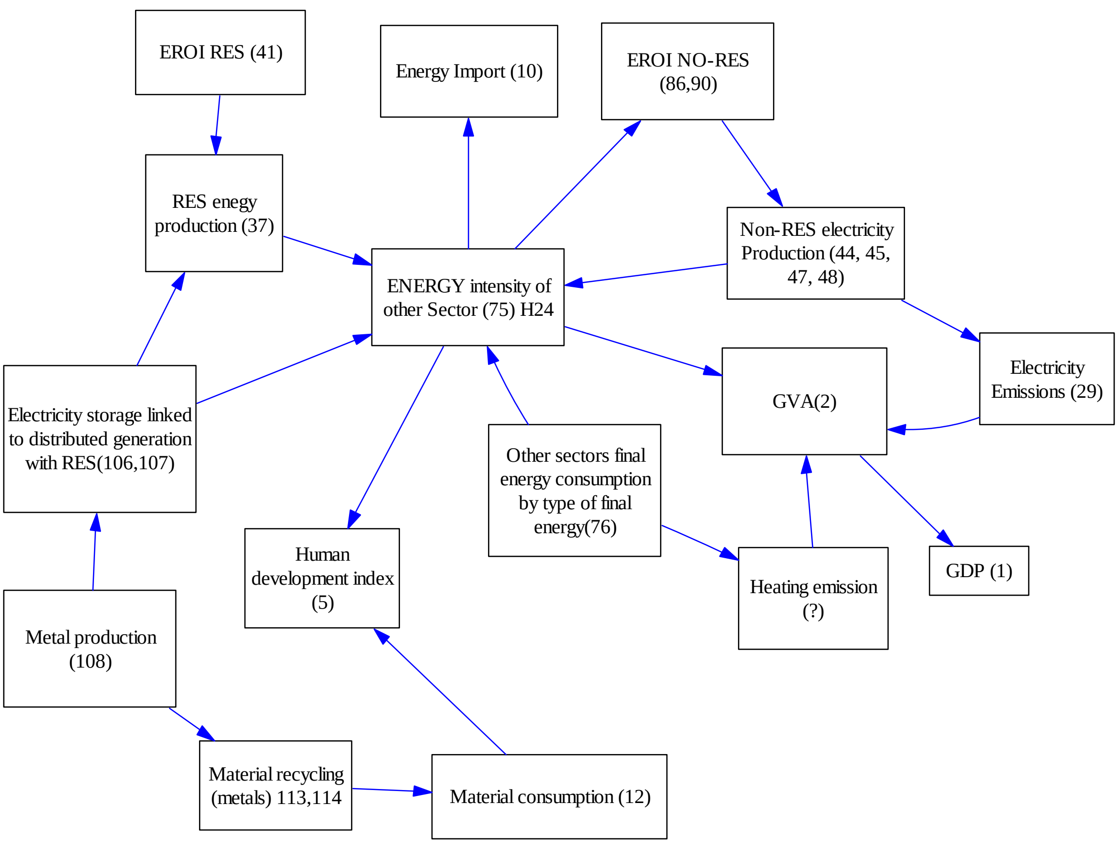

Figure 11: Feedback loop – Analysis between Energy Intensity of Other Sector and other Energy and Socioeconomic variables

Other sectors - Agriculture

Among other sector, also Agriculture can lead to an increase of Energy intensity (PAV 75). Here in the contribution from the emerging industries that produce biofuel (PAV 97) and biomass (PAV 56) are pointed out. As told for Services, the expected dynamic for agriculture involves mainly the contribution from both transportation sector and building sector, but now in a different way. The feedback connections here evidence the potential of change of agriculture sector, an in depth transformation from a 'passive' sector, that mainly consume energy, toward a sector that become key actors in energy production and in driving precisely both residential (biomass/biofuel) and transformation (biofuel).

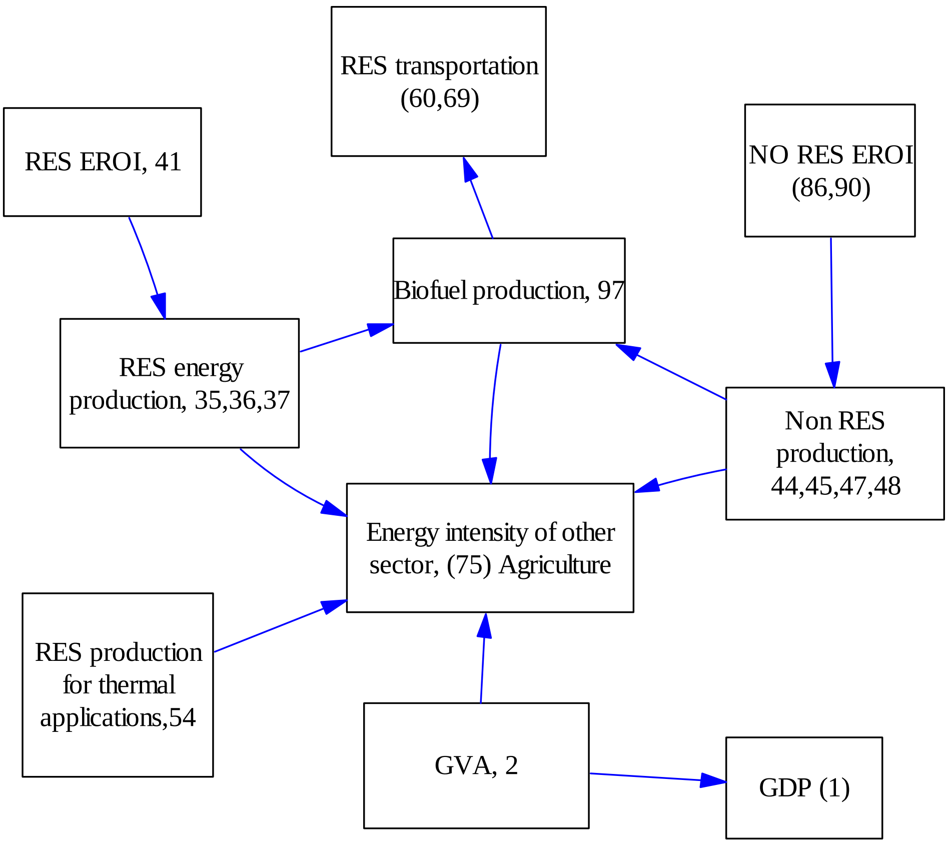

Figure 12: Feedback loop – Analysis between Energy Intensity of Other Sector (Agriculture) and other Energy and Socioeconomic variables

3.3. Physical limitations

3.3.1. Fossil fuel limitations

World proven reserves of fossil fuels all together are estimated by BGS to be 39,910 EJ, which is a modest estimation. Sorrell et al. (2009) argue that estimations of Peak Oil further than year 2030 are based on unrealistic assumptions. The argumentation is based on development of the new resources in the North Sea, which are compared to the estimations of resources that are yet to be found.

The amount of estimated reserves in an indicator of a great importance, especially for the future projections. Reserves are an ultimate biophysical constraint for fossil fuel use. Due to a lack of standardized measurement there are different estimations of ultimately recoverable reserves and the estimates differ significantly from 2000 to 4300 Gb[9] for conventional oil resources (Sorrell et al., 2009). In the same study we can find USGS estimations of global conventional URR of 3,345 Gb, which we might see as rather optimistic, but still relevant source. However, we see the estimation by a relatively recent study by McGlade and Ekins (2015) for remaining ultimately recoverable resources (RURR) of conventional oil at 2,615 Gb to be more likely. Future development of oil production depends on development of unconventional oil reserves.

The distribution of the resources is geographically uneven. Nearly half (47.7%) of the proven reserves are located in one region, 15.7% in Saudi Arabia alone (BP, 2015). The localization is hardly to express in variables for the global level of analysis.

Unconventional oil might be overrated for future oil production when the EROI of the resource is not considered. The probably best estimates for global reserves and resources are provided by McGlade and Ekins (2015), who estimate a global RURR for unconventional oil of 2,455 Gb. This is almost as large as the RURR for conventional oil.

Natural gas estimates follow the dynamics of oil. Also for gas we can talk about highly uneven distribution of reserves, while these are located in similar regions as oil.

[9] Giga barrels of petrol

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The ultimate constraint of natural gas is expressed in Remaining Ultimately Recoverable Resources (RURR).

As in the case of oil we can see that estimations by IEA are rather optimistic at 806 Tcm[10], while we tend to the more conservative estimation by Mc Glade and Ekins (2015) of 375 Tcm for conventional gas and 300 Tcm for unconventional gas.

Coal reserves are located in more countries then oil and gas. To identify the correct estimation of reserves we stick to rather conservative Best Guess Scenario of Mohr and Evans (2009). They identify URR of all types of coal to 1,143.7 Gt of coal.

3.3.2.EROI

The EROI is a key measure to highlight the decreasing efficiency of non-renewable energy sources. Gagnon et al. (2009) provided the most respectable estimation for global oil and gas EROIs. The source indicates a steadily decline from the year 1999 (35:1) to 2006 (18:1). Hall et al. (2009) provided estimations for a minimal EROI for basic functions of society to be 3:1, which, according to them will allow for conventional oil and gas till 2030 at the current rate of production. This estimation complements the qualitative dimension of estimated Peak-Oil.

Unconventional resources such as tar sands, oil shale and tight oil appears to have different EROI for every locality. The EROI of unconventional oil and gas is significantly lower (4:1 to 7:1) (Hall et al. 2014), which is of great importance concerning the changing character of reserves. Despite of the enormous deposits, the extraction rate is limited by environmental and other constraints.

The EROI at a global level for coal is estimated to be 46:1 (Hall et al. 2014), which is significantly higher than the EROI of oil and gas. However this estimation is very rough based on calculations only from China and US, which are the only countries with available data.

[10] Trillions of cubic meters

Hydropower as a most important renewable source has very site-specific EROI varying from 11.2:1 to 267:1. Lambert et al. (2012) provided estimation of average EROI of 84:1, deducted from different studies.

Unlike EROI of fossil fuels photovoltaic EROI has a tendency to grow, especially high values have been identified by CdTE (45:1 in year 2013) and CIGS (near 30:1 in the year 2013) technologies. However the most diffuse photovoltaic technology based on silicon appears to have EROI between 8-12:1 (Bhandari et al. 2015).

Energy generation from wind tends to have a greater EROI during time. EROI found by Kubiszewski et al. (2010) for all operational studies is 18.1:1.

Geothermal energy resource's EROI vary from 6 to 39:1 due to lack of standardisation (Hagens, 2008).

Tidal EROI is to be estimated to 15:1, however there are very limited data of wave energy plants (Banjeree et al., 2006).

Biofuels cannot be considered as a large scale energy source, when we consider large extent of land needed for the cultivation of the needed crops. EROI of biofuels is relatively small: bioethanol with slightly more than 1:1, while biodiesel between 3 and 5:1. A higher EROI can be found by biomass in particular case studies – 12-13:1 (Kolarikova et al. 2014).

3.3.3. Biofuel limitations

Biofuels are usually distinguished in first, second and third generation biofuels, while the IEA categorizes them according to their maturity into conventional (coinciding with first generation) and advanced biofuels, which are mainly still in their demonstration phase.

As projected by IEA, biofuels will play a significant role in the future, with sustainable biofuels providing 27% of transport consumption by 2050 and contributing by 23% to overall transport GHG emissions reduction (IEA, 2011).

Nevertheless, in order to exploit the full potential of biofuels in the future there are many barriers that need to be overcome. In specific, despite the initial sustainability rationale for the penetration of biofuels in the transport sector, later claims on land use changes, deforestation and food insecurity have restrained their full deployment and challenged their contribution to energy security, environment and social prosperity.

The main debated issues expressed in the last years that also form the most important constraints for their mass market deployment are fully developed in Annex 4 and are summarized below.

The inevitable increase in the required feedstock demand for the production of biofuels brings about the challenge of covering this demand without putting at risk food security, biodiversity and access to arable land. The main questions relate to biofuels impact on agricultural commodity markets, their role in the food price determination process, and how the current biofuel policies carry the risk of generating food insecurity in low-income countries. The main speculation expressed is that considering the relative importance of the energy markets compared to food markets, as well as the relative economic power of the consumers demanding more energy compared to the ones demanding more food, an increased production of biofuels could eventually lead to an increase of food prices and subsequently to imperiling access to food by vulnerable consumers.

On the other hand, when the increasing demand for biofuel feedstock imposes a direct or indirect change of the primary use of a land (e.g. deforestation) and considering that forests act as an absorber of CO_2 from the atmosphere, removing them for biofuel production may actually result in increasing the total GHG emissions instead of decreasing them. It is therefore considered imperative to take into account both GHG emissions and land use change, when assessing the environmental balance of biofuels.

As regards the competitiveness of biofuels, both conventional and advanced (except for Brazilian sugarcane ethanol) are currently far from competitive to gasoline and diesel, which is the reason why until now, biofuels are mainly supported by national policies.

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Moreover, as various studies have shown, projections on the timing at which biofuels will become competitive are rather hard to assess, since this depends a lot on the prices at which gasoline and diesel will eventually settle. This makes biofuels very sensitive to oil prices and market conditions.

Another major factor of uncertainty regarding the future of biofuels relates to their supply chain and logistics. The rather complicated nature of biomass feedstocks and biofuels as transported goods, combined with the high associated costs and impacts on the transportation of feedstocks and final product (such as low mass and energy density of feedstocks, high moisture content, inefficient capacity of harvesting, transportation and storing equipment, variability and inconsistency of feedstocks quality, costly transportation and risk of damaging roadways) have made it quite difficult to develop economically efficient supply chains. Moreover, the different and often competing interests of the parties involved in the entire supply chain could potentially impede an optimal supply chain design.

Considering all the above, it is important to introduce national and regional policies that will incentivize the technological development of advanced biofuels, with increased yields and efficiencies. This will allow the significant reduction of costs for the production of biofuels, making them in turn more competitive to fossil fuels for transport. Moreover, although numerous international initiatives are already in place to ensure a minimal negative impact of biofuels on the environment and society (e.g. binding sustainability criteria by EU, USA, Switzerland among others), an integrated global approach should be adopted. To be able to consider biofuels for the decarbonization of the transport sector, an analysis of environmental, economic and social implications has to be performed, taking into account the extensive and complicated impacts of biofuels production and supply on environment and society as well as on the associated sectors of agriculture and forestry.

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3.3.4. Raw material limitations in green technologies

In this section a summary of the main outcomes obtained through the bottom-up and top-down analysis of the different green technologies described in annexes 6 to 12 is shown, i.e. results from vehicles, RES for electricity generation, RES for heat generation and Domestic storage systems.

Firstly the exergy demand share of each Green Technology has been assessed considering the expected material requirements for their deployment in the period between 2016 and 2050 (Figure 13).

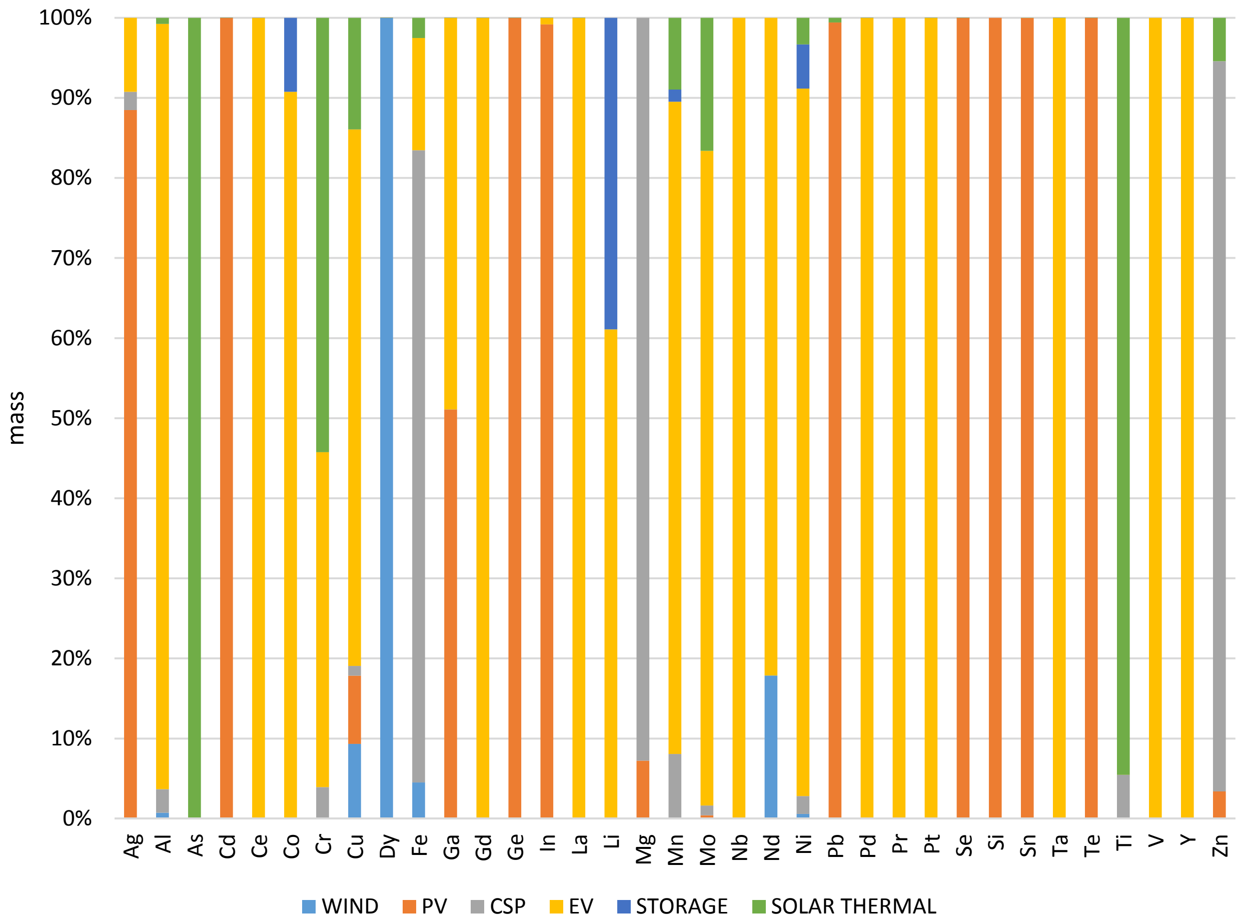

Figure 13. Gross of cumulative material demand of each technology for each studied materials, measured in exergy.

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The following conclusions can be highlighted:

- Solar photovoltaic demands the highest fraction of all green technologies analysed for the following materials: Ag, Cd, Ga, Ge, In, Mg, Pb, Si, Sn and Te.
- Passenger vehicles demand the highest fraction of all green technologies for the following materials: Al, Ce, Co, Cu, Fe, Gd, La, Li, Mn, Mo, Nb, Nd, Ni, Pd, Pr, Pt, Ta, V and Y.
- Solar thermal demands the highest fraction of all green technologies for the following materials: As, Cr, P and Ti.
- Solar thermoelectric demands the highest fraction of all green technologies for Zn.
- Wind power is the technology which demands the highest fraction of Dy. Moreover it will require a good production share of Nd.
- Batteries will demand a significant amount of Co, competing thus with passenger vehicles.

Figure 14 compares the material demand from 2016 to 2050 with current values of reserves and resources (due to data variations, the vertical axis is in logarithmic scale).

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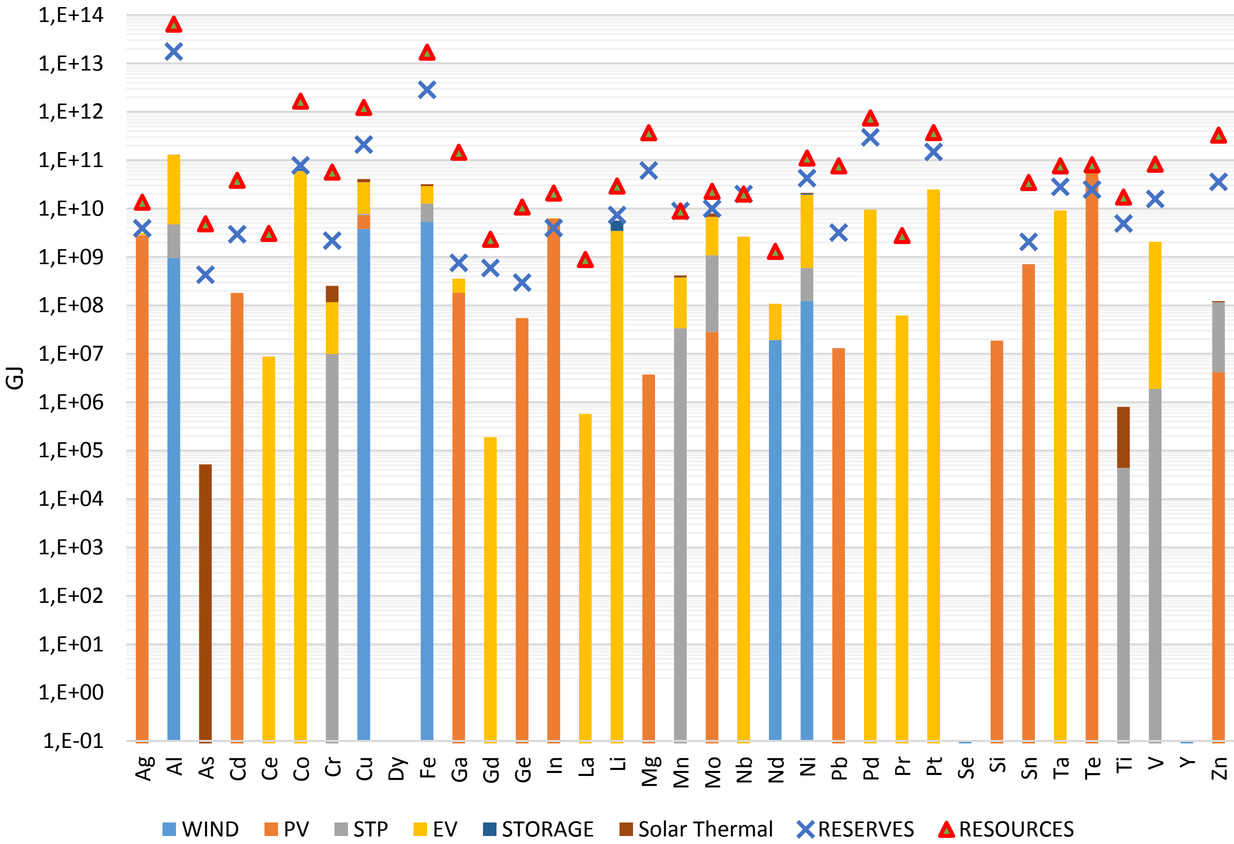

Figure 14. 2016-2050 Green Technologies cumulative material demand, resources and reserves, measures in exergy[11].

The following conclusions can be highlighted:

- Under a BAU scenario, there will be more cumulative demand from 2015 to 2050 than available reserves in the case of: In and Te.
- The technologies that might be affected by material constraints are:
  - In and Te: solar photovoltaic.

[11] There is no Dy and Se data as their exergy values have not been assessed yet. In mass terms, data suggests that there will be enough resources to cover demand.

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Comparing the rest of materials with current reserves values, and keeping in mind that these materials are used in other sectors (not only in the green technologies analyzed) and hence world global demand will for all metals be greater than assumed, the following results have been preliminarily obtained:

- Co 2016 – 2050 cumulative demand ≈ 84 % of current reserves.
- Ag 2016 – 2050 cumulative demand ≈ 81 % of current reserves.
- Li 2016 – 2050 cumulative demand ≈ 76 % of current reserves.
- Mo 2016 – 2050 cumulative demand ≈ 57 % of current reserves.
- Ni 2016 – 2050 cumulative demand ≈ 48 % of current reserves.
- Ga 2016 – 2050 cumulative demand ≈ 47 % of current reserves.
- Sn 2016 – 2050 cumulative demand ≈ 34 % of current reserves.
- Ta 2016 – 2050 cumulative demand ≈ 32 % of current reserves.
- Cu 2016 – 2050 cumulative demand ≈ 16 % of current reserves.
- V 2016 – 2050 cumulative demand ≈ 16 % of current reserves.
- Nb 2016 – 2050 cumulative demand ≈ 13 % of current reserves.
- Pt 2016 – 2050 cumulative demand ≈ 12 % of current reserves.

The aforementioned constraints are based on reserves data. It is important to reiterate the fact that reserves are dynamic, since additional geological information expands the known number of reserves. Likewise, commodity prices and the development of more efficient technologies play an important role, as previously unworkable grades become economically profitable.

In fact, total world reserves of most mineral commodities are larger now than at any time in the past (Highley et al., 2004). Yet the information about world resources remains relatively scarce, inaccurate and incomplete. Put simply, too little is known about the Earth's crust, due to extremely high exploration costs. This is why the identification of a constraint based on available reserves is just an indication of possible bottlenecks but in any case it means that the Earth is going to run out of minerals.

In addition to the reserves constraint, there is another short-term bottleneck that could appear, when word production cannot offset demand, even if reserves are high enough. For its assessment, annual demand for materials in green technologies is now compared with annual production estimations using Hubbert Peak curves, i.e. assuming a BAU exponential-like scenario. The methodology used to obtain those production curves and the limitations of this analysis are explained in detail in Annex 6 (Raw materials). The following conclusions have been obtained:

- In the case of Ag, Co, Dy[12], Ga, In, Li, Mo, Ni, Sn and Te, under a BAU scenario, the demand will likely exceed production at some point in the period from 2016-2050.
- In the cases of Cd, Cr, Cu, Ge, Nd and Ta demand will not likely exceed the production for the 2016-2015 time period, just considering the materials used for green technologies.
- For Cd, Cr, Ta and Cu, as a consequence of the decreasing in production values and the growing demand, there could be a possible bottleneck after 2050 when compared to the production data obtained with the Hubbert model.
- In the case of Nb, around 30% of current production goes to produce steel for manufacturing vehicles. Yet since Nb is used as an alloy to manufacture body parts, its demand will grow significantly if yearly sales for vehicles and other Nb-steel infrastructures grow.

To classify all constraints, the following bottleneck categories are used:

- **Very high:** if 2016-2050 cumulative demand is higher than current reported reserves.

[12] Hubbert peak curve is made with resources instead of reserves.

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- **High:** if annual demand is at some point higher that annual production (calculated using the Hubbert model) from 2016 to 2050.

- **Medium:** if the annual demand is lower than annual production (calculated using the Hubbert model) from 2016 to 2050 but it is expected to be greater from 2050 to 2060.

Table 2 shows a summary of all the identified constraints.

Table 2: Summary of constraints for each green technology.

		Technology					
	Physical bottleneck risk	LDV	PV	WP	STP	ST	DST
Indium	Very high		X				
Tellurium	Very high		X				
Lithium	High	X					X
Silver	High		X		X		
Cobalt	High	X					X
Dysprosium	High			X			
Gallium	High	X	X				
Molybdenum	High	X				X	
Nickel	High	X				X	X
Tin	High		X				
Cadmium	Medium		X				
Chromium	Medium	X				X	
Copper	Medium	X				X	
Germanium	Medium		X				
Neodymium	Medium	X		X			
Tantalum	Medium	X					
Niobium	Medium	X					

LDV	Light duty vehicles (ICE, PHEV, BEV)
PV	Photovoltaic
WP	Wind Power
STP	Solar Thermal Power
ST	Solar Thermal
DST	Domestic Storage

It should be stressed that this raw material criticality assessment is only based on available reserves and technology evolution forecasts. Neither geopolitical security of supply risk nor global economic importance constraints have been considered thus it cannot be compared to that of the EU[2].

4. CONCLUSIONS

This Deliverable has covered 116 Partially Aggregated Variables as candidates to feed MEDEAS Model. The variables were selected after a bibliographic revision of PAVs used in other available models such as LEAPS, TIMES, MARKAL and WOLIM and considering the objectives of MEDEAS tool. The variables are grouped into the following categories: socioeconomics, electricity transformation, electricity generation (from RES and non-RES), thermal energy generation, transport, industrial energy consumption, residential energy consumption, other sectors energy consumption, primary energy transformation, energy storage and distributed generation and raw materials. It should be stated that such PAVs might change throughout the project's lifetime, if new requirements for MEDEAS are detected.

Once the list of variables was selected, possible feedback loops among the key ones were outlined. Accordingly, feedback loops were sketched regarding: the link between socioeconomic variables with energy and materials; green technologies with materials; and within each of the analyzed sectors (transport, electricity, agriculture, industry, services and residential sectors).

Another activity carried out in Task 2.2 was the identification of physical constraints for the given PAVs, as this is one of the pivotal features of MEDEAS. Resources constraints regarding availability of fossil fuels, biodiesel and non-energy minerals have been identified.

As for biodiesel, additional constraints related to food security and use of land among others have been analyzed.

Additionally, the Energy Return on Energy Invested (EROI) of conventional and unconventional sources, as well as renewable energy sources has been analyzed. A general decline of EROI values for fossil fuels has been stated from a literature review. Current EROI values for conventional fossil fuels vary from about 18:1 (for oil and gas) to 46:1 for coal, whereas for unconventional sources such value decreases down to 4-7:1. Particularly for fossil fuels, an EROI limit of 3:1 to cover basic functions for society has been established by some authors.

As opposed to fossil fuels, the EROI of renewable resources increases steadily with technological improvement. The lowest values are attributed to biodiesel, with EROIs of 4-7:1. In turn, for biomass it is estimated at 12-13:1. These are followed by tidal and wind (15:1 and 18:1, respectively), geothermal and PV (6-39:1 and 30-45:1, respectively). The highest EROI values are found for hydropower, with a range of 11-267:1. That said, EROI as defined in the literature does not consider the fact that technological improvement will likely require critical raw materials. Hence, a raw minerals exergy analysis has been additionally performed in order to define a wider sustainability approach.

Accordingly and with an exergy approach, a thorough analysis of the materials contained in PV, solar thermal, solar thermal power, wind energy, light duty vehicles and batteries has been carried out.

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The criticality of materials in green technologies have been classified according to three categories: 1) very high if 2016-2050 cumulative demand is higher than current reported reserves; 2) high if annual demand is at some point higher that annual production (calculated using the Hubbert-peak model) from 2016 to 2050; and 3) medium if the annual demand is lower than annual production (calculated using the Hubbert-peak model) from 2016 to 2050 but it is expected to be greater from 2050 to 2060.

The most critical materials identified were In and Te (mainly used in PV). Minerals Ag, Co, Dy, Ga, Li, Mo, Ni and Sn are considered to have a high risk to constitute potential bottlenecks. Such elements are mainly found in light duty vehicles and domestic storage systems (as part of batteries – Li, Co, Ni), in steel alloys (for vehicles and solar thermal – Mo, Ni), in permanent magnets (Dy in wind turbines) and in PV (Sn – electric contacts). Other elements considered to have medium risks are Cd, Ge (PV), Nd (wind energy and vehicles), Ta and Nb (vehicles) and Cr and Cu (solar thermal). In summary, the technologies that will demand most of the critical materials identified will be light duty vehicles (ICE, PHEV and BEV) and photovoltaics.

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5. PAV List

5.1. Socioeconomic PAVs

nº	Name	Description	Sources
1	GDP	GDP based in Purchasing Power Standard	http://stats.oecd.org/Index.aspx?DatasetCode=SNA_TABLE1
2	GVA	Gross Value Added by sector (Transport, Industry, Residential, Other sectors)	http://stats.oecd.org/Index.aspx?DatasetCode=SNA_TABLE1
3	Green GDP	It adjusts GDP according environmental damages	http://stats.oecd.org/Index.aspx?DataSetCode=GREEN GROWTH
4	Median Income	Is another alternative to GDP, which is useful to check when trying energy intensity related to the income Medium income shows what the majority of the society can afford.	http://stats.oecd.org/Index.aspx?DataSetCode=IDD
5	Human Development Index	It shows the "real progress" of the society´s welfare, not just the amount of money which circulates through the economy.	http://hdr.undp.org/en/data
6	Population	Population	http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators
7	Urban population	It measures how many people live in urban areas	http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators
8	Rural population	It measures how many people live in rural areas	http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators
9	Unemployment rate	It measures how many people have an employ.	http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators
10	Energy imports (energy dependency)	It shows the extent to which an economy relies upon imports in order to meet its energy needs.	http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators
11	Final energy consumption per capita	It measures how much final energy is yearly consumed by person	it can be calculated through data from: http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators - http://www.iea.org/statistics/statisticssearch/
12	Water consumption	It measures how much water is consumed by people	http://www.fao.org/nr/water/aquastat/main/index.stm
13	Material consumption	It measures how many materials are consumed by people	http://www.eea.europa.eu/publications/material-resources-and-waste-2014/at_download/file
14	Energy intensity	It measures how much primary energy is needed to produce a money unit.	http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators
15	Electricity average cost for household consumers	It measures what is the average cost of electricity for household consumers	http://ec.europa.eu/eurostat/data/database
16	Electricity average cost for industrial consumers	It measures what is the average cost of electricity for industrial consumers	http://ec.europa.eu/eurostat/data/database

17	Natural gas average price for household consumers	It measures what is the average cost of natural gas for household consumers	http://ec.europa.eu/eurostat/data/database
18	Natural gas average price for industrial consumers	It measures what is the average cost of natural gas for industrial consumers	http://ec.europa.eu/eurostat/data/database
19	Diesel price for thermal applications and household consumers	It measures what is the average cost of diesel for household consumers	http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_price_statistics
20	Diesel price for thermal applications and industrial consumers	It measures what is the average cost of diesel for industrial consumers	http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_price_statistics
21	Coal price for heating applications and household consumers	It measures what is the average cost of coal for household consumers	http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_price_statistics
22	Coal price for heating applications and industrial consumers	It measures what is the average cost of coal for industrial consumers	http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_price_statistics
23	Diesel price for transport	It measures what is the average cost of diesel for transport applications	http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_price_statistics
24	Gasoline price for transport	It measures what is the average cost of gasoline for transport applications	http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_price_statistics
25	CO_2 certification prices	It measures what is the cost of CO2 certificates	http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_price_statistics
26	People mobility	It measures how many kilometres are travelled among all people for different transport systems (road, rail, maritime, aviation)	http://stats.oecd.org/Index.aspx?DatasetCode=SNA_TABLE1 - http://www.emta.com/spip.php?article267&lang=en - http://ec.europa.eu/eurostat/data/database
27	Freight mobility	It measures how many kilometres are travelled among all freight for different transport systems (road, rail, maritime, aviation)	http://stats.oecd.org/Index.aspx?DatasetCode=SNA_TABLE1 - http://www.emta.com/spip.php?article267&lang=en - http://ec.europa.eu/eurostat/data/database

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5.2. Electricity transformation PAVs

nº	Name	Description	Sources
28	Primary energy consumption to produce electricity by source	Annual primary energy consumption of electric sector by type of source (oil, coal, natural gas, RES, nuclear)	http://www.iea.org/statistics/statisticssearch/
29	Electricity emissions	Average CO_2 emission of electricity sector	http://data.worldbank.org/indicator/EN.CO2.ETOT.ZS
30	Electricity demand	Annual final electricity demand	http://www.iea.org/statistics/statisticssearch/
31	Electricity supply losses	Electrical grid transportation and distribution losses	http://www.iea.org/statistics/statisticssearch/
32	Electricity self-consumed from fossil fuels	It measures how much electricity comes from self-consumption systems which use fossil fuels, like CHP plants	http://www.iea.org/statistics/statisticssearch/
33	Electricity self-consumed from RES	It measures how much electricity comes from self-consumption systems which use RES resources (solar, wind or biomass)	http://www.iea.org/statistics/statisticssearch/

5.3. Electricity generation from RES PAVs

nº	Name	Description	Sources
34	Capacity factor of RES	productivity of each technology according not only to technology evolution but also to renewable resources potential (wind, solar pv, solar CSP, hydro, biomass for electricity production)	http://www.eurobserv-er.org/
35	Investment cost of RES	Investment costs for each RES technology (wind, solar pv, solar CSP, hydro, biomass for electricity production)	http://www.eurobserv-er.org/

36	Electricity cost from RES	Levelage Cost of Electricity for each RES technology (wind, solar pv, solar CSP, hydro, biomass for electricity production)	http://www.eurobserv-er.org/
37	RES production by technology	Yearly production of each RES technology (wind, solar pv, solar CSP, hydro, biomass for electricity production)	http://www.iea.org/statistics/statisticssearch/report/?&country=SPAIN&product=Indicators
38	RES power density from technology point of view	Power density of each RES technology (wind, solar pv, solar CSP, hydro)	http://www.eurobserv-er.org/
39	RES power density from a resource point of view	Surface needed to generate 1 MWh/yr from biomass	http://www.eurobserv-er.org/
40	RES lifetime	Life time of each RES technology (wind, solar pv, solar CSP, hydro, biomass for electricity production)	http://www.eurobserv-er.org/
41	RES EROI (from cradle to grave)	EROI of different RES (wind, solar pv, solar CSP, hydro, biomass from electricity production) from LCA point of view	http://www.eurobserv-er.org/

5.4. Electricity generation from non RES PAVs

nº	Name	Description	Sources
42	Investment cost of conventional power plants	Investment costs for conventional power plants (nuclear, coal, fuel, gas)	http://world-nuclear.org/
43	Conventional power plants lifetime	Life time of conventional power plants (nuclear, coal, fuel, gas)	http://world-nuclear.org/
44	Electricity production from nuclear	Electricity production from nuclear power plants	http://www.iea.org/statistics/statisticssearch/report/?&country=SPAIN&product=Indicators
45	Electricity production from oil sources	Electricity production from oil sources	http://www.iea.org/statistics/statisticssearch/report/?&country=SPAIN&product=Indicators
46	Efficiency of oil power station	Efficiency in oil power station	https://www.eia.gov/tools/faqs/faq.cfm?id=107&t=3
47	Electricity production from gas sources	Electricity production from gas sources	http://www.iea.org/statistics/statisticssearch/report/?&country=SPAIN&product=Indicators

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nº	Name	Description	Sources
48	Efficiency of gas power station	Efficiency in gas power station	https://www.eia.gov/tools/faqs/faq.cfm?id=107&t=3
49	Electricity production from coal	Electricity production from coal sources	http://www.iea.org/statistics/statisticssearch/report/?&country=SPAIN&product=Indicators
50	Efficiency of coal power station	Efficiency in coal power station	https://www.eia.gov/tools/faqs/faq.cfm?id=107&t=3

5.5. Thermal energy generation from RES PAVs

nº	Name	Description	Sources
51	Capacity factor RES	Productivity of each technology according not only to technology evolution but also to renewable resources potential (solar thermal, geothermal, biomass)	http://www.eurobserv-er.org/
52	Investment cost RES	Investment costs for each RES technology (solar thermal, heat biomass, geothermal)	http://www.eurobserv-er.org/
53	Thermal energy cost from RES	Levelage Cost of heat for each RES technology (solar thermal, heat biomass, geothermal)	http://www.eurobserv-er.org/
54	RES production for thermal applications	Yearly production of each RES technology (solar thermal, heat biomass, geothermal)	http://www.eurobserv-er.org/
55	RES power density from technology point of view	Power density of each RES technology (solar thermal, geothermal)	http://www.eurobserv-er.org/
56	RES power density from resource point of view	Surface needed to generate 1 MWh/yr of heat from biomass	http://www.eurobserv-er.org/
57	RES lifetime for thermal applications	Life time of each RES technology (solar thermal, heat biomass, geothermal)	http://www.eurobserv-er.org/
58	RES EROI (from cradle to grave)	EROI of different RES (solar thermal, heat biomass, geothermal) from LCA point of view	http://www.eurobserv-er.org/

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5.6. Transport PAVs

nº	Name	Description	Sources
59	Energy intensity of transport sector	It measures how much energy is needed in transport sector to contribute to the GVA (gross value added)	http://www.worldenergy.org/data/
60	Transport final energy consumption by source and type of transport system	Annual energy consumption share of transport sector by subsector (road, aviation, maritime, train) and type of final energy (coal, petrol products, gas, electricity, biofuels)	http://www.iea.org/statistics/statisticssearch/
61	Passenger light-duty vehicles fleet	Total number of passenger light duty vehicle fleet	http://www.acea.be/
62	Electrical power train light duty vehicles share	Electric power train vehicles share with respect to total vehicles (BEV, REEV, FCV)	http://www.acea.be/
63	Electrical powertrain light duty vehicles sales	Electric vehicles sales with respect to total vehicles sales (BEV, REEV, FCV)	http://www.acea.be/
64	Mechanical and Electrical power train light duty vehicles share	Hybrid vehicles share with respect to total vehicle fleet (HEV and PHEV)	http://www.acea.be/
65	Mechanical and Electrical power train light duty vehicles sales	Hybrid vehicles sales with respect to total vehicles sales (HEV and PHEV)	http://www.acea.be/
66	Mechanical power train light duty vehicles share	ICE (petrol, diesel and gas) vehicles share with respect to total vehicle fleet	http://www.acea.be/
67	Mechanical power train light duty vehicles sales	ICE (petrol, diesel and gas) vehicles sales with respect to total vehicles sales	http://www.acea.be/
68	GHG evolution of light duty vehicles	GHG evolution as a result of regulation evolution for different polluting emissions (NOx, CO, CO2, PM10, HC)	http://ec.europa.eu/environment/air/transport/road.htm
69	Biofuel share	Biofuel share in transport fuels	http://ec.europa.eu/environment/air/transport/road.htm

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5.7. Industrial Energy consumption PAVs

nº	Name	Description	Sources
70	Energy intensity of industrial sector	It is how much energy is needed in industrial sector to contribute in the GVA (gross value added)	http://www.worldenergy.org/data/
71	Industrial final energy consumption by type of final energy	How much energy is consumed from (RES, electricity, petroleum products, gas, solid fuels)	http://www.iea.org/statistics/statisticssearch/

5.8. Residential Energy consumption PAVs

nº	Name	Description	Sources
72	Energy intensity of residential sector	It measures how much energy is needed in the residential sector to contribute to the GVA (gross value added)	http://www.worldenergy.org/data/
73	Residential final energy consumption by type of final energy	How much energy is consumed from (RES, electricity, petroleum products, gas, solid fuels)	http://www.iea.org/statistics/statisticssearch/
74	Residential final energy consumption mandatory share from RES	Mandatory share of RES in residential energy consumption by adoption of legislation requirements	http://www.iea.org/statistics/statisticssearch/

5.9. Other sectors energy consumption PAVs

nº	Name	Description	Sources
75	Energy intensity of other sectors	It measures how much energy is needed in “other sectors” to contribute to the GVA (gross value added)	http://www.worldenergy.org/data/
76	Other sectors final energy consumption by type of final energy	How much energy is consumed from (RES, electricity, petroleum products, gas, solid fuels)	http://www.iea.org/statistics/statisticssearch/

5.10. Primary energy transformation PAVs

nº	Name	Description	Sources
77	Coal to liquid fuel	Annual quantity of liquid fuel coming from coal that is consumed	http://www.worldcoal.org/
78	Coal to liquid efficiency	Efficiency in coal to liquids process	http://www.worldcoal.org/
79	Gas to liquid fuel	Annual quantity of liquid fuel coming from gas that is consumed	http://earlywarn.blogspot.com.es/2010/01/gas-to-liquids-production-statistics.html
80	Gas to liquid efficiency	Efficiency in gas to liquids process	http://earlywarn.blogspot.com.es/2010/01/gas-to-liquids-production-statistics.html
81	Conventional Oil production	Annual quantity of fuel coming from conventional production ways	http://www.bp.com/
82	Unconventional Oil production	Annual quantity of fuel coming from unconventional production ways	http://www.bp.com/
83	Conventional Gas production	Annual quantity of gas coming from conventional production ways	http://www.bp.com/
84	Unconventional Gas production	Annual quantity of gas coming from unconventional production ways	http://www.bp.com/
85	Coal production	Annual quantity of coal produced	http://www.bp.com/

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nº	Name	Description	Sources
86	Coal production EROI	EROI assessment to get coal	http://www.worldcoal.org/
87	Conventional Gas production EROI	EROI assessment from conventional ways to get gas	http://www.bp.com/
88	Conventional Oil production EROI	EROI assessment from conventional ways to get oil	http://www.bp.com/
89	Unconventional Gas production EROI	EROI assessment from unconventional ways to get gas	http://www.bp.com/
90	Unconventional Oil production EROI	EROI assessment from unconventional ways to get oil	http://www.bp.com/
91	Oil exergy reserves	It measures what is the quality of oil reserves	http://www.bp.com/
92	Oil exergy production	It measures what is the rhythm of oil extraction	http://www.bp.com/
93	Coal exergy reserves	It measures what is the quality of coal reserves	http://www.bp.com/
94	Coal exergy production	It measures what is the rhythm of oil extraction	http://www.bp.com/
95	Gas exergy reserves	It measures what is the quality of gas reserves	http://www.bp.com/
96	Gas exergy production	It measures what is the rhythm of oil extraction	http://www.bp.com/
97	Biofuels production	It measures how many biofuels are produced	http://www.bp.com/, International Energy Agency (IEA)

5.11. Energy storage and distributed generation PAVs

nº	Name	Description	Sources
98	Energy storage density from chemical technologies to be used in light-duty vehicles	Energy density storage system evolution (NiMH and Li-ion technologies)	http://ewfa.org/sites/default/files/rev_of_battery_executive_web_1.pdf

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n°	Name	Description	Sources
99	Energy storage cost from chemical technologies to be used in light-duty vehicles	Energy storage system evolution (NiMH and Li-ion technologies)	http://ewfa.org/sites/default/files/rev_of_battery_executive_web_1.pdf
100	Energy storage density from chemical technologies to be used in household applications	Energy density storage system evolution (NiMH and Li-ion technologies) coming usually from a second life of vehicle storage systems	http://ewfa.org/sites/default/files/rev_of_battery_executive_web_1.pdf
101	Energy storage cost from chemical technologies to be used in household applications	Energy storage system evolution (NiMH and Li-ion technologies) coming usually from a second life of vehicle storage systems	http://ewfa.org/sites/default/files/rev_of_battery_executive_web_1.pdf
102	Energy storage lifetime of chemical technologies	Battery lifetime	http://ewfa.org/sites/default/files/rev_of_battery_executive_web_1.pdf
103	Hydrogen energy density for transport applications	Energy density of hydrogen for transport application to different modes of supply (300 bar; 600 bar; liquid)	http://www.fchea.org/
104	Hydrogen cost for transport applications	Energy cost of hydrogen for transport application to different modes of supply (300 bar; 600 bar; liquid)	http://www.fchea.org/
105	H_2 EROI	Energy consumption from H2 generation to tank for different modes of supply (300 bar; 600 bar; liquid) - considering energy consumption to compress and storage Hydrogen	http://www.fchea.org/

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nº	Name	Description	Sources
106	Electricity storage linked to distributed generation with RES	It measures the storage capacity linked to the promotion of RES technologies in a distributed generation scenario.	https://www.irena.org/DocumentDownloads/Publications/IRENA_REmap_Electricity_Storage_2015.pdf https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapEnergystorage.pdf https://www.rolandberger.com/media/pdf/Roland_Berger_TAB_Solar_PV_20150610.pdf
107	Transport and distributed grid material demand	It measures the material demand of the grids as a consequence of the increase of electrical grid in a distributed generation context.	García Olivares et al. (2012)

5.12. Raw material PAVs

nº	Name	Description	Sources
108	Metal production	Metal production measured in exergy terms for each material considered as critical (the big six will be also included, i.e. Fe, Al, Zn, Cu, …). This relates to material production for all sectors, not just RES and transport. It will be derived from Hubbert curves.	US Geological Survey
109	Material intensity for RES	Material requirements, measured in exergy terms needed to manufacture 1 MW of each RES technology	IEA, WEC, RES associations
110	Material intensity for transport	Material requirements, measured in exergy needed to manufacture 1 unit of vehicle for different types of vehicles (ICE,HEV, PHEV, REEV, FCE, BEV)	IEA, EMTA (European Metropolitan Transport Authorities)
111	Total reserves	Quantity of known reserves, measured in exergy terms	USGS (2015); Emsley (2001); Frenzel et al. (2014; 2016); Sverdrup and Ragnarsdottir, 2014.
112	Total resources	Quantity of known resources in exergy terms	USGS (2015); Emsley (2001); Frenzel et al. (2014; 2016); Sverdrup and Ragnarsdottir, 2014.
113	Recycling rates	It is the rate of recycling for each studied material	UNEP (2011)

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nº	Name	Description	Sources
114	Recycling energy demand	It is the quantity of energy required to recycle materials comparing this with the exergy of materials.	Grimes et al (2008, 2016).
115	Material extraction energy demand	It is the quantity of energy required to extract materials measured in exergy.	Valero and Valero (2014)
116	Material extraction emissions	It is the quantity of CO_2 emissions associated to material extraction.	Valero and Valero (2014)

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D2.1: *Report with an analysis of the main limitations of variables and indicators selected to represent the pathways and scenarios.*

Annex 1: *Socioeconomic implications of biophysical constraints*

Grant agreement: 691287

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TABLE AND FIGURE INDEX

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1. Scope and goal

This document is part of MEDEAS Deliverable D2.1. The objective of this Annex is to review and evaluate the data sources available for selected socioeconomic PAVs. The Annex provides a summary of the PAV database values that can be implemented in the MEDEAS model.

The Annex also focuses on relations between PAVs and thereby provides the basis for feedback loop relations between the PAVs to prepare their implementation in MEDEAS. This means that selected PAVs will be related to each other to identify and evaluate their relationships. The literature regarding these variables has been reviewed to identify potential sources for building PAV relationships and resulting feedback loops in MEDEAS.

The PAVs covered in this Annex are from the field of socioeconomic variables, including economic activity measured in GDP and population development.

The Annex further includes additional variables that have been considered as crucial physical constraints. This includes *sink constraints*, namely the quantities of emissions that can be absorbed by the atmosphere and the resulting damages.

Table 1. Links between socioeconomic variables and PAV list.

No.	Field	Variable	Description	Reason
1	Socioeconomic	GDP	GDP based in Purchasing Power Standard	It is linked with the growing and resources (water, energy, materials) demand capacity of a country. On the other hand It is also linked with the capacity to invest in new technologies.
6	Socioeconomic	population	population	It is linked with the amount of resources (water, energy, materials) consumed by a country as a whole.

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2. Model: PAV links

In this section we provide model relationships of PAV links for MEDEAS. To some extend we repeat there the information already included in the Executive summary (part 3.1.1). This is done in order to remind the key relationships, which interconnections are subject of this Annex. These relationships aim to contribute to explain the feedback loops between the variables for socioeconomic activity and physical constraints, including carbon emissions and the variables that connect them. Key relationships will then be reviewed and evaluated in the subsequent section.

We consider population dynamics as a key determinant for economic activity, energy use, and resulting emissions. Population growth is influenced by the birth rate and mortality. Therefore, we state that population is a function of birth rate, mortality, and the current population size:

Population (PAV6) = f(birth rate, mortality, current population size)

Mortality and birth rate, in turn, are influenced by per capita GDP levels. Therefore, also the population size is indirectly determined by GDP:

Population (PAV6) = f(birth rate(GDP), mortality(GDP), current population size)

Population is related to the economic activity measured as GDP via per capita productivity. Therefore, GDP is a function of population size and per capita productivity.

GDP (PAV1) = f(per capita productivity, current population size)

Per capita productivity is influenced by available capital and energy supply. Therefore, GDP is indirectly influenced by capital and energy supply.

GDP (PAV1) = f(per capita productivity(energy, capital), current population size)

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GDP is related to actual sectorial energy demand via price elasticity of demand and actual market prices and resulting energy intensity. Energy demand from each source is influenced by the energy intensity of sectorial GDP and the related price elasticity of demand from each sector, which, together with the current energy prices, determine the actual demand.

We focus on electric energy supply in the Resource availability and EROI annex (Annex 3).

We now focus on the physical constraints of carbon emissions from fossil sources. Depending on the production costs and policies related to renewable energies, and the production costs of fossil energy (see the Resource availability and EROI annex), a demand share for fossil energy from coal, gas, and oil will result. The production costs of fossil energies are not only influenced by EROI and actual production, but also by policies, including taxes and regulations. This leads to emissions that may constrain energy and specifically electricity generation from fossil fuels. Emissions may also lead to damages that negatively influence per capita productivity and therefore reduce socioeconomic activity. Therefore, we need to revise the function for GDP, including climate impacts:

GDP (PAV1) = f(per capita productivity(energy, capital, climate), current population size)

3. Methodology

The approach to reviewing data and related literature proceeds along the following lines. First, literature on the key PAVs are summarized and data is compared for different sources.

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Second, whenever a PAV is a composite or relation between different basic data sources, the specific methodology will be discussed. On the other hand population measures are clear, and GDP accounting is relatively standardized, there are not so many things to be discussed.

Third, the key findings and conclusions are summarized in the final section, providing the key insights as to why one data source is preferred over the other, or where a synthesis of multiple data sources should be used, or whether data sources should in general be used with caution, which may require sensitivity analyses when used with MEDEAS.

4. Data and relations between PAVs

This section discusses the PAVs, related data sources, and key relationships between the variables. We will first focus on source constraints, then proceed with socioeconomic activity that leads to a certain demand from different sources, and then proceed with the sink constraints, specifically carbon emissions.

4.1. Emissions and socioeconomic activity

The idea behind this section is to identify relations between socioeconomic variables (GDP and population growth), biophysical impacts of socioeconomic activity (with special focus on emissions from greenhouse gases, mostly CO_2), and the capacity of the biosphere to absorb the emissions from socioeconomic activity. Every part consists of literature review, and then explanation and reasoning of choosing one particular approach/assumptions about the relationships between selected variables. Finally we present relevant data and discuss them.

We have identified three important subtopics that need to be addressed:

- **Socioeconomic activity** (population and GDP);
- **Emissions production and emissions intensity of the socioeconomic activity** (linking emissions to GDP);

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- **Carbon sinks capacity** (biophysical limits to socioeconomic activity).

Socioeconomic activity refers to population and GDP data (PAVs 1 and 6 from the MEDEAS dataset), and to the nature of their interconnections (what kind of feedback loop there is and why; how GDP depends on population development, etc.).

Emissions production and emissions intensity per unit of GDP (plus the issue of **decoupling)** serves as the necessary leverage to link the socioeconomic variables to the biophysical constraints, and also possibly to energy variables. As the interconnections are quite simple and straightforward in this part (the main link is the emissions intensity per GDP, calculated from emissions production on the one hand and GDP development on the other), the aim is to present historical data and projections about how much one unit of GDP (US dollars) "costs" in terms of units of carbon (usually billions of metric tons). This would create the necessary feedback loop between socioeconomic (GDP, connected to population development) and biophysical and also energy variables (fossil fuels burning).

Carbon sinks capacity part we use to set up the necessary biophysical limits to emissions production based GDP growth. Once we know the historical ratio between emissions production and GDP growth, and what is the estimated future relation of fossil fuels burning, greenhouse gas emissions, and GDP growth, it is also necessary to tackle the issue of environmental limits of such socioeconomic activity. The question basically stands "how much carbon can we burn, if we want to stay in these and these boundaries?" Setting these "limits to growth" is crucial, if we want to be sure that we do not exceed some external, planetary limits – which would e.g. imply threatening some very important ecosystem functions. To set up these limits as fixed may also help to the model dynamics, from which we would be then able to see how other variables react, given the biophysical limits.

The three parts are following the main approach we take in this annex. First, we have considered the physical resource constraints (quantity of the resources somehow available for the socioeconomic activity), then conversion constraints (EROI) and the

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issue of resource quality, and now we move to the socioeconomics as the "demand side" (GDP and population development) concerning the resources consumption, and then sink constraints as the ultimate limits of such socioeconomic activity.

Logically, the socioeconomics are first followed by emissions intensity (based on energy intensity, as will be seen), which then results in total emissions production. Thus, even though we do not deal with energy intensity as a PAV, this is one of the main outcomes of our analysis, that energy intensity and overall energy consumption of fossil fuels should be considered as PAV and analyzed for the needs of MEDEAS.

4.2. Socioeconomic activity

What we call here "socioeconomic activity" refers exclusively to two variables: GDP development and population growth. Global GDP projections for the 21st century are needed for the exploration of long-term global environmental problems, in particular climate change, as will be described more in detail in part "Emissions production and emissions intensity". Greenhouse gas emissions also strongly depend on growth of per capita income, again related to GDP (e.g. Leimbach et al., 2015) – although we do not analyze per capita income here.

What also seems quite intuitive is that GDP and population are somehow interconnected. The first question of this part then is, how exactly the relationship between GDP and population growth looks like.

In general, growing economies need growing populations, increasing the supply of both workers and consumers, although the precise nature of this relationship is much more complex and variable. *Although economic growth is more volatile than population growth, and both indicators grow at vastly different rates, the fact that populations and economic output tend to grow in tandem, albeit at different rates, has been well-documented.*

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In the mainstream economic theory, in the absence of the so-called market frictions, the maximum attainable economic growth rate is (1+P)*(1+T)-1, where *P* is the population growth rate *and T* is the productivity growth rate. If market frictions exist and then decrease, the realized growth rate will exceed (1+P)*(1+T)-1. If frictions increase, then the realized growth will be less than (1+P)*(1+T)-1.

There is also a historical evidence of this positive relationship between population growth and GDP. The remarkable success of Western economies in the past 200 years is very often interpreted to be associated with strong population growth. On the other hand, the situation might be different in the today's so-called developing countries (The effect of population growth on per capita GDP growth is negative in developing countries, 2012). Population growth often starts to be problematic if it outpaces increases in productivity, and/or if it is outpaced by strong population growth. Then GDP per capita stagnates, although it may be that aggregate GDP growth would have been even lower without population growth. But generally, when the link between population growth and economic growth appears to weaken, the implications of this shift are not often clear and every case has its specific causes.

Nevertheless, for the goals of this deliverable, we will take the relationship between GDP and population growth– in general and in the long term – as direct and positive (i.e. that population growth helps also GDP to grow), but – with regard to the facts described in the previous paragraphs – without setting any exact quantified ratio between those two. We realize that the exact interplay can vary and every case is specific. To define exactly this relationship, it would be necessary to identify also the changes in productivity, income per capita and possibly other (interstitial?) variables.

Figures for population development and GDP, respectively, can be seen below. For population see Figure 1, for GDP see Figure 2 and 3, respectively.

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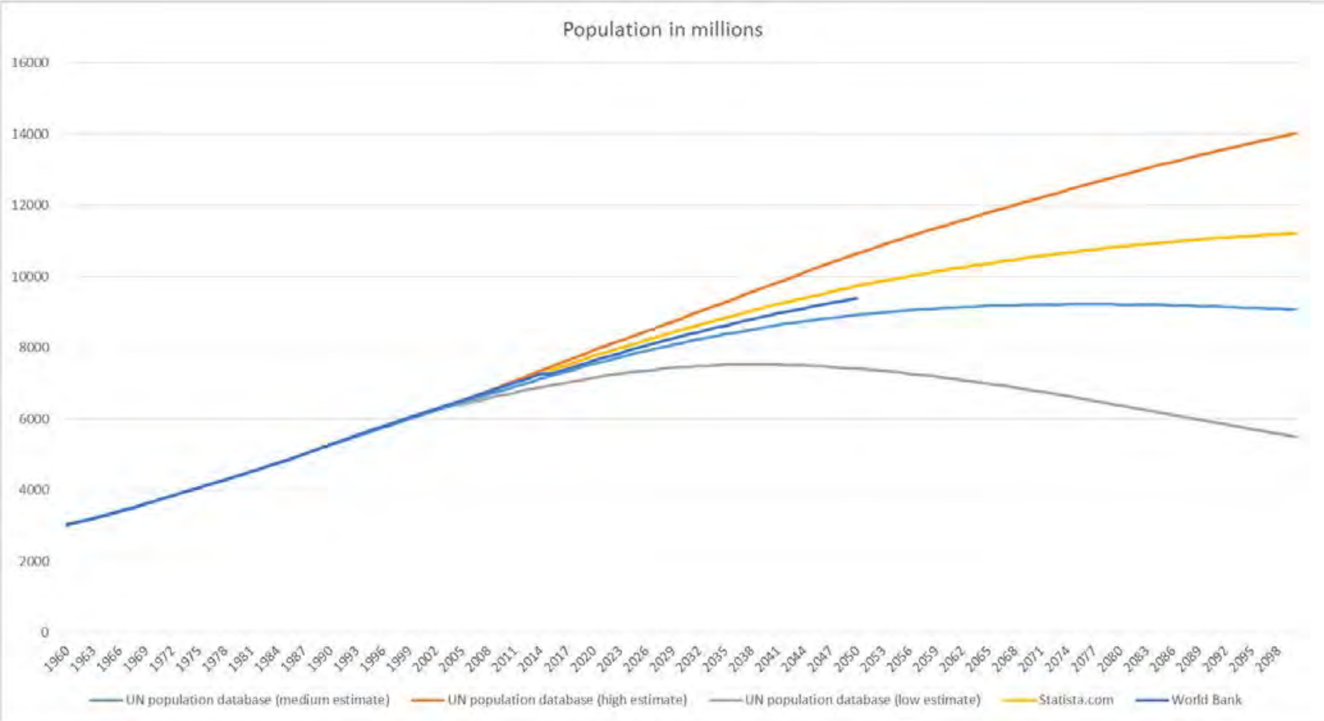

Figure 1. Population development: historical pathways and future projections[1].

[1]Sources: *http://data.worldbank.org/indicator/SP.POP.TOTL; http://www.un.org/esa/population/publications/longrange2/WorldPop2300final.pdf; http://www.statista.com/statistics/262618/forecast-about-the-development-of-the-world-population/*

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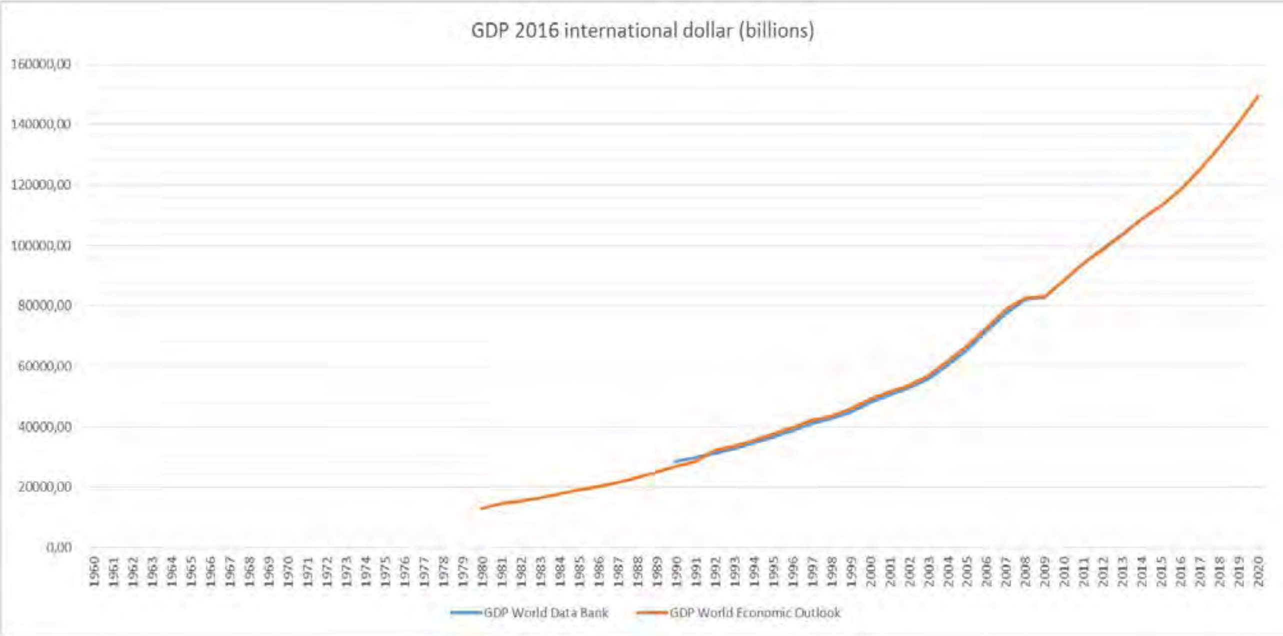
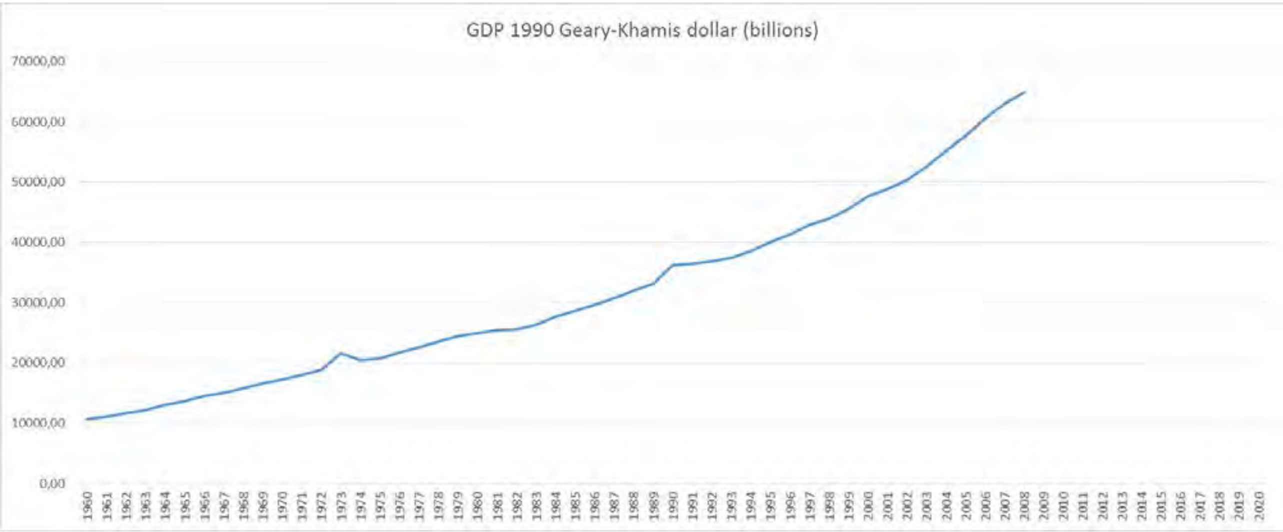


Figure 2. Historical GDP development and future projections up to 2020 (2016 international dollar)[2].



[2] Sources: *http://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG; http://www.imf.org/external/pubs/ft/weo/2016/update/01/; http://nextbigfuture.com/2010/12/world-economic-trends-through-2100-and.html.*

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Figure 3. Historical GDP development and future projections up to 2020 (1990 Geary-Khamis dollar)[3].

Depending on the scenarios, especially for the population development, it is quite obvious that the socioeconomic pressure will increase substantially in the next decades (this of course takes as an assumption that there are many links between the socioeconomic activity and ecological pressure). If we keep to the medium estimates[4] (from the World Bank, UN medium estimate and from Statista.com), population is expected to increase at least until +/-2070. Even though we do not have reliable data for GDP future development[5], we can estimate from the past interplay between population and GDP that GDP will increase as well, which will require more inputs to the economy. To deal with the biophysical "option space" seems to be crucial, then.

The link between the socioeconomic activity and its biophysical constraints/limits will be discussed below in the next sections.

4.3. Emissions production, emission intensity per unit of GDP and the issue of decoupling

In this part we intend to link the socioeconomic variables with their unintended, though environmentally significant outcomes, i.e. emissions. They are part of the "negative externalities" (to use the economic language) of the socioeconomic activity. Obviously, one first need to look at the total amount of emissions production, and only then try to link them with the socioeconomic activity via the so-called emission intensity.

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[3] *http://www.ggdc.net/maddison/maddison-project/data.htm*

[4] Given that the low UN estimate seems highly unrealistic in the light of the current data – we have already exceeded what this scenario had projected.

[5] We decided to follow only the data from the most „trustful" sources such as international organizations (which make their projections only up to 2020) – World Bank and International Monetary Fund – as there are institutes projecting GDP growth up to 2050 or even 2100, but their results differ so widely that we have decided not to rely on these calculations.

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Emission intensity is an *average emission rate of a given pollutant from a given source relative to the intensity of a specific activity*. This means, for example, grams of carbon dioxide released per megajoule of energy produced. In our case, we will be interested in the amount of greenhouse gas (respectively CO_2) emissions produced per unit of gross domestic product (GDP). The concept of emission (or carbon, in our case) intensity is used to derive estimates of greenhouse gas emissions based on the amount of fuel combusted, or industrial production levels. Emission intensity may also serve as a basis for comparison of environmental impact for different fuels.

A commonly used figure for measuring emissions intensity is carbon intensity per kilowatt (CIPK). However, in our main source, the World Bank database, kilograms of CO_2 emissions per Power Purchasing Parity $ of GDP are used. Among carbon dioxide emissions are those stemming from the burning of fossil fuels and the manufacturing of cement. They include carbon dioxide produced during consumption of solid, liquid, and gas fuels and gas flaring.

The current data for the global emissions production can be seen below in Figure 4.

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Figure 4. Global emissions production (metric tons per capita)[6].

Similarly, the World Bank data for emission intensity (CO_2 emissions per Power Purchasing Parity $ of GDP) for the aggregated world level can be seen below in Figure 5.

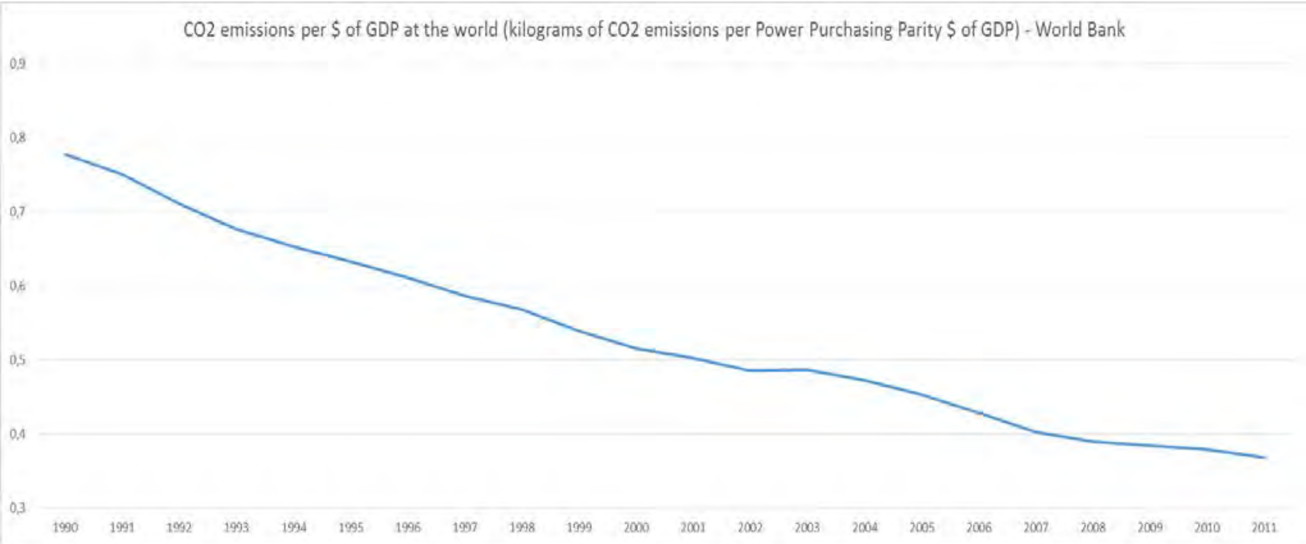

Figure 5. CO2 emissions per Power Purchasing Parity $ of GDP for the world aggregate level[7].

We can see that the ratio between CO_2 emissions and GDP was declining in the period, i.e. lesser CO_2 emissions was needed to produce one unit of GDP. However, whether there is decreasing need of emissions per one unit of GDP or not, there is still argued to be a positive correlation between these two variables.

The possibility of delinking the ratio between CO2 emissions and one unit of GDP production leads some to the idea of **decoupling**. Decoupling refers to the a*bility of an*

[6] *source: http://data.worldbank.org/indicator/EN.ATM.CO2E.PC*

[7] *source: http://data.worldbank.org/indicator/EN.ATM.CO2E.PP.GD*

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economy to grow without corresponding increases in environmental pressure, among others CO_2 emissions production. According to some authors (e.g. Schandl et al., 2015), now there are signs that GDP growth and carbon emissions need not necessarily rise together. For the first time in the 40 years since both metrics (i.e. GDP and carbon emissions) have been recorded, a recent study by the International Energy Agency found that global GDP grew, but global carbon emissions were decreasing ("Decoupling of global emissions and economic growth confirmed", 2016).

This could mean a temporary exception, but the trend from 2014 continued even in 2015. In another study, Nathaniel Aden (2016) from the World Resources Institute, found that since the start of the 21st century, in 21 countries, including the United States, while GDP went up over the past 15 years, carbon pollution went down. The case of USA can be seen below in Figure 6.

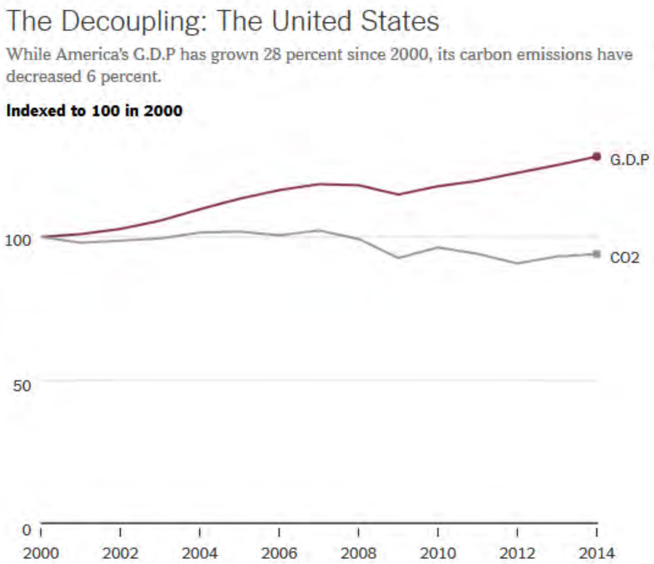

Figure 6: Decoupling in the United States of America[8].

[8] *source: World Resources Institute, http://www.nytimes.com/2016/04/06/upshot/promising-signs-that-economies-can-rise-as-carbon-emissions-decline.html?_r=1*

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On the other hand, for the issue of decoupling it is much more relevant to follow the data on the global level, as there may happen cost-shifting from high-income countries to low-income ones. In the high-income countries the GDP growth can theoretically decouple while increasing emission intensity in low-income or just other countries with "dirtier" production.

Moreover, ecological economist Tim Jackson (2011) stresses the importance of *differentiating between relative and absolute decoupling*. Relative decoupling refers to a decline in the ecological intensity per unit of economic output (which is happening, as was already discussed above). In contrast, absolute decoupling represents a situation in which emissions decline in absolute terms (Jackson, 2011). It means that an economy can relatively decouple in terms of emission production (associated with energy inputs) per unit of GDP. However, in this situation, total environmental impacts would still be increasing, albeit at a slower pace.

On the idea of decoupling is based also the concept of green growth, from recent studies critically discussed e.g. by Gazheli et al. (2015). Green growth, i.e. growth of GDP without growing ecological pressure, including emissions, is being criticized for lack of empirical evidence, or for the evidence of its contrary, respectively.

Moving back from decoupling to emission intensity, emissions production and their connectedness to socioeconomic variables, it is worth mentioning that in general, the period after WWII was characterized by rapid growth of the global economy, driven by both population and economic growth. Materials use increased as well, albeit at a slower pace than the global economy (but on the other hand faster than world population) (Krausmann et al., 2009). Krausmann et al. (2009) show that during the last century, global materials use increased 8-fold. According to them, our socioeconomic system currently uses almost 60 billion tons (Gt) of materials per year.

As a consequence, material intensity (i.e. the amount of materials required per unit of GDP) declined, while materials use per capita doubled from 4.6 to 10.3 t/cap/yr (Krausmann et al., 2009). From the main material groups, especially the mineral

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fractions grew at a rapid pace. So far there is no evidence that growth of global materials use is slowing down or might eventually decline and Krausmann's et al. (2009) results indicate that an increase in material productivity is a general feature of economic development.

Materials use also requires energy input, which is related to the emissions production and emission intensity, respectively. Admitting that materials use is a core feature of growing economies that produce emissions, then economic development and technology advancement significantly influence carbon dioxide emissions.

An older, though interesting study was done by Heil and Selden (2001), who collected historical data and calculated future projections for greenhouse gas emissions in connection to GDP growth. Heil and Selden estimate the historic relationship between carbon emissions and GDP using data across countries and across time. Then they combine this relationship with plausible projections for GDP and population growth to construct a model that offers insights into the likely path of global emissions in the 21st century.

Their calculations are derived from emission intensity, and as such offer a good approach to be possibly also applied in the case of MEDEAS. The most striking results from Heil and Selden's study are shown below. First, we show a comparison of different scenarios of emissions production from 1992 to 2100 (Figure 7). Second, we show charts with Heil and Selden's calculations of emissions production forecasts (Figure 8). Third, we show a table with calculations of emissions production in relation to GDP and population growth, by income groups (Table 9).

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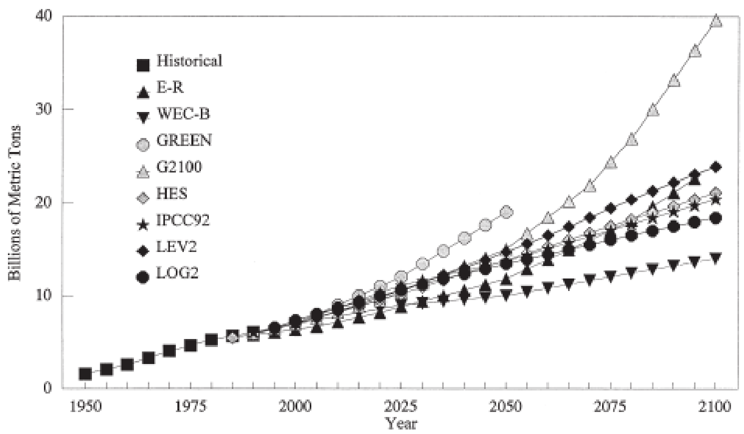
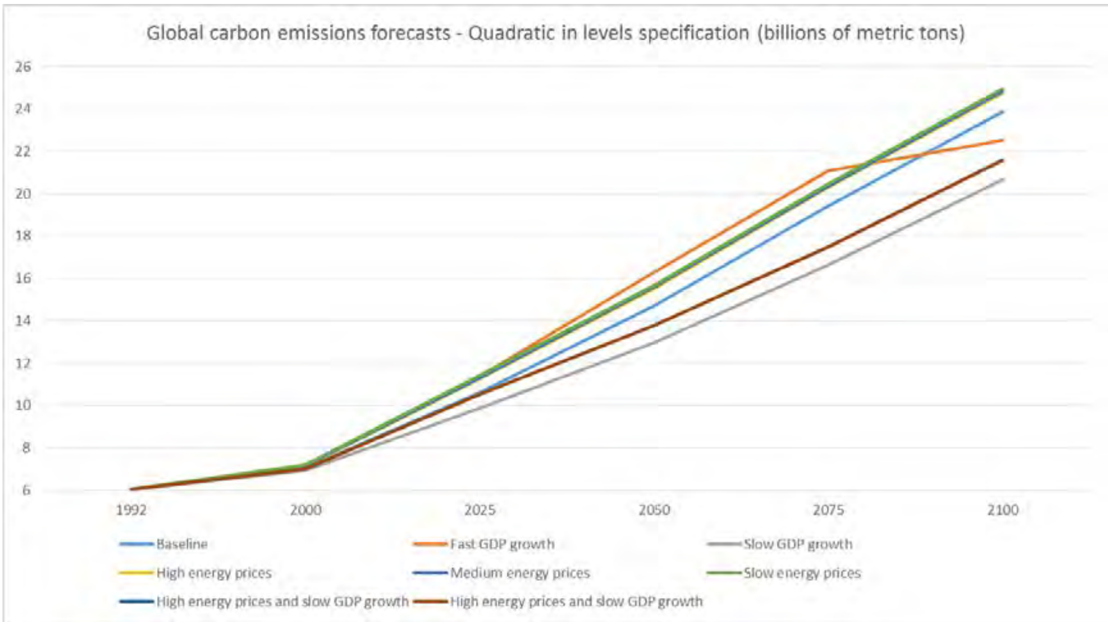


Figure 7. Comparison of annual emissions forecasts (source: Heil and Selden, 2001).[9]



[9] "Historical" is the 1950 to 1992 series from ORNL6. "IPCCC92" stands for IPCC IS92a scenario (IPCC, 1992). "GREEN" is the OECD general equilibrium model as run by Burniaux et al. (1992). "G2100" is Global 2100, the primary model constructed by Manne and Richels (1992). "E-R" is the Edmonds-Reilly model (see Barns, Edmonds and Reilly, 1992). "WEC-B" refers to the World Energy Council scenario B model (WEC, 1995). "HES" is the Holtz-Eakin and Selden levels forecasts (HES, 1995). "LEV2" and "LOG2" are quadratic in levels and quadratic in logarithms models done by Heil and Selden (2001), respectively.

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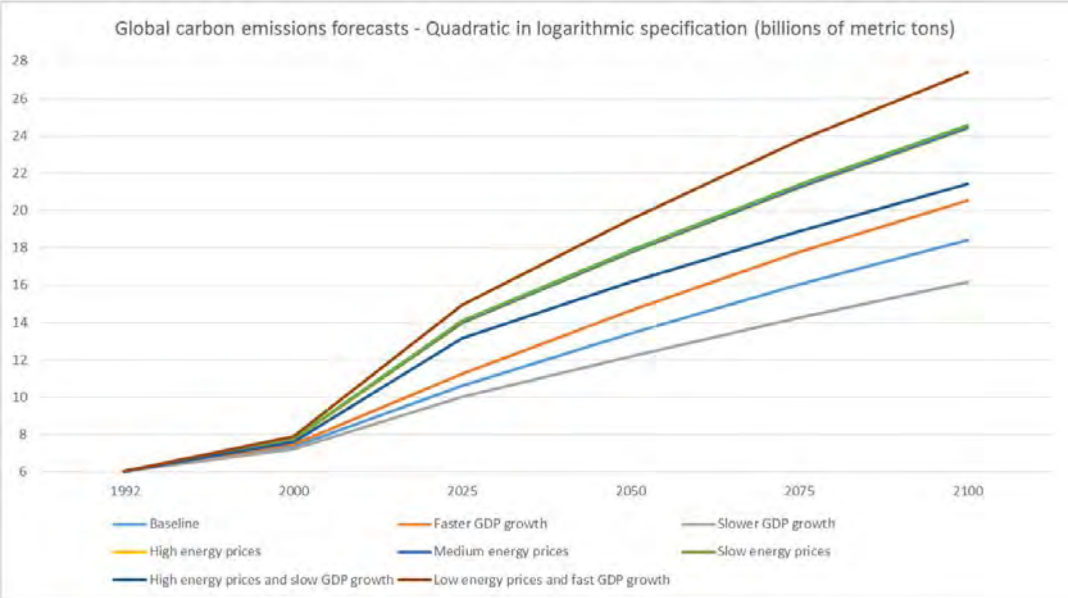

Figure 8. Global carbon emissions forecasts 1992-2100 in relation to GDP. 1992 figures are actual global carbon emissions from fossil fuels combustion and cement manufacture (source: Heil and Selden, 1992).

Table 9. Population, GDP, and emissions forecasts, by income group. Note: Population totals are in millions, GDP totals are in billions of 1992 US dollars, and emissions are in billions of metric tons. All calculations are limited to the sample of countries used to estimate the models (source: Heil and Selden, 2001).

Population, GDP, and emissions forecasts, by income group					
Income group	*Low*	*Lower-middle*	*Upper-middle*	*High*	*Total amounts*
Population share					
1992	*0,57*	*0,2*	*0,06*	*0,17*	*4,829*
2025	*0,6*	*0,22*	*0,06*	*0,12*	*7,308*
2100	*0,64*	*0,22*	*0,05*	*0,09*	*9,914*
Aggregate GDP share					
1992	*0,17*	*0,13*	*0,09*	*0,6*	*20,213*
2025	*0,2*	*0,18*	*0,12*	*0,5*	*52,487*
2100	*0,35*	*0,28*	*0,12*	*0,25*	*234,504*
Aggregate carbon emissions					
Actual (1992)	*0,99*	*0,38*	*0,4*	*2,72*	*4,49*

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Levels (2025)	*1,88*	*1,21*	*0,77*	*3,95*	*7,81*
Levels (2100)	*9,09*	*4,84*	*1,25*	*2,39*	*17,57*
Logarithms (2025)	*1,63*	*0,77*	*0,62*	*4,84*	*7,86*
Logarithms (2100)	*4,31*	*1,94*	*1,21*	*6,15*	*13,61*
Emissions share					
Actual (1992)	*0,22*	*0,08*	*0,09*	*0,61*	*4,49*
Levels (2025)	*0,24*	*0,16*	*0,1*	*0,51*	*7,81*
Levels (2100)	*0,52*	*0,28*	*0,07*	*0,14*	*17,57*
Logarithms (2025)	*0,21*	*0,1*	*0,08*	*0,62*	*7,86*
Logarithms (2100)	*0,32*	*0,14*	*0,09*	*0,45*	*13,61*

Although the calculations by Heil and Selden are more than 15 years old, their approach can serve as a good starting point for MEDEAS calculations with updated data. What can be also seen from the current data (above in the "Socioeconomic activity" part) is, that the old forecasts tend to keep to the today's medium estimates, concerning the growth of population, compared to the current projections from different sources.

From the other studies, Perman and Stern's (Perman and Stern, 2003) one suggests that GDP has a significant positive impact on CO_2 emissions production. Their study was done on 78 different countries. Similarly, Richmond and Kaufmann (2006a, 2006b), or Soytas et al. (2007) state that there is a positive relationship between energy consumption, per capita GDP and CO_2 emissions even in the industrialized (developed) countries. It therefore seems that total energy consumption from "dirty" (i.e. fossil fuels producing CO_2 emissions based) sources is a crucial variable to analyze, and as such should be included to the model.

One of the most recent evidence done by Kais and Sami (2016) confirms that there is still in general a positive correlation between GDP growth and emissions production. Their econometric study shows the impact of economic growth and energy use on carbon emissions on the panel data evidence from fifty eight countries. The paper provides a new empirical evidence on the impact of economic growth and energy use on carbon emissions (CO_2 emissions) over the period 1990–2012.

The results reveal that the per capita GDP has a positive and statistically significant impact on carbon for the global panel, for the Europe and North Asia, and for the Middle

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East, North Africa, and sub-Saharan Africa. Furthermore, the results indicate the presence of an inverted U-shaped curve between carbon dioxide emissions and GDP per capita.

Kais and Sami (2016) also – similarly to Richmond and Kaufmann (2006a, 2006b) – suggest that the relationship between GDP and emissions production is rather leveraged through energy use, in the sense that GDP is positively associated with energy use, which is positively linked to growing emissions production.

One of the main outcomes or conclusions from this section then is, that *energy use (or total energy consumption) and emissions intensity (as well as emissions production) should be added as PAVs for the needs of MEDEAS.* This would allow the consortium to analyze how energy use influences the emissions production and emissions intensity per unit of GDP.

These (and other similar) socioeconomic data can serve as a necessary basis for estimating the biophysical limits to the socioeconomic development. Once the relationship between GDP, population growth and emissions intensity will be set and identified (i.e. quantified), we can see what are the correlations between the growth of population, (fossil fuels burning based) economic development measured by GDP and emissions production. From the other side, it is also necessary to define the "limits to growth", which is to estimate the capacity of the biosphere to absorb the emissions from socioeconomic activity.

4.4. Carbon sinks capacity (biophysical limits to emissions based GDP growth)

Carbon sinks are *natural or artificial reservoirs that accumulate and store carbon-containing chemical compound for an indefinite period*. Carbon sinks remove carbon dioxide (CO_2) from the atmosphere by **carbon sequestration**. A carbon sink absorbs more carbon that it releases (whilst a carbon source is anything that releases more

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carbon than it absorbs). Forests, soils, oceans and the atmosphere all store carbon and this carbon moves between them in a continuous cycle ("What are carbon sinks?", 2016). The capacity of carbon sinks is included even in attempts to meet emission reduction targets of the Kyoto Protocol.

Carbon sinks capacity is very much linked with the previous sub-section, in the sense that knowing the carbon sinks capacity (globally), we are informed about the external limits of the socioeconomic activity. For example, if we want to keep some amount of emissions fixed (in order to not destroy ecosystems etc.), we should count with some "safe" amount of emissions, i.e. not exceeding the capacity of carbon sinks, for example. Therefore, a relation between the capacity of carbon sinks and economic activity (mostly GDP, but also other indicators that reflect emissions-based socioeconomic activity), needs to be set up.

Carbon sinks capacity is also part of the Earth's carrying capacity concept (Daily and Ehrlich, 1992; 1996), an overarching concept that already takes into consideration carbon sinks capacity, population growth, energy use, and emissions production. In MEDEAS we take a conceptually similar approach to estimate the planetary boundaries of socioeconomic activity.

The point of the literature review in this part is to find data and calculations from previous studies that can serve as a basis for setting the limits (and the capacity of carbon sinks) for the needs of MEDEAS.

2 degrees threshold

Starting from the most cited reports, the Stern Review on the Economics of Climate Change from 2006 (as a book: Stern, 2007) discusses the effect of global warming on the world economy. Although not being the first economic report on climate change, it is significant as the largest and most widely known and discussed report of its kind.

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According to the Stern Review, the current level of greenhouse gases in the atmosphere is equivalent to around 430 parts per million (ppm) CO_2, compared with only 280ppm before the Industrial Revolution. These concentrations have already caused the warming by more than half a degree Celsius. Moreover, they will result into further half degree warming over the next decades (due to the inertia in the climate system). Even if the annual flow of emissions did not increase beyond today's rate, the stock of greenhouse gases in the atmosphere would reach 550ppm CO_2 emissions (and would continue growing).

But from the current trends (i.e. the flow of emissions still accelerating) it is estimated that the level of 550ppm CO_2 emissions could be reached as early as 2035. At this level there is at least a 77% chance – and perhaps up to a 99% chance, depending on the climate model used – of a global average temperature rise exceeding 2°C (Stern, 2007).

Under a business-as-usual scenario, the stock of greenhouse gases could more than treble by the end of the century. This would mean at least a 50% risk of exceeding 5°C global average temperature change during the following decades. This can be compared for example to the fact that we are now only around 5°C warmer than in the last ice age (Stern, 2007). The 2°C threshold is also confirmed by another very relevant and recent study by Hansen et al. (2016).

However, there are also different (more "optimistic") views by IPCC, which we do not elaborate here, sticking to the "precautionary principle".

Carbon sequestration and 2 degrees threshold

So far we were talking about limits in terms of temperature. But this part should answer also a question "How much carbon has to be stored to keep to the 2°C threshold"? To answer this question, we need to address three main carbon sinks – soil,

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forests, and oceans. Each of them has their own capacity and each of them develops in a different manner in relation to the ongoing socioeconomic activity.

The world has already warmed by 0.85 degrees Celsius above the pre-industrial average. If emissions stay high we are probably about to reach more – three to five degrees Celsius by 2100, according to the Intergovernmental Panel on Climate Change (IPCC) reports (e.g. IPCC, 2014).

Broadly speaking, however, it is still theoretically possible to limit warming to the two degrees threshold as long as we stick within a fixed "carbon budget" (the total amount of emissions we "can" emit from the beginning of the industrial revolution until the day we stop adding carbon to the atmosphere). In concrete numbers, it is likely (66 per cent chance) that *we will stay below two degrees as long as we emit no more than about 2,900 billion tonnes of carbon dioxide*, according to the IPCC (2014). However, we have already emitted 1,900 billion tonnes. This means we are left with a remaining budget of just 1,000 billion tonnes that we can emit. At current rates we will use that quota up within 21 years (IPCC, 2014).

Soil

A study by Lal (2004a, 2004b), which focuses on soil, suggests that the global potential of soil organic carbon sequestration is 0.9 +/- 0.3 Pg C/year, which may offset one-fourth to one-third of the annual increase in atmospheric CO_2 estimated at 3.3 Pg C/year. The cumulative potential of soil carbon sequestration over 25–50 years is 30–60 Pg. The soil carbon sequestration is according to the author a good way how to deal with restoring degraded soils, while enhancing biomass production, purifying surface and ground waters, and reducing the rate of enrichment of atmospheric CO_2 by offsetting emissions due to fossil fuels.

Smith (2004) discusses the role of soil/cropland carbon sinks, and the potential for carbon sequestration in the European carbon budget and globally. Croplands are

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estimated to be the largest biospheric source of carbon lost to the atmosphere in Europe each year. There is significant potential within Europe to decrease the flux of carbon to the atmosphere from cropland, and for cropland management to sequester soil carbon, relative to the amount of carbon stored in cropland soils at present.

The biological potential for carbon storage in European (EU15) cropland is of the order of 90–120 Mt C/year. The sequestration potential, considering only constraints on land-use, amounts of raw materials and available land, is up to 45 Mt C/year. The realistic potential and the conservative achievable potentials may be considerably lower than the biological potential due to socioeconomic and other constraints, with a realistically achievable potential estimated to be about 20% of the biological potential (Smith, 2004).

However, soil carbon sequestration is according to Smith (2004) a riskier strategy for climate mitigation than direct emission reduction and can play only a minor role in closing carbon emission gaps by 2100. However, if atmospheric CO_2 concentrations are to be stabilized at reasonable levels (450–650 ppm), drastic reductions in carbon emissions will be required over the next 20–30 years. Given this, carbon sequestration should form a central role in any portfolio of measures to reduce atmospheric CO_2 concentrations over the next 20–30 years – whilst new energy technologies are developed and implemented.

Oceans

Regarding the oceans' ability for carbon sequestration, according to a report in Nature magazine (Khatiwala et al., 2009), the first year-by-year accounting study of the oceans carbon sequestration mechanism, "the oceans are struggling to keep up with rising emissions". With total world emissions from fossil fuels growing rapidly, the proportion of fossil-fuel emissions absorbed by the oceans since 2000 may have declined by as much as 10%, indicating that over time the ocean becomes probably "a less efficient sink of manmade carbon". The report concludes that "we cannot count on

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these [ocean] sinks operating in the future as they have in the past, and keep on subsidizing our ever-growing appetite for fossil fuels."

Figure 10 shows how Carbon released by fossil fuel burning (black) continues to accumulate in the air (red), oceans (blue), and land (green). The oceans take up roughly a quarter of manmade CO_2, but evidence suggests they are now taking up a smaller proportion.

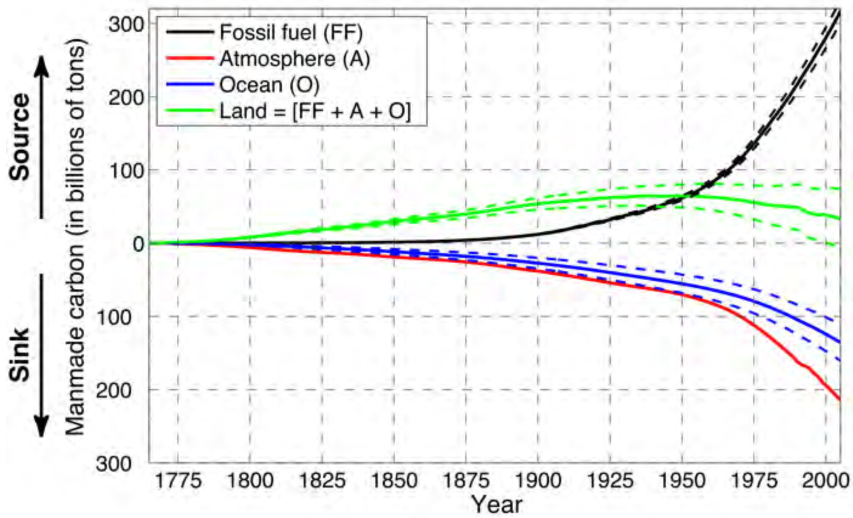

Figure 10. Carbon soils and sink evolution (source: Khatiwala et al., 2009).

Forests

A study by Pan et al. (2011), focusing on forest carbon sinks, shows that the terrestrial carbon sink has been large in recent decades, but its size and location remain uncertain. Using forest inventory data and long-term ecosystem carbon studies, the authors estimate a total forest sink of 2.4 ± 0.4 petagrams of carbon per year (Pg C/year) globally for 1990 to 2007. They also estimate a source of 1.3 ± 0.7 Pg C/year from tropical land-use change, consisting of a gross tropical deforestation emission of 2.9 ± 0.5 Pg C/year partially compensated by a carbon sink in tropical forest regrowth of 1.6 ± 0.5 Pg C/year (Pan et al., 2011). Together, the fluxes comprise a net global

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forest sink of 1.1 ± 0.8 Pg C/year, with tropical estimates having the largest uncertainties. Total forest sink estimate is equivalent to the terrestrial sink deduced from fossil fuel emissions and land-use change sources, minus ocean and atmospheric sinks.

Cannell (2003) discusses the issue of forest sinks as well. He presents an overview of the forest carbon sinks capacities for the world, the EU15 countries and the UK over the next 50–100 years (since 2003) divided into: (1) theoretical potential capacities, (2) realistic potential capacities, and (3) conservatively achievable capacities. The range of capacities is determined principally by judgements of the areas of land that are likely to be devoted to sequestration or energy crops (Cannell, 2003). Theoretically, enhanced carbon sequestration and energy cropping could offset 2000–5000 Mt C/year globally, but a more realistic potential offset is 1000–2000 Mt C/year and there are good reasons to suppose that only 200–1000 Mt C/year is actually achievable. Similarly, 'conservative achievable' estimates for the EU15 and the UK are about 10 times less than theoretical potentials. In the EU15, 'realistic potential' and 'conservative achievable' estimates for energy crop substitution were 21–32% and 11–21% of current annual emissions, respectively, compared with 5–11% and 2–5% for carbon sequestration (Cannell, 2003).

Finally, an overarching study for all types of carbon sinks (though just for seven years) was done by Battle et al. (2000). *The authors found that the capacity of global carbon sinks annually sequestered 1.4 (±0.8) and 2.0 (±0.6) gigatons of carbon, respectively, between mid-1991 and mid-1997.*

5. Results and conclusions

This section contains the key findings from the literature review concerning each PAV, including key highlights, and conclusions concerning data source availability and reliability.

Socioeconomic activity:

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- Although economic growth is more volatile than population growth, and both indicators grow at vastly different rates, populations and economic output tend to grow in tandem, albeit at different rates.
- Population is expected to rise at least until +/-2070. From the past interplay between population and GDP, GDP will very likely grow further as well (even though it is hard to estimate the exact rate), which will require more inputs to the economy, increasing the ecological pressure.
- We have decided to choose the data from United Nations and the World Bank for the GDP development, population development and projections, respectively. These institutions collect the data already for a long time, and as such can serve as a trustful basis for other calculations. For population, UN medium estimate seems to be (so far) confirmed by the real population development, and as far it is probably the closest projection to reality.

Emissions production and emission intensity:

- There is a link between emissions production and GDP growth, albeit the ratio is far from fixed.
- Emission intensity is, in this case, the amount of greenhouse gas (respectively CO_2) emissions produced per unit of gross domestic product (GDP).
- The ratio between CO_2 emissions and GDP is declining, i.e. lesser CO_2 emissions is needed to produce one unit of GDP. However, there is still well-documented positive correlation between these two variables.
- The possibility of (absolute) delinking the amount of CO_2 emissions produced from GDP growth (i.e. that GDP can grow without growing CO_2 emissions) is being discussed and confirmed by some studies, though not generally accepted.
- Materials use also require energy input, which is related to the emissions production and emission intensity, respectively. Admitting that materials use is a core feature of growing economies that produce emissions, then economic

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development and technology advancement significantly influence carbon dioxide emissions.

- There is a positive relationship between energy consumption, per capita GDP and CO2 emissions. The relationship between GDP and emissions production is leveraged through energy use (GDP is positively associated with energy use, which is positively linked to growing emissions production). Total energy consumption from fossil fuels (producing CO_2 emissions) should be analyzed for the needs of the model.
- For the emissions production and emission intensity, we – similarly – choose to stick to the data from the World Bank, for the reasons stated above, similar to the case of socioeconomic variables.
- We discuss the study by Heil and Selden (2001) especially because of the approach the authors take there – taking into account GDP, population development and emissions production, and dividing the population by income groups. This can serve as a very good example for MEDEAS, with updated data and projections.

Carbon sinks capacity:

- Carbon sinks are natural or artificial reservoirs that accumulate and store carbon-containing chemical compound for an indefinite period. Carbon sinks remove carbon dioxide (CO_2) from the atmosphere by carbon sequestration.
- Knowing the carbon sinks capacity (globally), we are informed about the external limits of the socioeconomic activity. For example, if we want to keep some amount of emissions fixed (in order to not destroy ecosystems etc.), we should count with some "safe" amount of emissions, i.e. not exceeding the capacity of carbon sinks, for example.

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- We stick to the 2°C threshold limit for the "sustainable" (i.e. not causing huge irreversible changes) increase of global temperature, agreed by Stern (2007) and Hansen (2016). It is likely (66 per cent chance) that we will stay below two degrees as long as we emit no more than about 2,900 billion tonnes of carbon dioxide, according to the IPCC (2015). We choose the data from IPCC as from the most respected institution in the field of climate change monitoring.
- For soil carbon sequestration, we chose to follow the studies by Lal (2004), which focuses on soil, suggesting that the global potential of soil organic carbon sequestration is 0.9 +/- 0.3 Pg C/year, which may offset one-fourth to one-third of the annual increase in atmospheric CO_2 estimated at 3.3 Pg C/year. Smith (2004) shows that the biological potential for carbon storage in European (EU15) cropland is of the order of 90–120 Mt C/year. The sequestration potential, considering only constraints on land-use, amounts of raw materials and available land, is up to 45 Mt C/year. The realistic potential and the conservative achievable potentials may be considerably lower than the biological potential due to socioeconomic and other constraints, with a realistically achievable potential estimated to be about 20% of the biological potential.
- For ocean sinks, we followed a study by Khatiwala et al. (2009), the first year-by-year study for oceans carbon sequestration trends.
- Finally, for forest sinks, we stick to the data brought by studies from Pan et al. (2011) and Cannell (2003), found as one of those most cited with relevant data regarding the capacity of forests as carbon sinks.

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D2.1: *Report with an analysis of the main limitations of variables and indicators selected to represent the pathways and scenarios.*

Annex 2: *Efficiency evolution curves for different economic sectors*

Grant agreement: 691287

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Document info sheet

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TABLE AND FIGURE INDEX

This work is part of the MEDEAS project, funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

1. Scope and goal

This document is part of MEDEAS Deliverable 2.1. This report addresses the energy intensity of the five economic sectors (residential, transport, industry, agriculture and services) and how these have evolved during time, from 2000 to 2015.

The results of this Deliverable will be implemented in MEDEAS model through PAVs database values. For this reason, the following table shows the information covered in this document and its link to the PAV list specified in Deliverable 2.1.

Table 1: PAVs for measuring energy intensity of sectors and EROI and covered in this Annex.

D2.1 Results	PAV	PAV description
Evolution of energy intensity of primary energy	14	Energy intensity
Evolution of energy consumption of transport sector	59	Energy intensity of transport sector
Evolution of energy consumption of industrial sector	70	Energy intensity of industrial sector
Evolution of energy consumption of residential sector	72	Energy intensity of residential sector
Evolution of energy consumption of residential sector	75	Energy intensity of other sectors

2. Methodology

2.1 Energy Intensity

2.1.1 Energy intensity of primary energy (1990-2012)

The energy intensity level is the ratio between energy supply and gross domestic product (GDP) measured at purchasing power parity (PPP). Energy intensity is an indication of how much energy is used to produce one unit of economic output. Lower ratios indicate that less energy is used to produce one unit of GDP output. Energy Intensity levels for primary energy data can be obtained from World Data Bank from 1990; they are reported in 1MJ/$ 2011. Such units are transformed in KWh/€, dividing all values by 3.6*0.719 (conversion factor of MJ in KWh * conversion factor of $ in € in 2011 year). The reference year of the index is 2011, when the annual average rate of exchange of 1€ was 1.39$.

2.1.2 Energy Intensity of the Transport Sector (2000-2014)

The energy intensity of the transport sector (http://www.worldenergy.org/data/) is calculated as the energy consumption of transport as a function of the GDP. It is not related to the value added of the sector as this value added only reflects the activity of transport companies, which only represent a part of the total consumption of the sector (about less than 60% usually in the EU countries). This index reflects the activity of transport companies that represents only a part of the total consumption of the sector, less than 60% usually in the EU countries.

eitottra =totfctra/gdp$xxppp

With eitottra being the energy intensity of the transport sector (measured in koe/$2005ppp), totfctra being the final consumption of transport (in Mtoe) and gdp$xxppp being the GDP at exchange rate and purchasing power parity of the year 2005 in dollar (in US$2005bn ppp).

The unit is transformed in toe/M€ dividing the values by 0.806. The reference year is 2005 when the annual average rate of exchange of 1€ was 1.24$.

2.1.3 Energy Intensity of the Industrial Sector (2000-2014)

The energy intensity of industry (http://www.worldenergy.org/data/) is defined as the ratio between the final energy consumption of industry and the value added measured in constant purchasing power parities (ppp).

eitotind =totfcind/vadind$xxppp

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With eitotind being the energy intensity of industry (koe/$2005ppp), totfcind being the final consumption of industry (Mtoe) and vadind$xxppp being the value added of industry at exchange rate and purchasing power parity of the year 2005 in dollar (US$2005bn ppp).

The reference year is 2005 when the annual average rate of exchange of 1€ was 1.24$.

2.1.4 Average Electrical Consumption per capita (2000-2014)

The average electrical consumption per capita data are obtained from the world energy council. The electricity used by households per capita is the ratio between the electricity consumption of households and the number of inhabitants.

$$elefcrespop = elefcres/pop$$

With elefcrespop being the electricity use of households per capita(kWh/cap), elccfres being the electricity consumption of households (MWh) and pop being the number of inhabitants (million). These values are divided by GDP per capita PPP constant 2011 international $ (reference year 2011, currency $, GDP data from World bank).

The ratio unit is KWh/$ that is successively divided by 11630 (the factor of conversion of KWh in toe) and multiplied by 0.719 (the factor of conversion of $ in 2011) in order to obtain data in toe/M€.

2.1.5 Energy Intensity of Agriculture (2000-2014)

The energy intensity of agriculture (http://www.worldenergy.org/data/) is defined as the ratio between the final energy consumption of the sector and the value added measured in constant purchasing power parities. Calculated as follows:

$$eitotagr = totfcagr/vadagr\$xxppp$$

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With eitotagr being the energy intensity of agriculture (koe/$2005ppp), totfcagr being the final consumption of agriculture (Mtoe) and vadagr$xxppp being the value added of agriculture at exchange rate and purchasing power parity of the year 2005 in dollar (US$2005bn ppp).

2.1.6 Energy Intensity of the Service Sector (2000-2014)

The energy intensity of the service sector is defined as the ratio between the final energy consumption of the sector and the value added measured in constant purchasing power parities (ppp). Calculated with the following equation:

eitotser =totfcser/vadser$xxppp

With eitotser being the energy intensity of services (koe/$2005ppp), totcfser being the final consumption of services (Mtoe) and vadser$xxppp the value added of services at exchange rate and purchasing power parity of the year 2005 in dollar (US$2005bn ppp).

3. Results

3.1 Energy intensity level of primary energy

Table 2 shows the raw data extrapolated by World Data Bank in MJ/$, successively converted in kWh/€.

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Table 2: Energy intensity level of primary energy

	Raw Data_Energy intensity level of primary energy (MJ/$2011 PPP GDP)			Energy intensity level of primary energy (KWh/€) [raw data/3.6*0.719]	
year	European Union	World	year	European Union	World
1990	5.83	7.96	1990	2.25	3.08
2000	4.95	6.85	2000	1.91	2.64
2006	4.58	6.33	2006	1.77	2.44
2007	4.36	6.14	2007	1.68	2.37
2008	4.31	6.05	2008	1.66	2.34
2009	4.25	6.03	2009	1.64	2.33
2010	4.33	6.05	2010	1.67	2.34
2011	4.11	5.93	2011	1.59	2.29
2012	4.09	5.84	2012	1.58	2.26

Figure 1. shows the Global and European trends of energy intensity from 1990 to 2012.

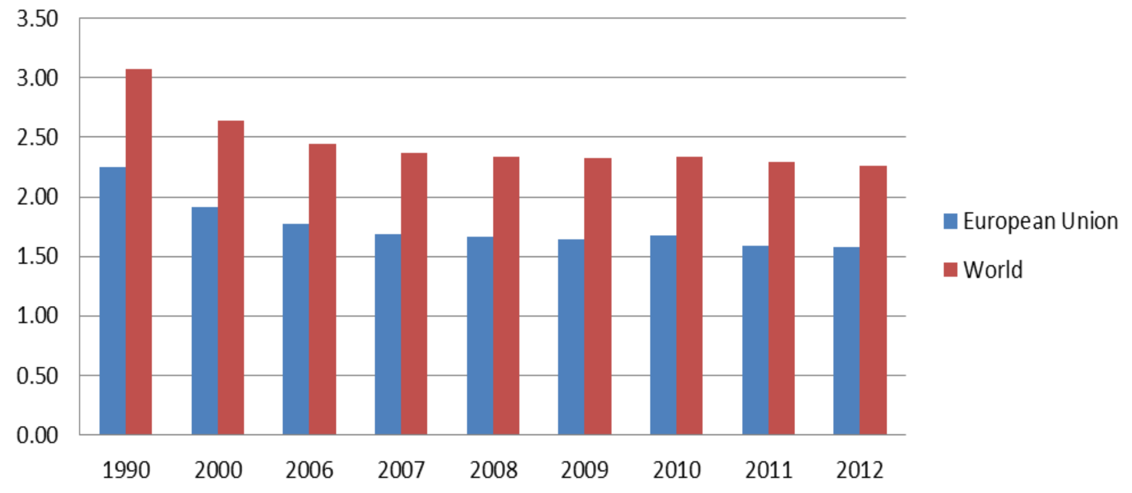

Figure 1: Energy intensity level of primary energy (kWh/€) as a function of time (1990-2012).

3.1.1 Energy intensity of transport sector

Table 3 shows the raw data energy intensity of transport to GDP in koe/$05p that are converted in toe/M€.

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Table 3: Energy intensity of transport

	Raw data Energy Intensity of transport to GDP (koe/$05p)			Energy Intensity of transport to GDP (toe/ M€)	
year	World	Europe Union	year	World	Europe Union
2000	0.036	0.025	2000	0.0447	0.0310
2005	0.033	0.024	2005	0.0409	0.0298
2010	0.031	0.022	2010	0.0385	0.0273
2011	0.03	0.022	2011	0.0372	0.0273
2012	0.029	0.021	2012	0.0360	0.0261
2013	0.029	0.021	2013	0.0360	0.0261
2014	0.028	0.021	2014	0.0347	0.0261

Figure 2 show the Global and European trends of transport energy intensity (toe/M€) from 2000 to 2014.

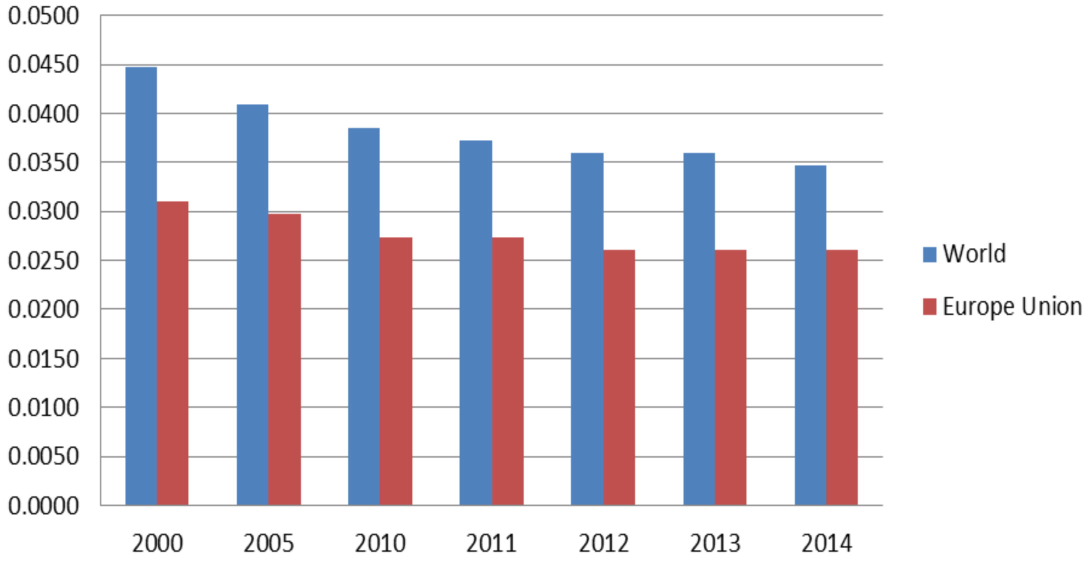

Figure 2: Energy intensity (toe/M€) for transport sector as a function of time (2000-2014).

3.1.2 Energy Intensity of industrial sector

Table 4 shows the raw data in koe/$05p that are transformed in toe/M€.

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Table 4: Energy intensity of industry

	Energy intensity of industry (koe/$05p)			Energy intensity of industry (toe/ M€)	
year	World	Europe Union	year	World	Europe Union
2000	0.133	0.107	2000	0.165	0.133
2005	0.134	0.099	2005	0.166	0.123
2010	0.122	0.086	2010	0.151	0.107
2011	0.123	0.083	2011	0.153	0.103
2012	0.119	0.083	2012	0.148	0.103
2013	0.118	0.083	2013	0.146	0.103
2014	0.115	0.081	2014	0.143	0.100

Figure 3 shows the Global and European trends of industry energy intensity from 2000 to 2014.

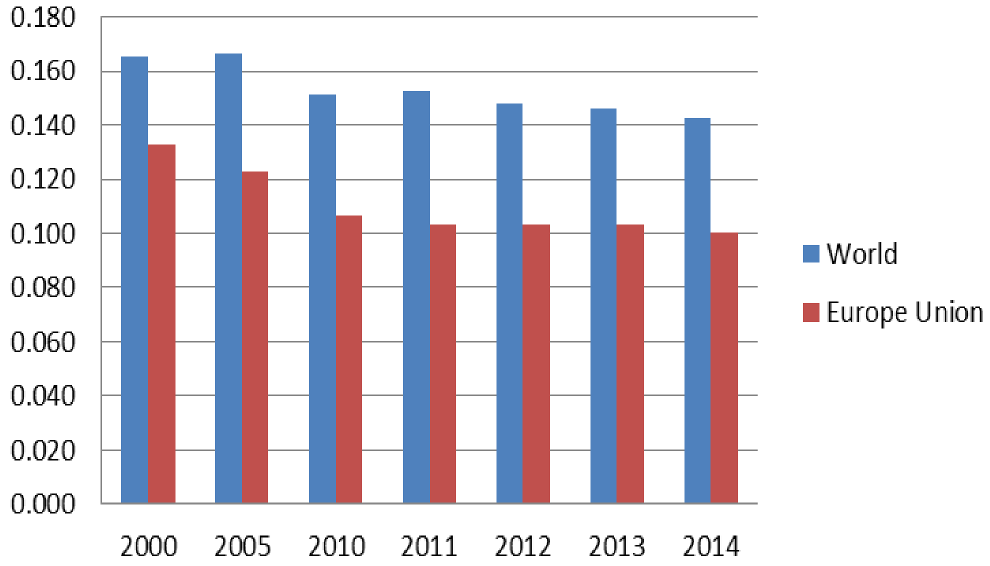

Figure 3: Energy intensity (toe/M€) for industry as a function of time (2000-2014).

3.1.3 Average electrical consumption per capita (2000-2014)

Table 5 shows the procedure followed to calculate the average electricity consumption per capita divided by GDP per capita (toe/M€).

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Table 5: *Average electricity consumption per GDP for residential sector*

	Average electricity consumption per capita (KWh/cap)		GDP per capita (constant 2011 international $)		Average electricity consumption per capita divided by GDP per capita (PPPconstant) (KWh/$)		Average electricity consumption per capita divided by GDP per capita (PPPconstant) (toe/M€)	
	World	Europe Union	World	Europe Union	World	Europe Union	World	Europe Union
2000	587.968	1476.327	10227.1	30283	0.057491175	0.048751015	6.875314717	5.830087338
2005	652.002	1624.472					0	0
2010	721.702	1676.701	13070.2	34035	0.055217365	0.049264022	6.603391867	5.891437344
2011	716.441	1587.575	13431.6	34559.3	0.053339959	0.045937707	6.378874775	5.493646482
2012	724.652	1639.924	13708.4	34422.5	0.052861895	0.047641049	6.321703486	5.697347483
2013	739.695	1631.746	13994.2	34302.1	0.052857255	0.047569857	6.321148623	5.68883376
2014	739.291	1544.27	14290.6	34795.6	0.051732677	0.044381186	6.186661448	5.30750363

Figure 4 shows the trend of electricity consumed by households from 2000 to 2014.

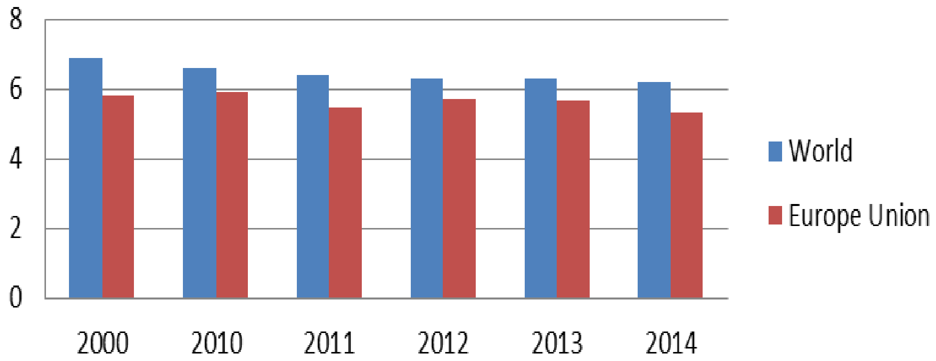

Figure 4: Average electricity consumption per GDP (PPPconstant) (toe/M€) for residential sector as a function of time (2000-2014).

3.1.4 Energy intensity of agriculture sector

Table 6 shows the energy intensities of agriculture converted in unit toe/M€ obtained dividing raw data by 0.806 (factor of conversion between $ and €). The reference year is 2005 when the average annual rate of exchange of 1 € was1.24$.

Table 6: Energy intensity for agriculture sector

	Raw data_Energy intensity of agriculture (koe/$05p)			Energy intensity of agriculture (toe/M€)	
	World	Europe Union		World	Europe Union
2000	0.045	0.122	2000	0.05583127	0.15136476
2005	0.044	0.118	2005	0.05459057	0.14640199
2010	0.037	0.107	2010	0.04590571	0.13275434
2011	0.038	0.103	2011	0.0471464	0.12779156
2012	0.037	0.107	2012	0.04590571	0.13275434
2013	0.037	0.106	2013	0.04590571	0.13151365
2014	0.036	0.103	2014	0.04466501	0.12779156

Figure 5 shows the Global and European trend of energy intensity of agriculture from 2000 to 2014.

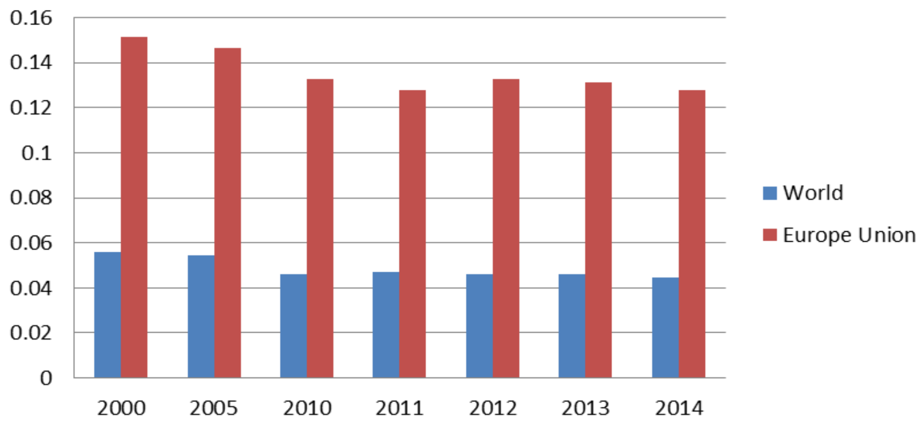

Figure 5: Energy intensity for agriculture (toe/M€) as a function of time (2000-2014).

3.1.5 Energy intensity of service sector

Table 7 shows the energy intensities of service sector converted in unit toe/M€, obtained dividing raw data by 0.806 (factor of conversion between $ and €). The reference year is 2005 when the average annual rate of exchange of 1 € was1.24$.

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Table 7: Energy intensity for service sector

	Raw data_Energy intensity of service sector (koe/$05p)			Energy intensity of service sector (toe/M€)	
	World	European Union		World	European Union
2000	0.019	0.016	2000	0.0236	0.0199
2005	0.019	0.017	2005	0.0236	0.0211
2010	0.018	0.017	2010	0.0223	0.0211
2011	0.017	0.016	2011	0.0211	0.0199
2012	0.017	0.016	2012	0.0211	0.0199
2013	0.017	0.016	2013	0.0211	0.0199
2014	0.016	0.015	2014	0.0199	0.0186

Figure 6 shows the European and global trend of energy intensity of service sector from 2000 to 2014.

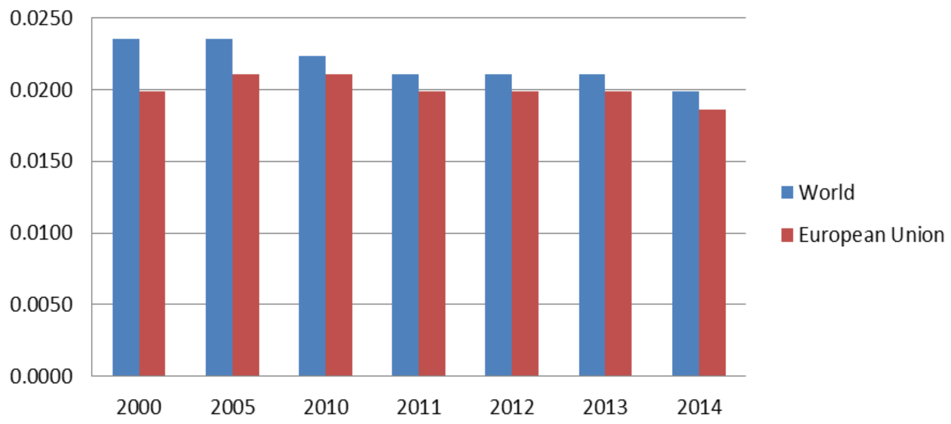

Figure 6: Energy intensity (toe/M€) for service sector as a function of time (2000-2014).

4. Conclusions

The Energy Intensity is a difficult parameter to model because it does not have a specific physical significance (as it is, instead, the case of EROI). Its evolution is affected by different phenomena that are sometimes lumped together into the concept of "dematerialisation" of the economy assumed to become more and more "efficient".

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Such an aggregation is hardly justified, since the energy intensity can diminish because of completely different factors. For instance, that will happen if a factory invests in becoming more efficient in its productive process, but also if the factory is dismantled and replaced by a shopping mall. As another example, the owner of a building may decide to insulate it in order to use a lower amount of fossil energy for the heating system. Alternatively, the owner can invest the same amount of money to build a PV plant on the roof of the building. The first case will result in a reduced energy intensity, whereas the latter will not, even though it could well result in lower CO_2 emissions.

These internal inconsistencies in the concept of energy intensity make it a parameter to be handled with great caution. Nevertheless, we may try to discuss its possible evolution both in general and for the sectors examined in the MEDEAS project.

In general terms, the ongoing trends seem to indicate that the energy intensity will continue to decline in all industrialized countries. This is due to the general phenomenon of the "financialisation" of the economy that involves, for instance, the relocation of heavy industries to third world countries, which generates a reduction of the need of energy. At the same time, many activities become more efficient in the sense of requiring less energy for the same services provided, e.g. space heating in building. How long this phenomenon will continue it is impossible to say, although it is unlikely to see it change in the near future.

1. The industrial sector. In most Western industrialized countries, and in particular in the EU, the high costs of energy, in turn resulting from taxation and the lack or scarcity of domestic energy sources, has resulted in a generally high energy efficiency and in the concentration of the sector into high added value production lines. At this point, further increases in efficiency generate reduced economic returns. For this reason, the main factor that will continue to reduce the energy intensity of the

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industrial sector of the UE and other Western countries is the relocation in other countries of the heavy industrial sector.

2. The transport sector. In most Western industrialized countries, the transport sector is mainly the result of the interaction of the domestic system with the worldwide intermodal containerized system. Typically, this result in a strong reliance on a capillary road transportation system based on ICE powered vehicles. To this, we add a people transportation system, also mainly based on ICE vehicles, cars, buses, and planes, with the addition of trains. Here, we have a system that has been aggressively optimized during the past decades in terms of efficient engines and optimized routes. Further improvement in this sense faces diminishing economic returns.

The future sees two trends: one is the possibility of a reduction of the demand for transportation, in particular in terms of people transportation, owing to the phenomenon called "virtualization" which, however, doesn't seem to be happening as fast as some had predicted. The other phenomenon is the ongoing electrification of the road transport system with the diffusion of electric powertrain vehicles. This phenomenon seem to be starting, but it is not, in itself, bringing a significant change in the energy intensity.

3. The agricultural sector. Also this sector is heavily optimized in Western countries and it is unlikely, at present that its evolution will result in important changes in its energy intensity.

4. The residential sector. Much work has been performed in the past to reduce the energy needs of buildings. The success has been considerable but a large number of buildings in the EU turns out to be still built according to obsolete considerations that took scarcely into account the need of reducing the energy utilized for space heating/cooling. It is likely that this sector will see a continued reduction in the energy

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consumption per person and a consequent decline of the energy intensity of the sector.

5. The Service sector. The service (or "tertiary") sector is expanding in all Western industrialized countries, often at the expenses of the industrial sector. The energy demand for this sector is determined mainly by transportation and buildings. Therefore, the considerations already made for the two separate sectors of transportation and buildings hold. Specifically, however, both factors are heavily optimized in this sector, so that further optimization is unlikely to bring important reductions in the energy intensity.

5. References

http://data.worldbank.org/indicator/EG.EGY.PRIM.PP.KD

http://www.worldenergy.org/data/efficiency-indicators/

MEDEAS

MODELING THE RENEWABLE ENERGY TRANSITION IN EUROPE

D2.1: *Report with an analysis of the main limitations of variables and indicators selected to represent the pathways and scenarios.*

Annex 3: *Fossil fuels biophysical constraints and EROI of non renewable resources*

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TABLE AND FIGURE INDEX

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1. Fossil fuel resources: availability and biophysical constraints

When we are trying to identify key constraints for the model, we cannot omit the question of fossil fuel sources. The economy and society depend heavily on fossil fuels since the industrial shift. Since then fossil fuels – mostly coal and oil, recently also gas – as abundant and energy intensive resources provided cheap energy to the society.

According to BGR there are proven reserves of all fossil fuels in amount of **39,910 EJ,** while the energy consumption on primary level increased to **550** EJ in the year 2010 (Koppellaar, 2012). 80% of this amount is provided by fossil fuels nowadays, which shows the importance of these resources.

The main useful concept indicating the availability and scarcity of energy commodities can be derived from the term **Peak-Oil**. This term indicates that availability of resources during the time follows a Hubbert curve, which means that there is a certain point after which the availability of resources steeply declines. This concept is connected to the estimation of global oil supply. In this section we will take into account the aspect of availability of resources, which we found as a constraint of use of oil and other fossil fuels, as coal and gas.

Estimations of Peak-Oil are mostly counting with a peak in the current times or near future. Sorrell et al. state, that estimations of Peak Oil after the year **2030** do have unrealistic assumptions. This notion raises the question about the future prospects of fossil fuel consumption, specifically oil use.

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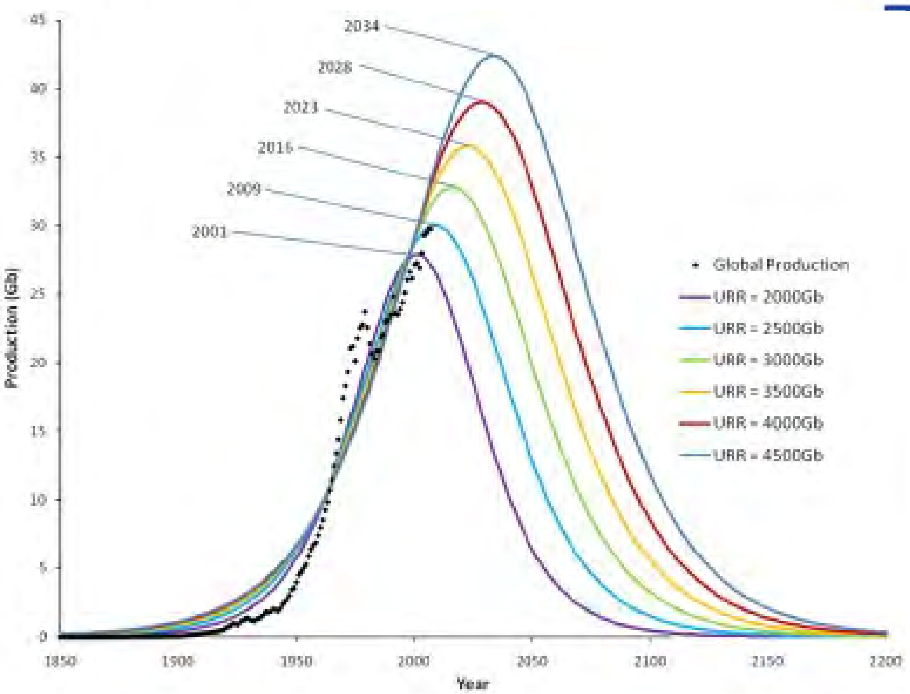

Figure 1: Peak of oil production (Sorrell, 2010)

Table 1: Key features of global supply models compared in Sorrell´s (2010) study

Category	**Model**	**Liquids covered by model**	**Demand modelling?**	**Level of aggregation for supply modelling**	**URR (Gb)**	**Date of global peak**
International	IEA	All-liquids	Yes	Physical/economic modelling of fields and projects. Regional curve-fitting for discovery trends	3,577	No peak, but conventional oil plateau by 2030
International	OPEC	All-liquids	Yes	Mix of project and field (short term) and regional (long term). Model is largely demand-driven	3,345	No peak

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National	US EIA	All-liquids	Yes	Regional, with some individual country modelling	Not given	No peak
National	BGR	Conventional oil	No	Regional/global with simple mid-point peaking assumption	2,979	~2020
Oil companies	Shell	All-liquids	Yes	Mix of project, field, basin and regional	Not given	~2030 (Blueprints) ~2020 (Scramble)
Oil companies	Meling (Statoil Hydro)	All-oil	No	Regional and country	3,149	2028 (base case)
Oil companies	Total	All-oil	No	Mix of field, basin and country	Not given	2020
Oil companies	Exxon Mobil	All-liquids	Yes	Regional (little detail provided)	3,345	No peak
Consultancies	Energyfiles	All-oil	No	Mix of project, field, basin and country depending on data availability	2,685	2017
Consultancies	LBST	All-oil	No	Field, country or regional. Simple curve-fitting for pre-peak countries	1,840	2006
Consultancies	Peak Oil Consulting	All-oil, GTL and biofuels	No	Project and field level	Not estimated	2011–2013

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Universities and individuals	Colin Campbell	All-oil	No	Regional and country. Assumes mid-point peaking and constant post-peak depletion rate	2,425, all-oil	1900, regular oil
Universities and individuals	University of Uppsala	All-oil	No	Giants fields and country/regional for remainder	Not given	2008–2018
Universities and individuals	Richard Miller	Crude oil	No	Field (~3500 fields included)	2,800	2013–2017

Peak-Oil is not a simple reserves/production ratio. When we consider the possibilities of production, there are other factors that need to be mentioned. One of the factors is the quality of produced oil.

Peak-Oil has two dimensions, which could be followed when we talk about the constraints. The first dimension is **quantitative**. The amount of reserves could be quantitatively expressed in units, which gives an overview about an amount of resources that could be extracted in the future. Together with oil production statistics we can estimate the moment, when oil supply cannot cover the oil demand anymore.

To identify the trend we will first describe the key data resources and the methodology behind them. Concerning biophysical limits we have to emphasize the availability and amount of reserves, rather than supply of the ready-made product.

Table 2: BP Statistical review of world proven reserves (Oil, Gas, Coal).

BP Statistical review 2015	1994	2004	2013	2014	Reserves/ production ratio
World oil proven reserves in thousands of millions barrels	1,118.0	1,366.2	1,701.0	1,700.1	52.5
Gas proven reserves in trillions of cubic meters	119.1	156.5	186.5	187.1	54.1
Coal proven reserves in millions of tonnes				891,531	110

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1.1 Resources

Available reserves of fossil fuel resources are one of the key energy indicators. Provided estimations of availability of fossil fuel resources can be readily accessed on the websites of EIA, IEA, etc. for long time series (EIA counts oil reserves since year 1980).

However, some scholars see the estimation of reserves as problematic and too optimistic in some cases. In this part of the text we would like to state a few general problems or estimations being made about this, especially in the case of oil.

First of all it is necessary to mention, that there are different terms which describe the availability of fossil fuel resources and reserves:

„The most common type of classification distinguishes between different categories of "resources" (no identified amounts that cannot be exploited at the moment of the assessment) and "reserves" (identified fraction of the resource base estimated to be economically extractable at the time of determination). However, these estimates are affected by critical ambiguities and inconsistencies leading to considerable uncertainty as well as fluctuations over time which are particularly problematic in long-term assessments, such as those required for the planning of an energy transition or the design of a sustainable economy." (Capellán-Pérez et al., 2016)

The estimation provided by different institutions might not reflect the state of art and might be too optimistic – examples are different estimations of reserves throughout several years of the World Economic Outlook (WEO). Alekett et al. (2010) identify critical points, where future projections of IEA seem to be too optimistic. One is a depletion rate of resources-to-be-found. They compare the estimation with the North Sea region as a relatively newly discovered field and with a high rate of depletion with the estimation of WEO and came to the conclusion that the estimation of WEO is based on presumptions never seen in history before.

Consistent critique of global estimations of proven reserves is provided by Sorrell et al. in their article *Global oil depletion: A review of the evidence.* They come to the conclusion, that estimations of a peak after the year 2030 are less plausible. They provide a list of assumptions involved in such a forecast that are problematic.

One of these assumptions is that a global URR (ultimately recoverable resources) that is comparable to or greater than the mean estimate of the USGS (cca 3,600 Gb); this estimation is seen as a change of historical trend. Authors do not discredit U.S. Geological Survey as a source, but are critical to the estimations of rate of new discoveries.

Forecasting of the future oil supply is provided by different institutions. Sorrell et al. provide a summarizing table where different estimations of global peak supply of oil is provided – together with URR estimations.

The fields yet to be found is a problematic indicator also for Aleklett et al. in their critical evaluation of IEA Outlook from 2008. They state that „fields yet to be found is based on an unrealistically high depletion rate never before seen in history. Depletion is a major factor for reservoir flows (Satter et al., 2008), and flows will naturally decrease as reservoirs are depleted. Certainly, these factors can be influenced by technology to a limited extent, but this requires increasing work input and investments to counter depletion-driven decline."

Another issue is confidentiality of the data, which goes hand in hand with the lack of standardization. The estimation of oil reserves is a crucial factor not only for the companies, but also for the states, where resources are located. Sorrell (2009) writes: „Only a subset of global reserves is subject to formal reporting requirements and this is largely confined to the reporting of highly conservative 1P data for aggregate regions. In the absence of audited estimates for individual fields, analysts must rely upon assumptions whose level of confidence is inversely proportional to their importance – being lowest for those countries that hold the majority of the world's reserves."

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McGlade and Ekins (2015) calculate the remaining ultimately recoverable resources (RURR) of **5,070** Gb globally for the year 2010 (as a sum of both conventional and unconventional oil RURR). USGS provided as estimation a number of **3,345** Gb for global conventional oil URR, which is significantly higher than **2,615** Gb for the same category provided by McGlade and Ekins (2015).

Contemporary estimates of the global URR for conventional oil fall within the range **2,000-4,300 Gb**, while the corresponding estimates of the quantity of remaining recoverable resources fall within the range **870 to 3,170 Gb** (Sorrell, 2009).

The second important dimension is a **quality** of resources – newly discovered reserves do not have as good a quality as the depleted resources, which cause also serious problems for production. The quality of resources is related to the energy return on investment (EROI), which we will discuss in the subsequent section.

We can also highlight that Sorrell et al. (2010) write „Most oil in a region tends to be located in a small number of large fields, with the balance being located in a much larger number of small fields. These large fields tend to be discovered relatively early, in part because they occupy a larger area. Subsequent discoveries tend to be progressively smaller and often require more effort to locate."

The reserves are geographically unevenly distributed – oil must therefore be subject of trade and transportation of the fuel, which becomes another factor to consider. According to the BP Statistical review 2015, **47.7%** of global proved reserves are located in the Middle East – **810.7** thousands of millions barrels. The leading country of the Middle East is Saudi Arabia with **15.7%** of total proved reserves.

Table 3: Location of the world's main fossil fuel reserves in 2006 (Shaffiee and Topal, 2008)

Region	Fossil fuel reserve (Gt of oil equivalent)				Fossil fuel reserve (%)			
	Oil	Coal	Gas	Sum	Oil	Coal	Gas	Sum
North America	8	170	7	185	0.86	18.20	0.75	19.81
South America	15	13	6	34	1.61	1.39	0.64	3.64
Europe	2	40	5	47	0.21	4.28	0.54	5.03

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Africa	16	34	13	63	1.71	3.64	1.39	6.75
Russia	18	152	52	222	1.93	16.27	5.57	23.77
Middle East	101	0	66	167	10.81	0.00	7.07	17.88
India	1	62	1	64	0.11	6.64	0.11	6.85
China	2	76	2	80	0.21	8.14	0.21	8.57
Australia and East Asia	2	60	10	72	0.21	6.42	1.07	7.71
Total	165	607	162	934	17.67	64.99	17.34	100.00

An especially important indicator is also the oil price. The expected interconnection between oil price and biophysical constraints is that newly discovered resources cannot generate oil at lower prices anymore. However, there are other factors also involved that influence the oil price. This is further discussed in the next section, dedicated to EROI.

1.2 Natural gas

A similar situation to oil constraints exists in the field of natural gas. The reserves of both fuels do often overlap and are located in the same place, with the largest reserves being located in the Middle East. Natural gas is rather efficient kind of the fossil fuels. Also it requires relatively low investment for electricity generation.

However, natural gas is so far not as important as oil due to various reasons: One is the physical state of the fuel, as gas requires technologically and energetically demanding ways to transport or to use – either as a compressed liquid or via pipelines. Therefore, in the history of fossil fuel exploitation, natural gas was mostly just burned while oil was extracted. Natural gas is a broad term for different types of gases from different fields: "The composition of natural gas can vary widely, depending on the gas field. Natural gas differs according to present substances and their ratio. These substances are methane, hydrocarbons or hydrogen sulphide. There are estimations in favour of future natural gas production – there are abundant proven reserves and estimations of four times larger technically recoverable resources at **806 tcm**" (WEO 2014, p. 146). Nearly half of this number comes from unconventional resources such as tight gas, shale gas and coal bed Methane.

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In the optimistic projections, gas production doubles by 2035 when compared to the year 2010 (IEA, 2011), which, again, mostly depends on technology and investments for extraction.

McGlade and Ekins (2015) estimate the RURR for Natural Gas at **675 Tcm** for both conventional and non-conventional natural gas. Because their estimation is rather moderate and both forms do have a similar share, we take their estimate as a reliable source.

1.3 Coal

Coal reserves seem to have different constraints than oil and gas. World estimated reserves of coal compared to today's rate of production do not indicate that we will be observing a peak coal soon. More to that, coal is geographically distributed in far more regions, with more than 70 countries worldwide, in each major world region. However, also coal reserves differ considerably in terms of quality (anthracite, lignite, etc.) as well as in the way of extraction (open cast mines, underground mines).

Table 4: Coal reserves by world regions

Region name	Coal reserves (ktoe)
Middle East and North Africa	625,865,375
North America	116,294,232
Latin America and The Caribbean	6,947,153
South and Central Asia	47,315,708
Africa	15,002,263
Asia	154,219,584
Southeast Asia and Pacific	50,868,280
East Asia	56,035,596
Europe	130,476,480

Coal is also characteristic for being used in a near distance of its extraction.

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This is the reason why coal is mostly used in the country of origin and not being as important a subject of international trade as oil is. Another reason is that coal usually has a lower energy density than oil, which makes the transportation less cost effective.

Coal is, according to some statistics, divided into hard coal and lignite – both vary when concerning energy intensity and CO2 emissions emitted during combustion. World estimates of ultimately recoverable reserves (URR) are **1143.7** in Gt. (Mohr & Evans; 2009), while it is often counted as a fuel of the future as its reserves are larger than that of oil. McGlade & Ekins (2015) estimate RURR of coal at **4085 Gt**, including both hard coal and lignite.

2. Energy return on investment (EROI)

EROI identifies the efficiency of energy sources as a relation between invested and gained energy. In other words, we can describe it as the net energy remaining after subtracting the amount necessary to explore, extract and refine an energy resource.

EROI is defined as the total energy output divided by the total energy input over the lifetime of an energy producing system. Cleveland *et al.* (2011) address four areas that are of particular interest and uncertainty within EROI analysis for fuel:

- System boundaries
- Energy quality corrections
- Energy-economic conversions
- Alternative EROI statistics

2.1 Relevance of EROI for the society

There are two key concepts to be mentioned as an example of the relevance of EROI for the society.

First, the EROI of each energy resource influences socioeconomic activity, which is visible in the relationship between GDP and EROI. This is mostly the case for oil, on which the economy and especially certain sectors hugely depend:

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“Murphy and Hall examined the relation between EROI, oil price and economic growth over the past 40 years and found that economic growth occurred during periods that combined low oil prices with an increasing oil supply. They also found that high oil prices led to an increase in energy expenditures as a share of GDP, which has led historically to recessions. Lastly, they found that oil prices and EROI are inversely related (figure 2), which implies that increasing the oil supply by exploiting unconventional and hence lower EROI sources of oil would require high oil prices.“ (Murphy and Hall, 2010; 2011)

This phenomenon is called the ***economic growth paradox***: Production from energy resources with higher EROI support economic growth, which then in turn demands more energy resources. However, these new resources do have a lower EROI and therefore their price is higher. This effect than slows down economic growth and thus lowers demand for energy resources. Lower demand then make the prices of energy resources lower, which starts again the increase of demand and GDP growth. As Murphy and Hall (2011) state:

“The growth paradox leads to a highly volatile economy that oscillates frequently between expansion and contraction periods, and as a result, there may appear to be numerous peaks in oil production. In terms of business cycles, the main difference between the pre and peak era models is that business cycles appear as oscillations around an increasing trend in the prepeak model while during the peak era model they appear as oscillations around a flat trend.“ (Murphy and Hall, 2011)

Murphy and Hall proceed: “First, increasingly supplies of oil originate from sources that are inherently more energy intensive to produce, simply because firms develop cheaper resources before expensive ones. For example, in 1990 only 2% but by 2005 60% of discoveries were located in ultradeepwater locations.“

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Murphy defines a ***net energy cliff*** (Murphy, 2014) and argues that "[t]he exponential relation between gross and net energy means that there is little difference in the net energy provided to society by an energy source with an EROI above 10, whether it is 11 or 100, but a very large difference in the net energy provided to society by an energy source with an EROI of 10 and one with an EROI of 5. It is the main reason why there is a critical point in the relation between EROI and price at an EROI of about 10."

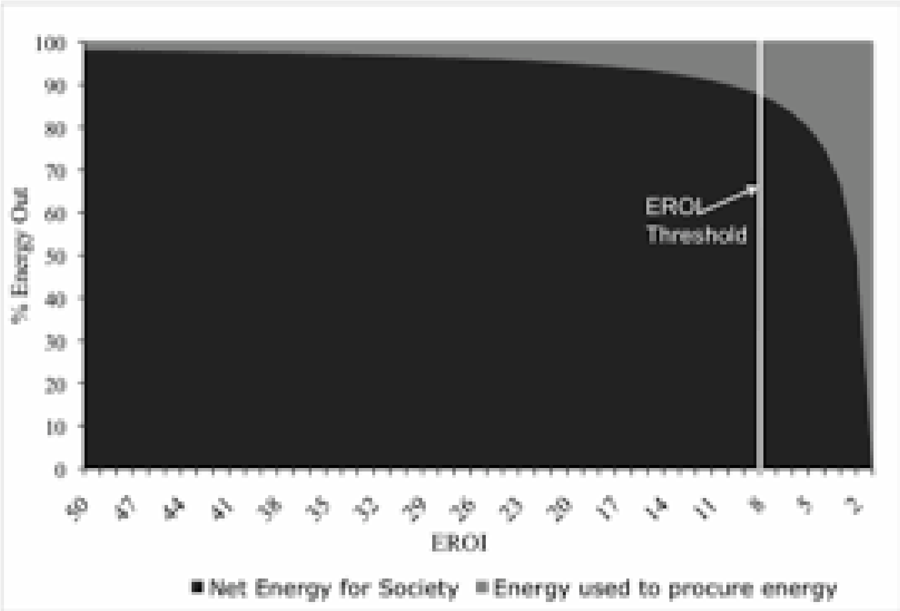

Figure 2: EROI – Net energy cliff (source: http://oilprice.com/Energy/Energy-General/Limits-To-Energy-Return-On-Investment-Calculations.html)

2.2 Constraints of EROI

There are several articles trying to calculate what the minimal EROI for the society is. Hall et al. (2009) were trying to formulate the ratio, which would indicate the accountability of energy sources. In their article "*What is the Minimum EROI that a Sustainable Society Must Have*?" they came to the conclusion, that an EROI lower than **3:1** would diminish even the most basic level of functioning in our society.

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This ratio is to be taken into account concerning any energy source, not only fossil fuel.

"The recent paper by Hall et al. on the minimum EROI for society indicates that society, even at its most basic level, cannot function on an EROI at the wellhead of less than about 3:1, and that considerably more than that would be required for the full suite of goods and services (such as medical care and education) that we have come to expect. At this time oil and gas still represent a favorable EROI compared to most alternatives (except coal)."

Hall et al. proceed: "So whether we should say "**The minimum EROI is 3:1**" or, somewhat more accurately, that to deliver one barrel of fuel to the final consumer and to use it requires about three barrels to be extracted from the ground, with two being used indirectly, is somewhat arbitrary, although the second way is technically more correct."

Murphy and Hall (2011) state: "If the EROI were to decrease to 3:1, then we would have only 20 years of conventional oil remaining, at current levels of consumption. If consumption of conventional oil increases we will exhaust our remaining crude oil supplies even faster. [..] The "extended EROI" includes also energy of transporting and using energy. This approximately triples the EROI required to use the fuel once obtained from the ground, since twice as much energy is consumed in the process of using the fuel than is in the fuel itself at its point of use."

2.3 Methodology of EROI measurement

Mulder and Hagens (2008) present a summary of methodologies used for indicating EROI, while paying attention to cost included and handling with non-energy resources. They divided different calculations of EROI into different levels. First level accounts only direct energy inputs and outputs. The methodology of this measurement is described as a most precise form, while on the other hand also „superficial" as not including indirect inputs and byproducts.

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We assume that this methodology provides the best data to consider, because it is commonly used and provides the data for mostly used fuels.

However it is necessary to mentioned also other methodologies of EROI accounting. Mulder and Hagens describe them as a second level of EROI, which includes also other indirect inputs. This method gives an overview on life cycle of energy technology, which is very important for the future projections. On the other hand there are no clear boundaries of involving indirect inputs, which raises a question, which indirect inputs are determining.

The other approaches reflect other critical points of EROI measurement – such as other materials used for energy generation. This is also very important, as it shows the systemic demands on energy. For example technology is seen by some authors as a way to gain unconventional/new energy resources with higher EROI. However if we count as an input also energy needed to invent and build such a technology the final EROI may again decline substantially. To include these inputs into analysis Mulder and Hagens propose second and third order of EROI measurement which might be complemented by so called bottom up approaches. We will characterize these approaches as unconventional and will not use them further in our model.

First of all, it is necessary to select the appropriate boundaries for an EROI analysis. There are a variety of direct and indirect energy and material inputs which determine the denominator of the EROI ratio. These inputs are distributed on different levels: level 1 includes internal energy consumption, level 2 external energy consumption, level 3 material consumption, level 4 labor consumption and level 5 auxiliary services consumption. There are two main techniques within energy analysis to assess the energy flows through a particular process or product: 1) process analysis known as bottom-up analysis, accounting inputs and outputs in a process by aggregating them through the sequential stages of production while 2) economic input-output a top-down method, consist in converting the economic tables in energy units.

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Expanding boundaries of energy tends to quickly increase the amount of data collection and the calculation of EROI becomes very difficult since the method is not flexible nor consistent. Simply considering a system composed of many plants Cleveland *et al.* (2011) define the EROI in this way:

$$EROI=E_g/(E_c+E_{op}+E_d)$$

Where:

E_g represents the gross flow of produced energy over the whole lifetime, E_c is the energy required for construction, E_{op} is the energy required to operate and maintain the project and E_d is required for decommission. Often, the only data available for capital equipment and other energy or material inputs is in form of monetary data. In this case, it is necessary to convert dollars into energy units.

Normally, the boundaries of the EROI calculation are based on the standards of LCA analysis as defined, for instance, in ISO 14040, and as described, for instance, by King *et al.* (2010) in terms of "System energy assessment". There are alternative methods, mentioned here for completeness: Fossil Energy Ratio, that compares the total energy gains from fossil fuel investment, the External Energy Ratio, which is useful for energy production techniques that consume a significant amount of energy derived in situ (as tar sand) and Net Energy Yield Ratio.

Cleveland et al. (2011) give the following instructions for EROI analysis:

- Step 1: define the objectives of the analysis.
- Step 2: create the flow diagrams and identifying system boundaries.
- Step 3: identify all the appropriate inputs and outputs within the system boundaries.
- Step 4: identify them for the calculation of standard EROI as well as other EROI calculations.
- Step 5: choose the method of energy quality adjustment.
- Step 6: convert to financial flows.
- Step 7: calculate EROI.

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Murphy *et al.* (2009) further clarify the boundaries used in the EROI calculations given here into the following categories:

1. Standard EROI ($EROI_{ST}$): in this estimate the energy output is divided for a project, region or country by the sum of the direct and indirect energy used to generate that output. This EROI calculation is applied to fuel at the point where it leaves the extraction and production facility (well-head, mine mouth, farm gate, etc).
2. Point of use EROI ($EROI_{POU}$): Point of Use EROI additionally includes the costs associated with refining and transporting the fuel, expanding the boundaries in the analysis, the energy cost to reach that point increases, resulting in a reduced EROI.
3. Extended EROI ($EROI_{EX}$): this analysis includes the energy necessary not only to get it but also that is minimally useful to society.

Societal EROI ($ERO_{ISO}C$) is the overall EROI obtained considering the whole transformation chain that starts from the energy produced as input and with the output as the output of the total economic activity of a country, and all costs to obtain them. It is not always possible to have this information, for this reason Lambert *et al.* (2013) developed a preliminary method for deriving $EROI_{SOC}$ (Lambert et al., 2013).

2.4 EROI estimations at the world level

The most frequently cited article concerning the EROI of global oil and gas production is provided by Gagnon et al. (2009) in an article called *A Preliminary Investigation of Energy Return on Energy Investment for Global Oil and Gas Production.*

In this article the EROI for global oil and gas production is estimated. However, attention should be given to the methodology used in the article too, because it reveals limitations of such estimations.

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In the following figure, there are EROI calculations for fossil fuels.

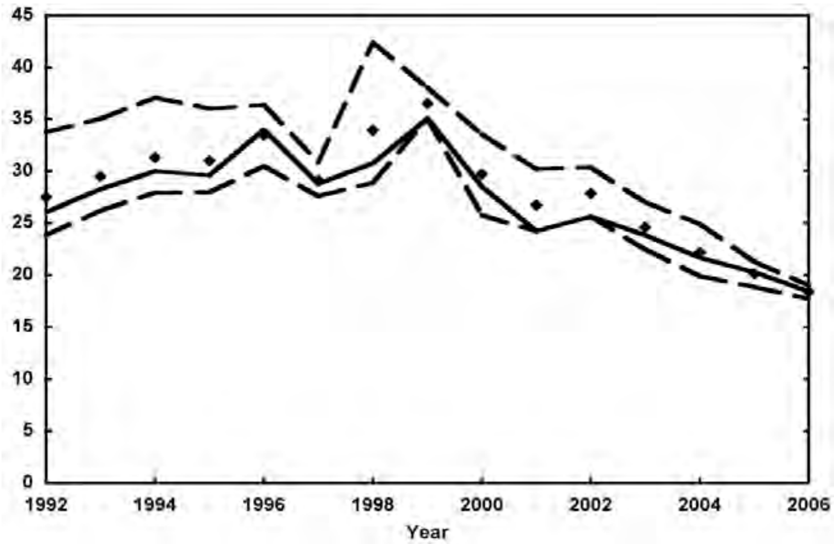

Figure 3: EROI calculations for fossil fuels (source: Gagnon et al., 2009)

The calculation is based on dollar cost of oil and gas as provided by Herold.[1] The dollar cost was converted to energy costs and then calculated as a time series for the EROI for oil and gas production globally. "There are only a few countries that maintain and make public such information (energy cost of exploited energy), let alone insure quality control. An even larger problem is that a large proportion (roughly half) of oil is produced by national oil companies (NOCs), which show little interest in making any of their information public, let alone having it audited."

The problem of data origin might be seen as crucial, especially when we take into account that energy cost might influence also the investment rate. Authors used data for UK and US, because these were the only known. The average for those two energy intensities multiplied by total world dollar expenditures of public companies, counted as energy investment, is calculated. The resulting EROI is a ratio of global oil and gas production divided by estimated global energy investment.

[1]Unfortunately not for free: http://www.herold.com/research/research_methodology.main

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Energy intensity is related to energy consumption derived from monetary expenditures in nominal dollars. Monetary expenditures on resource extraction are also an important variable, which is then used in different models for counting the EROI. Some authors also propose a derived indicator called MROI, which than serves as a base for a transfer to the EROI.

Problems with EROI calculations for time series arise, mainly because of two reasons: First, there are differences between every well and basin. Second, there is unknown data about the life cycle of different technologies, because some are still running.

Therefore Gagnon at el. introduce a "**rolling average**" calculation of EROI. This is a comparison of "energy input to the oil and gas extraction industry in a given year to the energy output of the industry in that same year." The most important part of the article is however the estimation for global gas and oil production:

"The quality-corrected EROI for global oil and gas production, as measured by megajoules (MJ) of oil and gas produced divided by the MJ equivalent of the dollars spent on exploration, development, and production was approximately **26:1 in 1992**, increased to about **35:1 in 1999**, and has since declined steadily to **18:1 in 2006.**" The decline of EROI is a trend that is supported by other articles, too.

2.5 EROI for Oil and conventional natural gas

Oil and conventional natural gas are usually treated together since the procedure of their production are overlapped (Gupta et al, 2011). Cleveland et al. (2005) considered that EROI for producing oil and gas was approximately 30:1 in the 1950's, decreased to 20:1 in the 1970's then fell again to 11-18 in the mid 2000's. They observed that EROI tends to decrease when drilling rates become higher and increase when drilling was relaxed.

Because of the limited amount of available data, it is difficult to make precise calculations on the energy inputs required by the global (or any local) petroleum industry. Only few countries make this information available to the public. Gagnon et al. (2002) calculated the energy equivalent per dollar spent (i.e. the energy intensity) in the petroleum industry from data obtained for the U.S and the U.K. (Figure 13). In Fig. 13, a*ll known EROIs for oil and gas production as about 2008 are shown.* Specifically, *t*he triangle represents Cleveland’s estimate for EROI US oil and gas discoveries in 1930 (Cleveland, 1984). Crosses represent the estimate for EROI US oil and gas production. The line represents the trend of global oil and gas EROI while the dashed represents Cleveland’s estimate of U.S. EROI for production including a correction for quality.

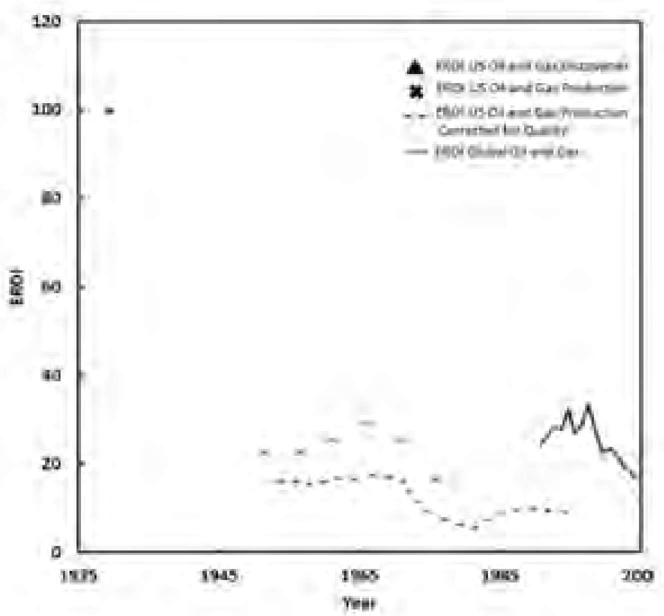

Figure 4: All known EROIs for oil and gas production as about 2008. (Gagnon et al. 2009)

Gagnon et al. (2009) concluded that global oil and gas EROI was approximately 26:1 in 1992, increased to 35:1 in 1999 and then decreased to 18:1 by 2006. Through linear extrapolation, the EROI for global oil and gas reach 1:1 as soon as about 2022 (Figure 14). The dashed lines in Fig. 14 show the linear extrapolations of the steepest and most gradual trends in EROI resulting from different methods of calculating energy input.

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These were obtained by calculated energy input using energy intensity defined as energy use per real (2005) dollar of gross product of the oil and gas extraction sector with a unique energy intensity for each year (steep slope), and using the average energy intensity overall years (gradual slope).

The authors note that the EROI for gas is likely much higher than for oil in most cases due to the difference in energy costs for raising the fuel in a well.

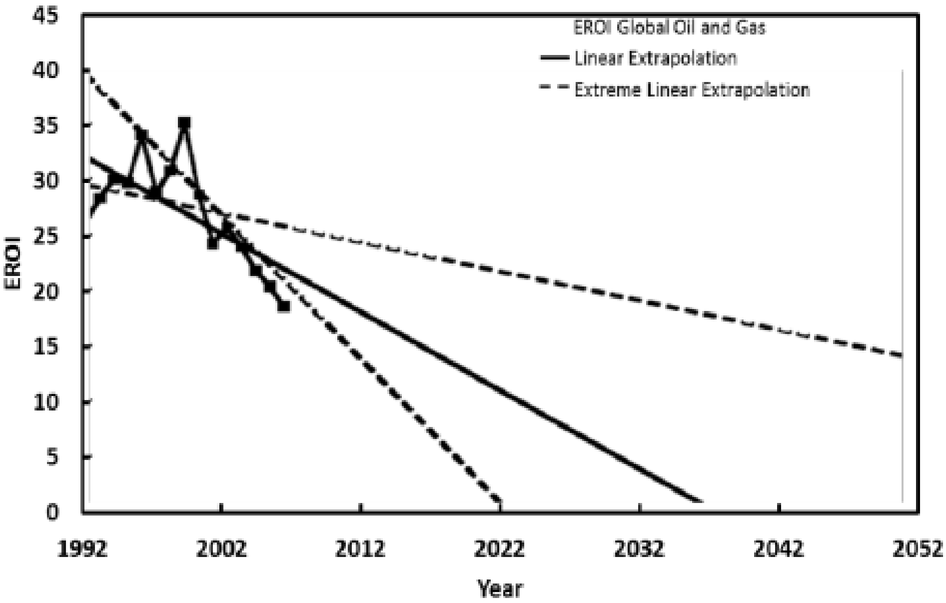

Figure 5: A linear extrapolation of trends in EROI for global oil and gas production (Gagnon et al. 2009).

2.6 EROI for coal

The only EROI analyses for coal production are from the US and China since in the other countries of the word the information about the energy spent to extract coal is not available.

The trends of coal EROI are illustrated in Figure 12, where the values are reported as a function of time from 1920 to 2010. Cleveland (1992) calculated the EROI of US coal considering thermal equivalents and also quality-corrected values.

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From Cleveland's studies, the EROI of US coal dropped down from 100:1 during 1960's to approximately 50:1 and then started to increase to higher than approximately 70:1 by 1987. There is not information on EROI of coal beyond 1987 (Gupta A.K. and Hall C.A.S., 2011).

Balongh et al. (unpublished) reproduced the trend of US Coal Bituminuos from 1920 to 2010. The US Bituminous coal reach a maximum production in 1950's and then the EROI fell to approximately 25 and then increase again in 1992 to 75:1.

Hu et al. (2013) established annual data for Chinese coal production for the years 1994 through 2009. This trend shows very little variation in EROI values.

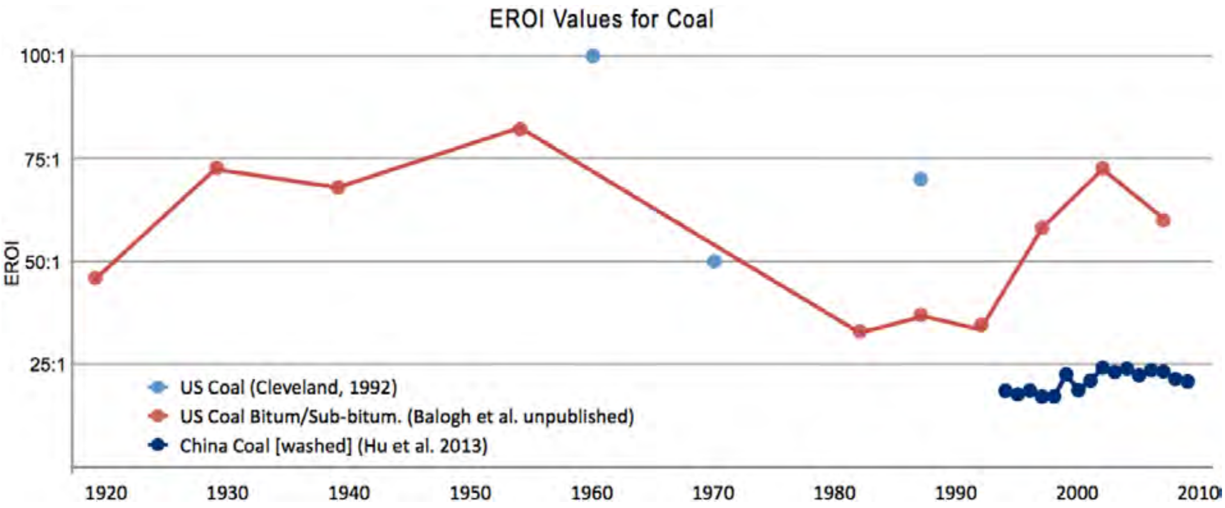

Figure 6: EROI values for US and Chinese coal production derived from Cleveland (1992), Balogh et al. (unpublished data) and Hu et al. (2013).

Some authors assume a significantly higher EROI measures for coal than for oil and gas. A rough estimation of the international EROI of coal made as an average of figures mentioned in different publications is **46:1** (n of 72 from 17 publications) (Hall et al. 2014).

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3. Unconventional resources

3.1 EROI for Tar Sands

Tar sands or oil sands are technically known as bituminous sands and they are a type of unconventional petroleum deposit. Oil sands are either loose sands or partially consolidated sandstone containing a mixture of sand, clay, water saturated with a dense and extremely viscous petroleum known as bitumen. It can be liquefied underground through the injection of steam, or mined at the surface, and then processed into liquid fuel called syncrude. Natural bitumen deposits are present particularly in Canada and Venezuela. Despite of the enormous deposits, the extraction rate is limited by environmental and other constraints.

Herweyer M.C. and Gupta A. (2008) calculate the EROI using a "bottom-up" approach. In this method the energy output is the equivalent of the energy content of one barrel of crude oil while the energy input represents the energy amount of the different processes involved within the research boundary (extraction, separation and upgrading). The authors admitted that the EROI calculation depends mostly upon the direct energy used and which alone suggests an EROI of about 5.8:1. Adding the indirect energy the EROI decreases to 5.2:1 and including labor and environmental costs have little effect.

In the 2009 Murphy posted on the The Oil Drum a preliminary calculation of the EROI of producing syncrude from the new Toe to Heel Air Injection (THAI) method. The THAI method is a combustion process which uses a vertical air injection well and a horizontal production well. A portion of bitumen on site is burned with the inserted air so that the remaining bitumen will warm up and attain a lower viscosity (Mawdsley et al, 2005). Depending on different assumptions, Murphy (2009) determined an EROI of 3.3-56:1. Considering the oil burned in situ is "free" in the financial sense, it is a required energy input to the THAI process and, from this perspective, this energy should be included in the estimation of EROI resulting in an EROI of 8.9:1.

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Murphy's EROI estimate for syncrude production processes is higher than that considered previously by Herweyer and Gupta (2008). This is due to the smaller fractions of water and natural gas employed in the THAI process.

Table 5: Other analyses of oil sands EROI

Author	Date	Technique	Resource	System Boundary	EROI
Kymlicka W.	2006	-	Alberta	-	<5:1
DOE	2006	Surface; in situ	Alberta	-	7.2:1, 5:1
Günter, F.	2008	-	Alberta	Shallow sands	1.5:1
Heinberg, R.	2003	-	-	-	1.5:1
Swenson, R.	2005	-	-	-	3:01
Homer-Dixon, T.	2005	-	Alberta	-	4:01
Sereno, M.	2007	-	-	-	1-3:1
Legislative Peak Oil and Natural Gas Caucus	2007	-	Alberta	-	3:01

3.2 EROI for Oil Shales

Oil Shales are defined as fined grained sedimentary rocks containing organic matter (kerogen) that yields abundant amounts of oil and gas by industrial processing. Oil shales occur in many deposits in 27 countries including Australia, Brazil, Canada, China, among others. Contrary to periodic predictions that shale oil would soon be needed to replace diminishing crude oil supplies, shale oil production has actually dropped threefold since 1980.

Gupta et al (2008) reviews a number of studies from 1975 to 2007 which had made some kind of EROI of 1.5:4.1. A few earlier studies suggested an EROI of 7:1 to 13:1. (Gupta et al, 2011).

More recent analyses of the "Shell technique", an approach meant to be relatively environmentally benign and currently in operation, gave estimates of about 3-4:1, although since most of the inputs are electricity and the output is oil, one might think that a quality –corrected analysis would lead to near 1:1.[2]

3.3 Shale oil (or tight oil)

"Shale Oil" should not be confused with "oil shale". The latter is mainly solid kerogen, as described above, whereas "shale" or "tight" oil is liquid oil which, however, cannot flow because of the low connectivity of the pores of the rock that contains it. Because of this feature, tight oil cannot be extracted by means of conventional drilling techniques but requires a process of fracturing (commonly referred to as "fracking") in order to mobilize it and make it flow to the surface, this technique requires special hydraulic equipment and the technology of "horizontal drilling". Both are expensive but, as a compensating feature, shale oil wells are often not very deep in terms of distance from the surface.

The EROI of shale oil produced from the Bakken formation in the US has been studied by Brandt et al (2015) finding a large spread of values that depend on the specific geological features of the field being exploited. The median value of the EROI turned out to be between 25 and 30. Data on other shale formations do not appear to be available and it appears that, in many cases, shale fields outside the US have such poor EROIs that they cannot be economically exploited at present (this is the case, for instance, of the shale fields in Poland). Comprehensive data for tight oil are not listed in the Annex because of lack of generalized data valid for the average resources being exploited.

[2] Source:www.blm.gov/pgdata/etc/medialib/blm/co/field_offices/white_river_field/oil_shale.Par.79837.File.dat/OSTPlanofOperations.pdf

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4. Summarized EROI calculations

A summary of EROI calculations in different studies provided by Hall is found bellow. We can see that each article used different data sources; therefore it is necessary to mention the methodology behind the calculations.

Table 6: Summary of EROI calculations in different studies provided by Hall et al. (2014) – table.

Resource	Year	Country	EROI (X:1)[1]	Reference
Fossil fuels (Oil and Gas)				
Oil and gas production	1999	Global	35	Gagnon, 2009
Oil and gas production	2006	Global	18	Gagnon, 2009
Oil and gas (Domestic)	1970	US	30	Cleveland et al. 1984, Hall et al. 1986
Discoveries	1970	US	8	Cleveland et al. 1984, Hall et al. 1986
Production	1970	US	20	Cleveland et al. 1984, Hall et al. 1986
Oil and gas (Domestic)	2007	US	11	Guilford et al. 2011
Oil and gas (Imported)	2007	US	12	Guilford et al. 2011
Oil and gas production	1970	Canada	65	Freise, 2011
Oil and gas production	2010	Canada	15	Freise, 2011
Oil, gas & tar sand production	2010	Canada	11	Poisson and Hall, in press
Oil and gas production	2008	Norway	40	Grandell, 2011
Oil production	2008	Norway	21	Grandell, 2011
Oil and gas production	2009	Mexico	45	Ramirez, in preparation
Oil and gas production	2010	China	10	Hu et al. 2013
Fossil fuels (Other)				
Natural Gas	2005	US	67	Sell et al. 2011
Natural Gas	1993	Canada	38	Freise, 2011
Natural Gas	2000	Canada	26	Freise, 2011
Natural Gas	2009	Canada	20	Freise, 2011
Coal (mine-mouth)	1950	US	80	Cleveland et al. 1984
Coal (mine-mouth)	2000	US	80	Hall and Day, 2009
Coal (mine-mouth)	2007	US	60	Balogh et al. unpublished
Coal (mine-mouth)	1995	China	35	Hu et al. 2013
Coal (mine-mouth)	2010	China	27	Hu et al. 2013
Other non-renewables				
Nuclear	n/a	US	5 to 15	Hall and Day, 2009, Lenzen, 2008
Renewables[2]				
Hydropower	n/a	n/a	>100	Cleveland et al. 1984
Wind turbine	n/a	n/a	18	Kubiszewski et al. 2010
Geothermal	n/a	n/a	n/a	Gupta and Hall, 2011
Wave energy	n/a	n/a	n/a	Gupta and Hall, 2011
Solar collectors[2]				
Flat plate	n/a	n/a	1.9	Cleveland et al. 1984
Concentrating collector	n/a	n/a	1.6	Cleveland et al. 1984
Photovoltaic	n/a	n/a	6 to 12	Kubiszewski et al. 2009
Passive solar	n/a	n/a	n/a	Cleveland et al. 1984
Biomass				
Ethanol (sugarcane)	n/a	n/a	0.8 to 10	Goldemberg, 2007
Corn-based ethanol	n/a	US	0.8 to 1.6	Patzek, 2004, Farrell et al. 2006
Biodiesel	n/a	US	1.3	Pimentel and Patzek, 2005

(1) EROI values in excess of 5:1 are rounded to the nearest whole number.

(2) EROI values are assumed to vary based on geography and climate and are not attributed to a specific region/country.

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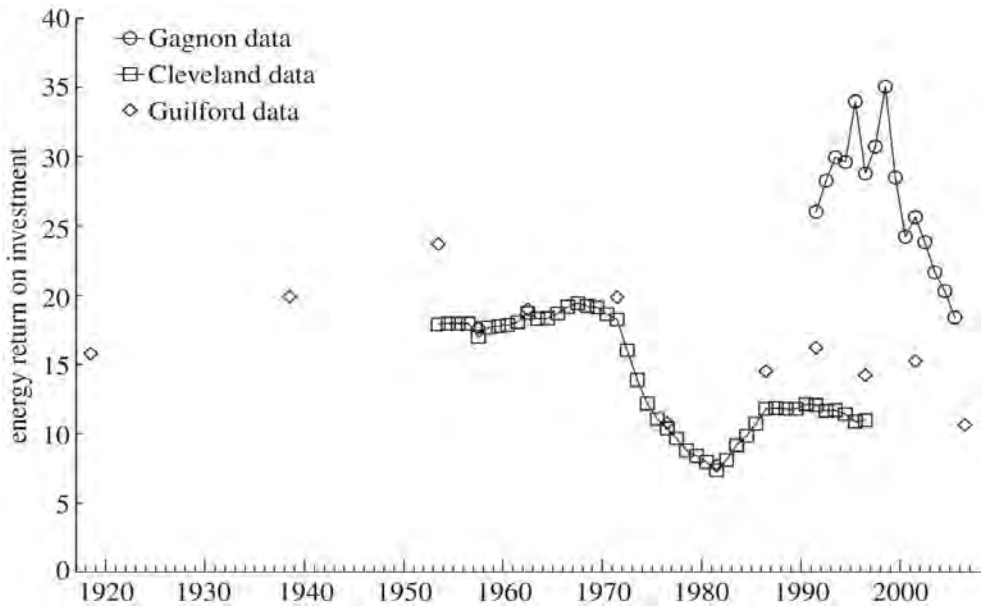

Figure 7: Summary of EROI calculations in different studies provided by Murphy. (2014) – graph.

Figure 7 shows another comparison of oil and gas production EROI estimates from three sources – Gagnon et al. for a global level, Cleveland and Guilford for the U.S.

5. Renewable Energy Sources EROI

5.1 EROI for hydropower

Hydropower is energy produced from water power (Schoenberg, 2008). Water generates electricity when it drops gravitationally, driving a turbine and a generator. While most hydroelectricity is produced by water falling from dams, some is produced by water flowing down rivers (run-of-the-river electricity).

For hydropower, the EROI is calculated as the ratio between the lifetime of the station and the energy costs necessary for creating and maintaining it. The published data are often unclear on whether the energy costs of site decommissioning is part of the analysis. If that's the case that would obviously lower the EROI.

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The EROI of hydropower is site-specific and the variability of the performance is such that a single general EROI value is not applicable to describe all projects. SUNY ESF (Schoenberg 2008) reported EROI values ranging from 11.2 to 267 both quality- and not quality-corrected for the fact that the output is electricity and the input is mostly oil or other fossil fuel (Clevaland et al., 1984; Gagnon et al., 2002). For specific favorable sites in Quebec, EROI has been reported at 205:1 (for a reservoir type) and 267:1 (for a run of the river type). The EROI figures examined in that report ranged from 11.2:267.1.

Table 7: Published EROI values for hydropower

Magnitude	EROI	Reference
Not given	33.6:1	Cleveland et al, 1986
Not given	48:1	Pimentel, Rodrigues 1994
Reservoir	205:1	Gagnon, Belanger, Uchiyama 2002
Run of River	267:1	Gagnon, Belanger, Uchiyama 2002
Not given	19:1	Odum et al. 1975
Run of river	16-101	Gilliland, Klopatek, Hildebrand 1981
Not given	100-300	Gagnon et al, 2002

Lambert et al. (2013) elaborated an average EROI for hydroelectric power in 2012 arriving to a value of 84:1, as deduced by the screening of 12 different publications for a total of 17 different plants.

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5.2 EROI for Photovoltaic

Globally, the solar generated electricity is, at present, only 0.38% of the global electric energy generation, about 87 TWh of the total 22700 TWh in 2015 (Doman et al., 2011).

However the PV market is rapidly growing, considering that the annually installed PV power capacity is expected to grow from 31 GW_p in 2012 to the range of 48-84 GW_p in 2017, representing an annualized growth rate 11-34% respectively (Masson et al., 2013). In the literature, an extensive study made by Bhandari et al. (2015) reports a meta-analysis on the values of such parameters as embedded energy, Energy PayBack Time, and EROI, of PV plants to produce more accurate evaluations and comparison of the energy performance of different types of PV technologies established 2000-2013.

For solar photovoltaic systems, the EPBT and EROI are calculated using the following equations respectively:

$$Energy\ PayBack\ Time\ (Year) = \frac{Embedded\ (primary)energy\ (MJ\ m^{-2})}{Annual\ (primary)energy\ generated\ by\ the\ system\ (MJ\ m^{-2}yr^{-1})} =$$

$$\frac{W1(MJm^{-2})}{W2\ (MJ\ m^{-2}yr^{-1})} = \frac{W1}{(1 \times\ \eta\ \times PR)/\varepsilon}$$

$$Energy\ return\ on\ energy\ invested = \frac{lifetime\ energy\ output}{Embedded\ energy} = \frac{W3(MJ\ m^{-2})}{W1\ (MJ\ m^{-2})} =$$

$$\frac{W2\ (MJ\ m^{-2}) \times LT\ (year)}{W2\ (MJ\ m^{-2}\ yr^{-1}) \times EPBT\ (year)} = \frac{LT\ (year)}{EPBT\ (year)}$$

Where:

$W1 = embedded\ (primary)energy\ (MJ\ m^{-2})$

$W2 = annual\ energy\ generated\ by\ the\ system\ expressed\ as\ primary\ energy\ (MJ\ m^{-2}\ yr^{-1})$

$W3$
$= total\ energy\ generated\ by\ the\ system\ \ over\ its\ lifetime\ expressed\ as\ primary\ energy\ (MJ\ m^{-2})$

$\varepsilon = electrical\ to\ primary\ energy\ conversion\ factor$

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$I = total\ solar\ insolation\ incident\ on\ the\ unit - surface, \quad per\ year\ (MJ\ m^{-2}yr^{-1})$

$\eta = average\ module\ efficency\ (\%)$

$PR = system\ performance\ ratio\ (\%)$

$LT = lifetime\ of\ the\ system\ (year)$

Bahndari et al. (2015) assumed that the factor of conversion ε from primary energy to the electrical one is 0.35.

The embedded energy *WI (MJm^{-2})* or embodied energy is the total energy required to extract and process the raw materials necessary to construct the module and the balance of system for the PV system being analyzed.

The Harmonized parameters are:

$$Solar\ cell\ efficiency\ (\eta\%) = \frac{ouput\ power\ of\ a\ cell\ at\ its\ maximum\ power\ point\ (Watts)}{incident\ radiation\ (W\ m^{-2}) \times surface\ area\ of\ the\ solar\ cell\ (m^{-2})}$$

The module efficiency reported by manufacturers represents the initial efficiency of the module under standard test conditions. There is a significant difference between module efficiency and fully packaged module efficiency. In the latter case we have to take into account many types of losses: losses due to the physical inhomogeneity present on the cell surface, optical loss due to the physical layout of the module including framing and absorption associated with encapsulation, and electrical loss due to series resistance developed from cell interconnections.

Bahndari et al. (2015) adopted in their harmonization, the average life time efficiency (in %) that are shown in Table 15.

Table 8: Module efficiencies used for harmonization (Bahndari et al., 2015).

Module Type	Mono-Si	Poly-Si	A:Si	CdTe	CIGS
Average lifetime efficiency (%)	13,0	12,3	6,3	10.9	11.5

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$$Performance\ ratio = \frac{actual\ output\ of\ a\ PV\ module}{theoretical\ energy\ output\ of\ a\ PV\ module}$$

PR is expressed in percentage, if PR is equal to 75% this means that 25% of the theoretical energy generation is lost due to environmental factors or reduced conversion efficiency. Bandhari et al. (2015) decided to use a PR value equal to 75% for their harmonization.

Solar insolation is the solar radiation incident per unit area per year. Bahandari et al. (2015) used the "universal insolation" for harmonization that is equal to *1700* $kWhm^{-2}yr^{-1}$.

A simple example of the calculation of EPBT or EROI and harmonized EPBT and EROI is shown below. For mono-Si photovoltaic systems (data from Garcia-Valverde et al., 2009), the authors take into account the following values:

Table 9: EROI harmonized value

Module efficiency (%)	0.12
harm_Module efficiency(%)	0.13
Performance Ratio (%)	0.62
harm_Performance Ratio (%)	0.75
Life time(year)	20
harm_ Life time (year)	30
Irradiance(kWh m-2yr-1)	1,932
harm_Irradiance (kWh m-2yr-1)	1,700
Embedded Energy (MJ prim m-2)	13,428
Factor of conversion from primary to electric energy ε	0.35
Factor of conversion from kWh-MJ	3.6
EPBT	9.08
EROI	2.20
harm_EPBT	7.88
harm_EROI	3.81

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In order to achieve this goal, Bhandari et al. (2015) collected EPBT and EROI data that were harmonized for the specific parameters (module efficiency, solar insolation and system lifetime) that affect the life cycle performance of the PV system. Their study is focused on the most relevant commercial technologies, falling into the categories of mono-crystalline silicon (mono-Si), poly-crystalline silicon (poly-Si), amorphous silicon (a:Si), cadmium telluride (CdTe), and copper indium gallium diselenide (CIGS).

Mono-Si Harmonized EROI are shown in tables 16, 18, 20, 22 and 24. For better understanding, data harvested in the same year are processed together to obtain the average and standard deviation.

Table 10: Harmonized EROI values for mono-Si PV

	Harmonized EROI		Average	
year	mono-Si	Year	mono-Si	Stand.Dev.
2005	6.34	2005	6.34	
2006	6.59	2006	6.59	
2007	4.59	2007	8.295	4.19
2007	12	2009	3.81	
2007	11.7	2011	9.47	
2009	3.81	2013	12.03	1.61
2011	9.47			
2013	13.17			
2013	10.89			
Tot.	8.73			
Stand. Dev.	3.47			

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Figure 8 shows harmonized and mean harmonized EROIs for mono-Si from 2005 to 2013.

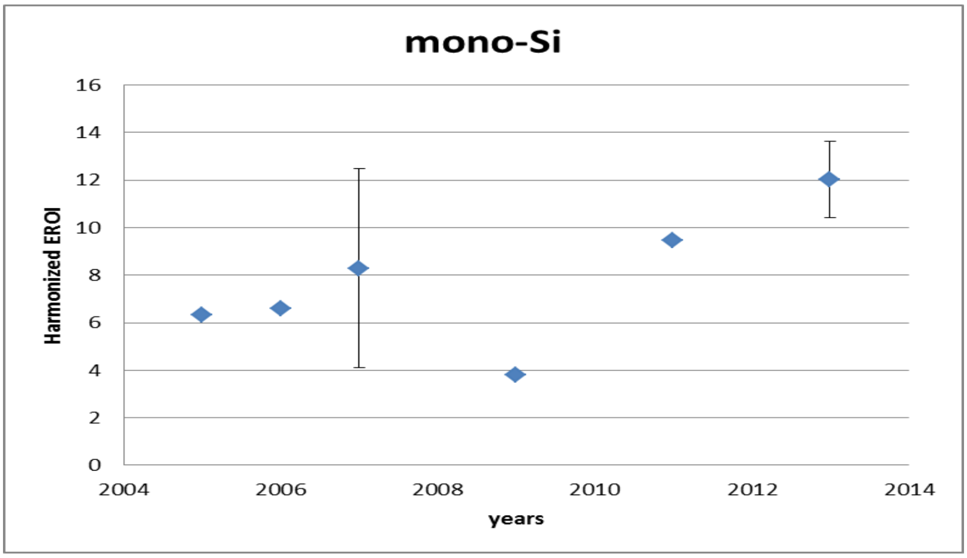

Figure 8: mean harmonized EROI for mono-Si with error bars representing one standard deviation

Table 11: Harmonized EROI values for poly-Si PV.

	poly-Si Harmonized EROI		Average Harmonized EROI	
years	poly-Si	years	poly-Si	Stand. Dev.
2000	8.75	2000	8.025	1.03
2000	7.3	2005	8.275	0.12
2005	8.36	2007	10.97	4.92
2005	8.19	2011	10.80	
2007	5.32	2013	19.95	2.47
2007	14.3			
2007	13.3			
2011	10.8			
2013	21.7			
2013	18.2			
Tot.	11.62			
Stand. Dev.	5.21			

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In Figure 9 the harmonized and mean harmonized EROI for poly-Si PV from 2000 to 2013 are represented, with error bars representing standard deviation.

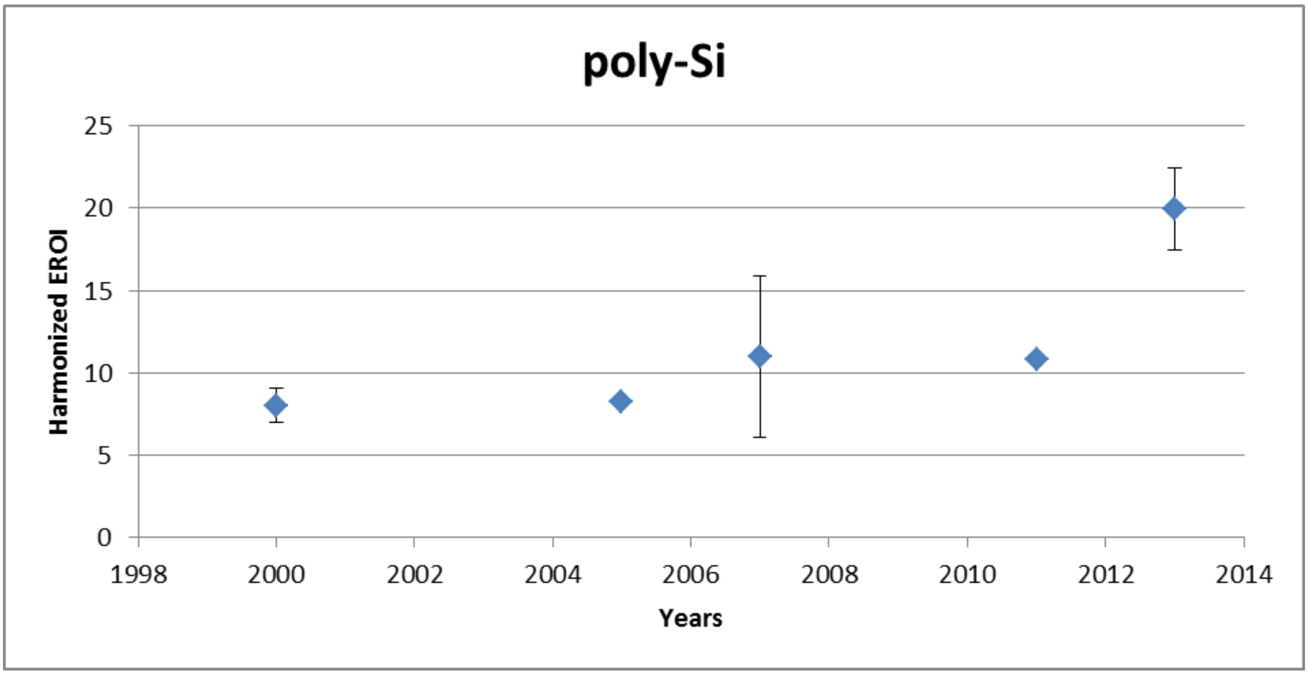

Figure 9: mean harmonized EROI for poly-Si PV

Table 12: Harmonized EROI values for a-Si PV.

	Harmonized EROI		Average Harmonized EROI	
years	a-Si	years	a-Si	Stand. Dev.
2000	10	2000	10	
2000	10	2011	12.4	
2011	12.4	2013	19.9	0.14
2013	19.8			
2013	20			
Average	14.44			
Stand. Dev.	5.08			

In Figure 11 harmonized and mean harmonized EROI for a Si PV from 2000 to 2013 are represented.

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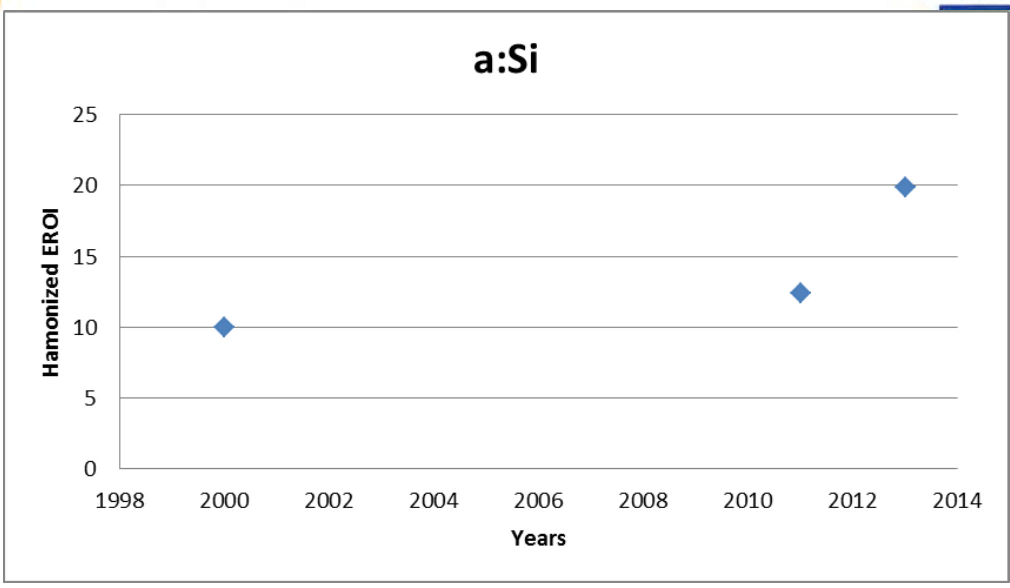

Figure 10: mean harmonized EROI for a-Si PV, with error bars representing standard deviation

Table 13: Harmonized EROI values for CdTE PV.

	Harmonized EROI		Average Harmonized	
year	CdTE	year	CdTE	Stand.
2007	23.6	2007	22.7	1.27
2007	21.8	2011	20.4	
2009	N/A	2012	48	
2011	20.4	2013	45.65	0.21
2012	48			
2013	45.5			
2013	45.8			
Tot.	34.18			
Stand. Dev.	13.49			

Figure 16 shows harmonized and mean harmonized EROI for CdTE from 2000 to 2013.

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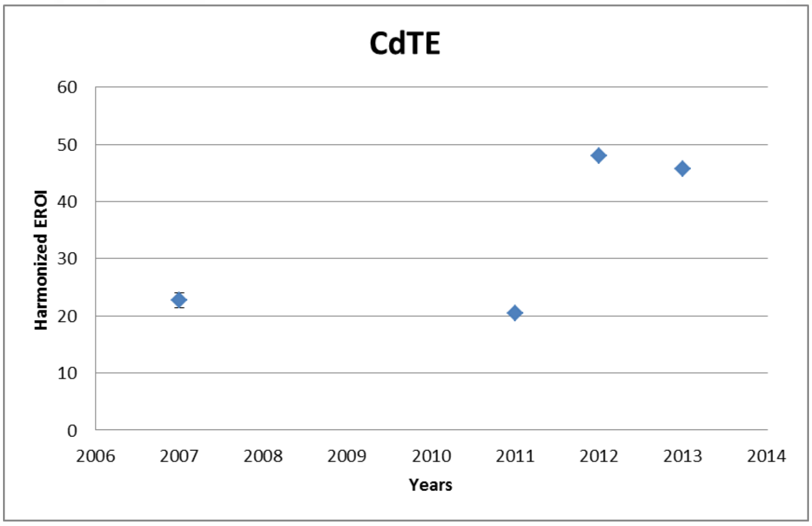

Figure 11: mean harmonized EROI for CdTE PV, with error bars representing standard deviation.

Table 14: Harmonized EROI values for CIGS PV.

	Harmonized EROI		Average harmonized	
years	CIGS	years	CIGS	Stand.Dev.
2007	18.8	2007	15.03	4.27
2007	15.9	2011	14.6	
2007	10.4	2013	29.9	0.14
2011	14.6			
2013	29.8			
2013	30			
Tot. Average	19.92			
Stand. Dev.	8.19			

In Figure 13 harmonized and mean harmonized EROI for CIGS from 2007 to 2013 are shown.

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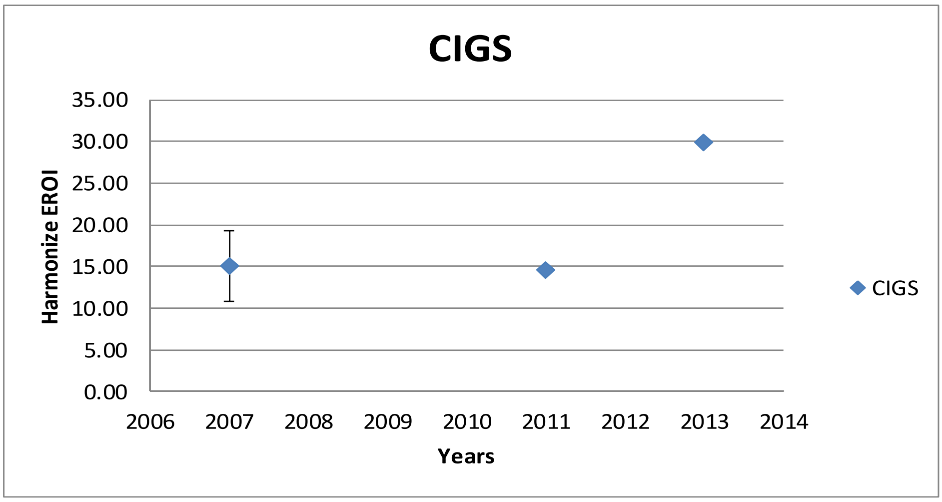

Figure 12: mean harmonized EROI for CIGS PV, with error bars representing standard deviation.

The summary of the all trends are shown in figure 13.

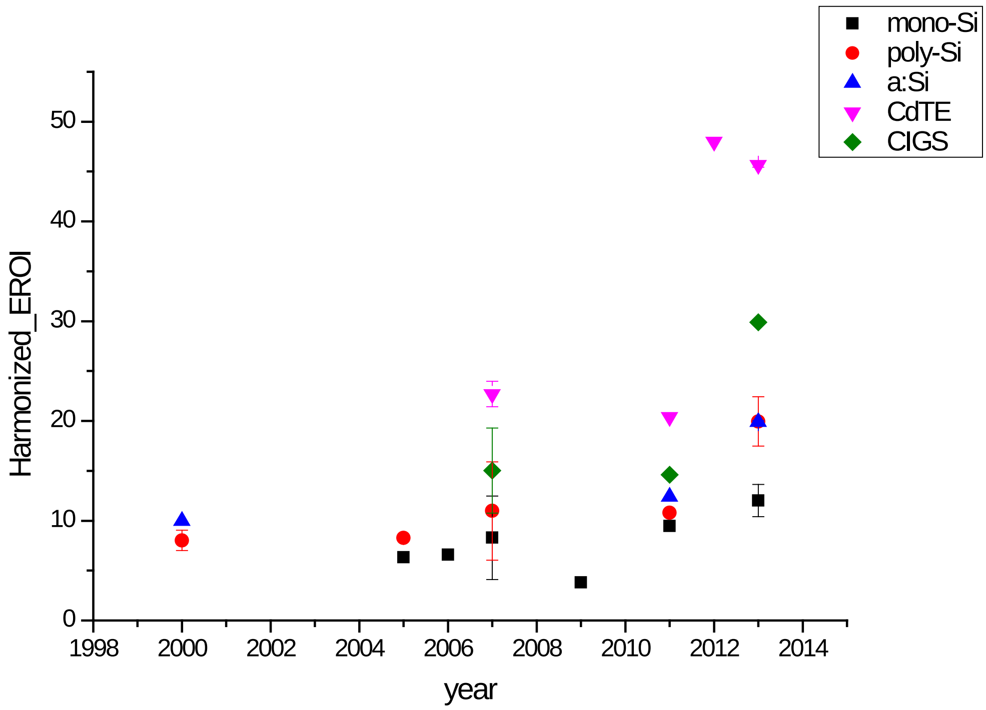

Figure 13: Harmonized EROI trend for the different PV technologies: mono-Si, poly-Si, a:Si, CdTE and CIGS.

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In figure 14, the curves obtained from the different tend of PV EROI are simulated with an exponential curve, demonstrating that EROI tends to increase during time thanks to the advancement in this field.

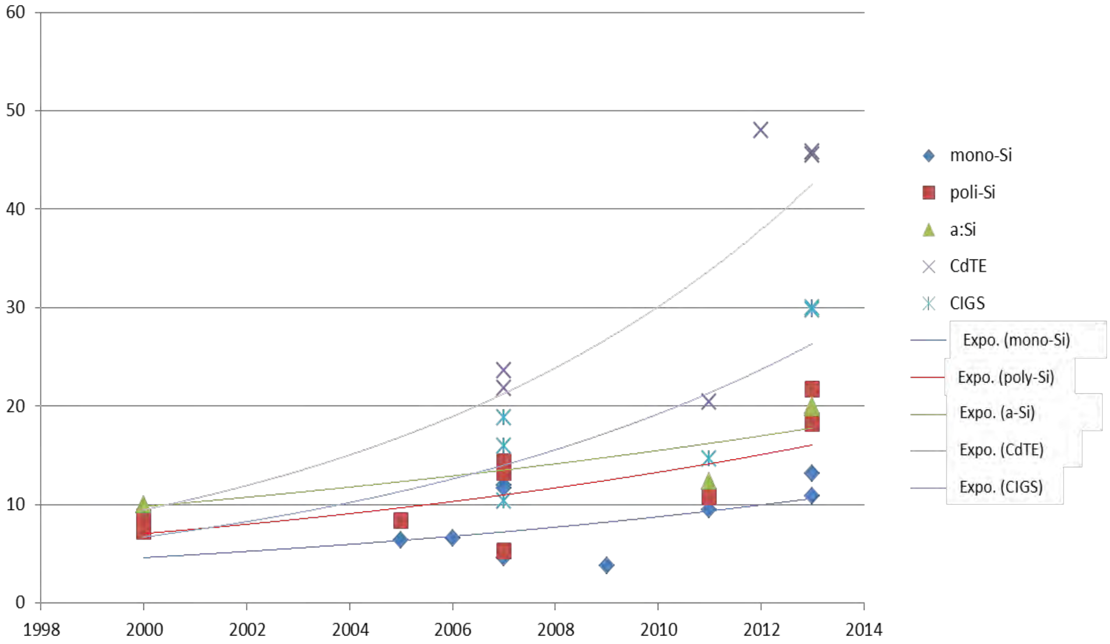

Figure 14: harmonized EROI for mono-Si PV, poly-Si PV, a:Si PV, CdTE PV and CIGS PV as a function of time.

All the trends are characterized by an increasing value of harmonized EROI during time, from 2000 to 2014. In particular for CdTE and CIGS, the value tends to grow more rapidly, indicating higher values for these two PV systems than mono-Si, poli-Si and a:Si PV.

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5.3 EROI for Wind

Wind devices convert the energy coming from the wind into electricity. In the literature, Kubiszewski et al. (2010) calculated the EROI for 119 wind turbines, reviewing 50 different analyses from 1977 to 2007. They extended the work previously done by Lenzen and Munksgaard (2002) distinguishing between important assumptions about system boundaries and methodological approaches and viewing the EROI as function of power rating.

Table 15: Wind turbines EROI

		Wind turbines EROI
1977*	USA	43.5
1980*	UK	12.5
1980*	UK	6.1
1981*	USA	1
1983*	Germany	2.3
1983*	Germany	3.4
1983*	Germany	5
1983*	Germany	8.3
1983*	Germany	1.3
1990*	Denmark	71.4
1990*	Denmark	47.6
1990*	Germany	32.3
1991*	Germany	18.9
1991*	Germany	32.3
1991*	Germany	27
1991*	Germany	22.2
1991*	Germany	11.8
1991*	Germany	20.4
1991*	Germany	14.7
1991*	Germany	19.6

		Wind turbines EROI
1991*	Germany	16.7
1991*	Germany	20.4
1991*	Germany	27
1991*	Germany	18.9
1991*	Germany	15.6
1991*	Germany	20.8
1991*	Germany	15.4
1991*	Japan	4
1992*	Germany	11.2
1992*	Germany	37
1992*	Japan	2.9
1992*	Japan	30.3
1992*	Japan	18.5
1993*	Germany	21.7
1994*	Germany	45.5
1994*	Germany	14.7
1995*	UK	23.8
1996*	Switzerland	3.1
1996*	Switzerland	5
1996*	Japan	2.3
1996*	Japan	2.2
1996*	Japan	5.8
1996*	Japan	8.5
1996*	Japan	11.4
1996*	Germany	8.3
1996*	Germany	28.6
1997*	Denmark	8.3
1997*	Denmark	8.1
1997*	Denmark	10

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		Wind turbines EROI
1997*	Denmark	15.2
1997*	Denmark	27
1997*	Denmark	33.3
1997*	Denmark	50
1998*	Argentina	5.9
1998*	Argentina	8.3
1998*	Germany	12.5
1998*	Germany	23.8
1998*	Germany	15.4
1998*	Germany	21.7
1998*	Germany	14.1
1999*	Germany	26.3
1999*	India	31.3
1999**	USA	23
1999**	USA	17
1999**	USA	39
2000*	Denmark	51.3
2000*	Denmark	76.9
2000***	Italy	7.7
2000*	Belgium	30.3
2000*	Belgium	27.8
2001*	Japan	6.3
2001*	Brazil	14.5
2002†	USA	80
2003††	Canada	123.5
2003††	Canada	125.8
2003††	Canada	109.6
2004†††	Germany	8.4
2004†††	Germany	7.8

		Wind turbines EROI
2004†††	Germany	6.2
2004†††	Germany	4.7
2004†††	Germany	4.9
2004†††	Germany and Brazil	22.5
2004†††	Germany and Brazil	21.2
2004†††	Germany and Brazil	16.4
2004†††	Germany and Brazil	12
2004†††	Germany and Brazil	12.4
2004†††	Germany and Brazil	27.7
2004†††	Germany and Brazil	25.7
2004†††	Germany and Brazil	20
2004†††	Germany and Brazil	15.6
2004†††	Germany and Brazil	16.4
2004†††	Brazil	32.7
2004†††	Brazil	30
2004†††	Brazil	24
2004†††	Brazil	18.9
2004†††	Brazil	18.9
2004†††	Brazil	40
2004†††	Brazil	40
2004†††	Brazil	32.7
2004†††	Brazil	25.7
2004†††	Brazil	25.7
2004‡	Germany	14.8
2004‡‡	Germany	70
2004‡‡	Germany	53
2004‡‡	Germany	38
2004‡‡	Germany	64
2004‡‡	Germany	50

		Wind turbines EROI
2004‡‡	Germany	39
2006‡‡‡	Italy	19.2
2006^	Germany	30
2006^	Germany	32.7
2006^	Germany	29.4
2006^	Germany	32.3
	Mean	25.20353982
	DEV ST	22.72011353

*Lenzen et al. 2004, **White S.W. et al. 1998, ***Brown et al., 2002, †Gagnon et al. 2002,†† Khan Fi et al, 2005,†††Lenzen et al., 2004,‡Tryfonidou R., 2004,‡‡ Wagner et al. 2004, ‡‡‡ Ardente et al. 2008, ^Pehnt et al. 2006.

Concerning the system boundaries, they included in the life cycle of wind turbines the manufacture of components, the transportation of components to the construction site, the construction of the facility itself, the operation and maintenance over the lifetime of the facility, overheads, possible grid connection costs, decommissioning, and recycling of component materials. External costs were excluded from the analysis (Kubiszewski et al., 2010). The average EROI found in this study for all systems studied is 25.2 (std. dev.= 22.3) and the one for all operational studies is 18.1:1 (std.dev = 13.7). Figure 29-30 below shows the EROI values for wind turbines as a function of time from 1975 to 2010.

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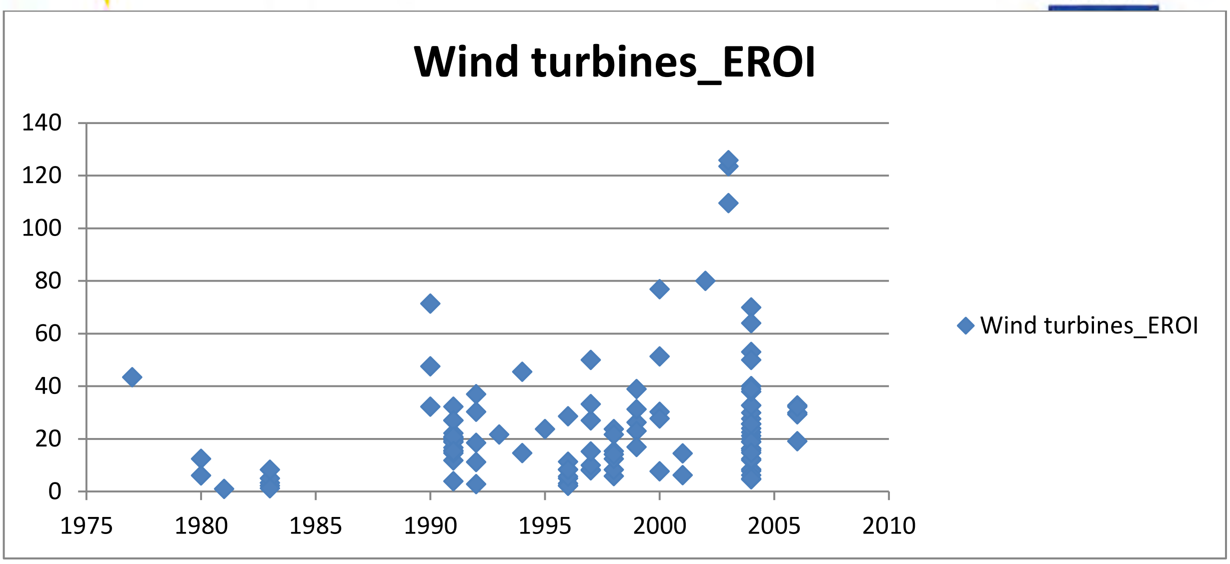

Figure 15: Wind EROI values as a function of time from 1975 to 2010

The trend described from this analysis is exponential, the EROI for wind turbines tends to grow during time.

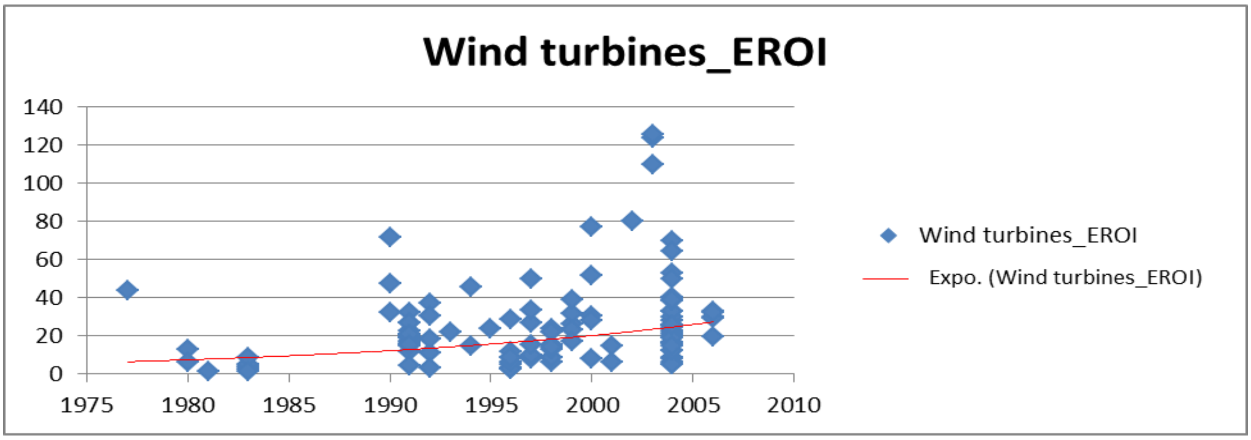

Figure 16: Exponential curve are used to describe the EROI trend for wind turbines as a function of time

The authors found that the EROI tends to grow with the size of the turbine. There are three main reasons for this. First of all, the smaller turbines have older designs and can be less efficient. Second, larger turbines have a greater rotor diameter so they can work at lower wind speeds and capture more wind energy at higher efficiencies all year round. Finally, because of their size, larger models are taller and can take advantage of the higher wind speeds farther above ground.

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5.4 EROI for Geothermal energy

Geothermal energy is the thermal energy generated and stored in the Earth that is used to do work by transferring the heat to a gas or a liquid. Geothermal capacity can be exploited to produce electricity or heat for commercial and residential buildings.

In many countries of the world, geothermal energy has been already chosen as a valuable and sustainable alternative to fossil fuels in order to reduce global warming. For instance, in 2013 the geothermal world power was 11,700 MW with another 11,700 MW planned (Geothermal Energy Association, 2013).

These geothermal facilities produced about 68 million kWh of electricity that are enough to supply 6 million of US-households. The geothermal plants account for more than 25 percent of electricity produced in both Iceland and El Salvador (U.S. EIA, 2012).

The best sites used to produce geothermal energy are close to the plate boundaries and are not available everywhere. Currently only hydrothermal resources are being utilized for commercial energy, where heat is transferred to groundwater at drillable depths. The Hot Dry Rock (HDR) technology plans to exploit heat at greater depths where there is no groundwater available, but it is a technology still in the development stage (Grupta and Hall, 2011).

The EROI for electricity generation from hydrothermal resources has been reported in table 18 with a range of 2.0-13.0:1. Corrected for quality as an electricity source, the EROI values are approximately 6-39.1. The large ranges are attributed to a lack of a standard method for EROI evaluation[3].

Table 16: Geothermal Power EROI.

		Geothermal EROI		
Reference	data year	Thermal only	Quality-	Plant type
Gilliland 1975	1975	3.6	12.6	dry steam
	1975	3.1	10.7	flash steam

[3] http://www.theoildrum.com/node/3949

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Herendeen and Plant 1981	1979	13	39	dry steam
	1979	4.4	13.2	flash steam
	1979	2.7	8.1	HDR-binary
	1979	3.4	10.2	HDR-binary
	1979	3.9	11.7	HDR-binary
	1979	1.9	5.7	HDR-binary
	1979	13	39	HDR-binary
Halloran 2007	1983	3.1	9	HDR-binary
	2007	7.8	23	HDR
	2007	6.6	20	HDR
	1981	2.1	6	dry stream
	1991	5.9	18	dry stream
Icerman	1980	1.8	5.5	dry stream

The trend of geothermal EROI as a function of the years is shown in Figure 32 (Thermal only) and in Figure 33 (Quality-corrected). Exponential curve is used to simulate the two trends.

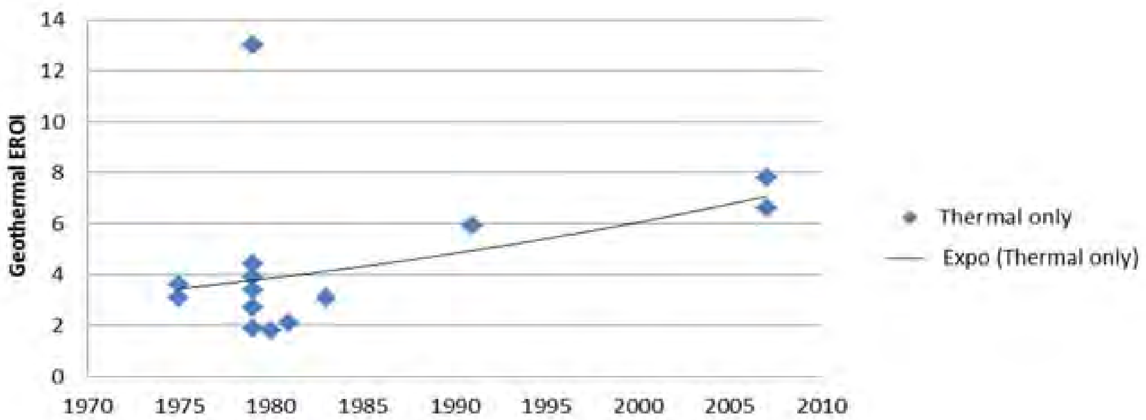

Figure 17: Geothermal EROI (considering that geothermal energy is used exclusively for thermal supply)

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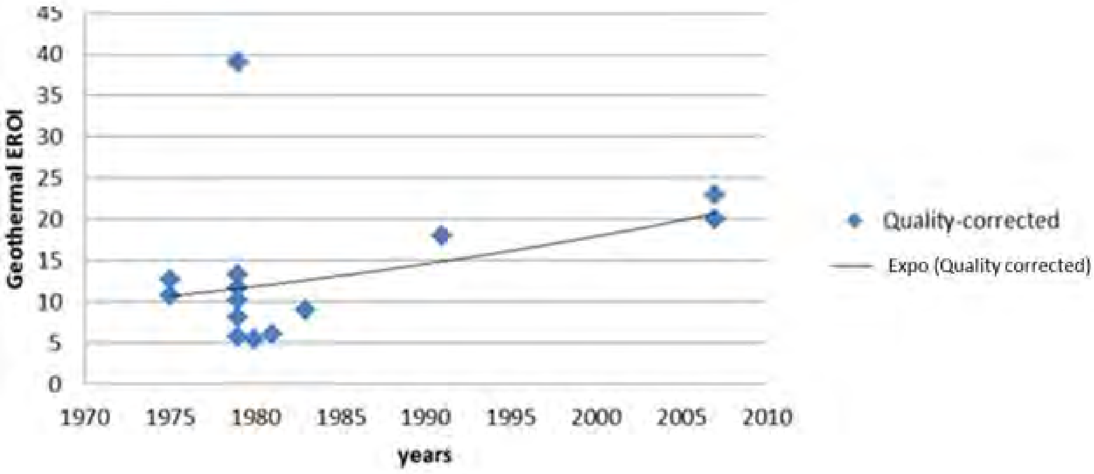

Figure 18: Geothermal EROI (corrected)

Geothermal electricity production has a mean EROI of approximately 9:1 (n of 30 from 11 publications) (Lambert et al., 2012).

5.5 EROI for Wave/Tidal

Wave energy is the power of the sea waves generated by wind that can be converted into mechanical energy for the production of electricity. The power obtained from waves depends on the speed, fetch and duration of the wind that created the waves. In the literature, the information available in this field is limited in terms of net energy and life cycle assessment.

The world's first wave energy plant, called the Aguacadoura Wave farm, is located 5km offshore near Póvoa de Varzim, north of Porto, in Portugal. This plant is designed to use three Pelamis Wave Energy Converters developed by the Scottish firm Ocean Power Delivery to convert the motion of the ocean surface waves into electricity, with a grid-connected capacity of 2.25 MW (Halloran, 2008b). There is few information about net energy or life cycle assessment of wave energy plant. Banjeree et al., (2006)report the life cycle emissions of 21.67gr CO_2 per KWh and EPBT of about 1 year for Pelamis off-shore device. Considering an expected lifetime of 15 years per device, the EROI could be nearly 15:1. It is difficult to deduce how this value varies including maintenance and other costs.

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5.6 Biofuels and biomass

Biofuels exist mainly in two forms, first bioethanol, obtained by the distillation of ethanol obtained by means of conventional fermentation process. The other form is "biodiesel" obtained from the esterification of triglicerids, commonly termed "vegetable oils". The EROI of biofuels has been studied in detail by Giampietro and Mayumi in their book "The Biofuel Delusion" (2009). Basically both bioethanol and biodiesel have relatively low EROIs. Bioethanol may have an EROI only marginally larger than one, whereas biodiesel may have an EROI between 3 and 5. Considering the large extent of land needed for the cultivation of the needed crops, biofuels cannot be considered as a large scale energy source, but only as an expensive fuel for whenever it is strictly necessary to keep internal combustion engines running.

Much has been said about the possibility of a new kind of biofuel, the so called "cellulose bio-fuel" that could be obtained from the digestion of cellulose scraps.

This biofuel would not be in competition with the biofuels derived from food stock, but there are no reports of it being commercialized, so far.

The case of biomass for the production of electricity is different. Wood biomass can be burned as such in order to generate energy from a conventional heat engine, or organic biomass (often derived from urban or agricultural waste) can be transformed into biogas that can be used to feed a turbine or a reciprocating engine. Other forms of biomass exploitation are possible, for instance transformed into charcoal that can then be burned. The EROI of these systems depends on the geographical characteristics of the region where it is implemented. If biomass (or its products) can be burned in-situ, the EROI can be reasonably good, but if biomass has to be transported over long distances, then the values can plummet to unacceptable values. A case study for energy production from biomass obtained briquettes in Moldova reports values of the EROI as 12-13 (Kolarikova et al, 2014). Another "on farm" study reports EROI values of about 8 (Preston and Rodríguez, 2009). Bioenergy from urban waste is also reported to have a relatively good EROI, from 5 to 15 (Shupel Ibrahim, 2012). Overall, the EROI of electrical bioenergy production from biomass is much better than that of biofuels and

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this kind of energy technology is often considered as a useful backup system to account for the intermittent nature of other renewable technology. It must also be noted, however, that the ultimate potential of this kind of technology is limited owing to the limited amount of biomass that can be harvested from a given territory.

In conclusion, the EROI for the most important fuels, oil and gas, has declined over the past one or two decades. Since these fuels provide roughly 60-65% of the world's energy, this will likely have enormous economic consequences for all economic sectors. The major challenge will be to replace fossil fuels with renewable sources whose EROI is becoming more competitive thanks to the improvements in the technology.

Summary table of EROI for the different RES are shown below.

Table 17: Summary tables for the different RES

Reference	Hydropower EROI
Lambert et al., 2012	84:1

	harm_EROI	std.dev.
mono-Si	8.73	3.47
poly-Si	11.62	5.21
a-Si	14.44	5.08
CdTE	34.18	13.49
CIGS	19.92	8.19

Reference	Wind EROI (total	Wind EROI (just
Kubiszewski et al, 2010	25.2 ±22.3	18.1±13.7

Reference	Geothermal EROI

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Lambert et al., 2012	9:1

Reference	Wave/Tidal EROI
Banjaree et al., 2006	15

Reference	Biofuels EROI
Giampiero et Mayumi, 2009	3-5

Reference	Biomass EROI
Kolarikova et al, 2014	12-13
Preston and Rodríguez, 2009	8
Shupel Ibrahim, 2012	5-15

6. Results and conclusions

World proven reserves of fossil fuels all together are estimated by BGR to be 39,910 EJ, which is a modest estimation. Sorrell et al. (2009) argue that estimations of Peak Oil further than to year 2030 are based on unrealistic assumptions. The argumentation is based on development of the new resources in the North Sea, which are compared to the estimations of resources that are yet to be found.

The amount of estimated reserves in an indicator of a great importance, especially for the future projections. Reserves are an ultimate biophysical constraint for fossil fuel use. Due to a lack of standartised measurement there are different estimations of ultimately recoverable reserves and the estimates differ significantly from 2000 to 4300 Gb for conventional oil resources (Sorrell, 2009). In the same study we can find USGS estimations of global conventional URR of 3345 Gb, which we might see as rather optimistic, but still relevant source. However, we see the estimate by a relatively recent

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study by McGlade and Ekins (2015) for remaining ultimately recoverable resources (RURR) of conventional oil at 2615 Gb to be more likely. Future development of oil production depends on development of unconventional oil reserves.

The distribution of the resources is geographically uneven. Nearly half (47,7%) of the proven reserves are located in one region, 15,7% in Saudi Arabia alone (BP, 2015). The localisation is hardly to express in variables for the global level of analysis. Unconventional oil might be overrated for future oil production when the EROI of the resource is not considered.

The probably best estimates for global reserves and resources are provided by McGlade and Ekins (2015), who estimate a global RURR for unconventional oil of 2455 Gb. This is almost as large as the RURR for conventional oil.

Natural gas estimates follow the dynamics of oil. Also for gas we can talk about highly uneven distribution of reserves, while these are located in similar regions as oil.

The ultimate constraint of natural gas is expressed in remaining ultimately recoverable resources (RURR). As in the case of oil we can see that estimations by IEA are rather optimistic at 806 Tcm, while we tend to the more conservative estimation by Mc Glade& Ekins (2015) of 375 Tcm for conventional gas and 300 Tcm for unconventional gas.

For a global level of coal reserves, there is no really comprehensive data source available. Coal reserves are located in more countries then oil and gas. To identify the correct estimation of reserves we stick to rather conservative Best Guess Scenario of Mohr and Evans (2009). They identify URR of all types of coal to 1143,7 Gt of coal.

EROI

The EROI is a key measure to highlight the efficiency of energy sources. Gagnon et al. (2009) provided the most respectable estimation for global oil and gas EROIs. The source indicates a steadily decline from the year 1999 (35:1) to 2006 (18:1). Hall et al. (2009) provided estimations for a minimal EROI for basic functions of society to be 3:1, which, according to them will allow for conventional oil and gas till 2030 at the current rate of production. This estimation complements the qualitative dimension of estimated Peak-Oil.

Unconventional resources such as tar sands, oil shale and tight oil appears to have different EROI for every locality. The EROI of unconventional oil and gas is significantly lower (4:1 to 7:1) (Hall et al. 2014), which is of great importance concerning the changing character of reserves. Despite of the enormous deposits, the extraction rate is limited by environmental and other constraints.

The EROI at a global level for coal is estimated to be 46:1 (Hall et al. 2014), which is significantly higher than the EROI of oil and gas. However this estimation is very rough based on calculations only from China and US, which are the only countries with available data.

Hydropower as a most important renewable source has very site-specific EROI varying from 11,2:1 to 267:1. Lambert et al. (2012) provided estimation of average EROI of 84:1, deducted from different studies.

Unlike EROI of fossil fuels photovoltaic EROI has a tendency to grow, especially high values have been identified by CdTE (45:1 in year 2013) and CIGS (near 30:1 in the year 2013) technologies. However the most diffuse photovoltaic technology based on silicon appears to have EROI between 8-12:1 (Bhandari et al. 2015).

Energy generation from wind tends to have a greater EROI during time. EROI found by Kubiszewski et al. 2010 for all operational studies is 18,1:1.

Geothermal energy resources EROI vary from 6 to 39:1 due to lack of standardization. (Halloran, 2008a)

Tidal EROI is to be estimated to 15:1, however there are very limited data of wave

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energy plants. (Hallorann, 2008b)

Biofuels cannot be considered as a large scale energy source, when we consider large extent of land needed for the cultivation of the needed crops. EROI of biofuels is relatively small: bioethanol with slightly more than 1:1, while biodiesel between 3 and 5:1. A higher EROI can be found by biomass in particular case studies – 12-13:1 (Kolarikova et al. 2014)

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D2.1: *Report with an analysis of the main limitations of variables and indicators selected to represent the pathways and scenarios.*

Annex 4: *Biofuels deployment and physical constraints.*

Grant agreement: 691287

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1. Scope and goal

This document is part of MEDEAS Deliverable 2.1. The main aim of this report is to explain in detail the physical constraints expected for the mass deployment of biofuels in the transport sector until 2050 through an analysis of the main challenges that have to be tackled.

This activity is implemented through a literature review on several issues that have arisen in the last 15 years linked to the criticism towards the promotion of biofuels as an alternative transport fuel. The literature review conducted here attempts to summarize a number of interesting methodologies that have been developed to assess the impact of biofuels in various socioeconomic and environmental domains.

The results of this Deliverable will be implemented in MEDEAS model through PAVs database values. For this reason, the following table shows the information covered in this document and its link to the PAV list specified in Deliverable 2.

Table 1. PAVs related to biofuels and covered in this Annex.

D2.1 Results	PAV	PAV description
Evolution of world biofuels production in the period 1995-2013	97	Biofuels production
Evolution of world biofuels consumption for transport in the period 1995-2013	69	Biofuel share in transport fuels
Biofuel share in transport consumption in 2050	69	Biofuel share in transport fuels
Biofuels consumption in road transport (2011, 2035)	69	Biofuel share in transport fuels
World use of crops for biofuels (2005, 2030, 2050)	97	Biofuels production
Average crop prices for biofuels production (2024)	97	Biofuels production
Biofuel use ratio for agricultural commodity demand/production (2004-2013)	97	Biofuels production
Corn ethanol GHG produced or absorbed	68	GHG evolution of light duty vehicles

2. Introduction

Biofuels have been steadily penetrating the global energy market for the past 15 years as this has been envisaged by the respective policies for reducing dependency on oil and in parallel decarbonizing the highly energy intensive transport sector.

Biofuels for transport have been commercially produced since the mid-1970s, mainly for managing the surpluses of agricultural production and waste and reinforcing rural development. Nevertheless, the latest energy and climate challenges have shifted the importance of biofuels from rural development to securing energy supply and decarbonizing the economy and in this context acted as a much more powerful policy tool to accelerate biofuels deployment. The most common policy instrument implemented has been a mandate for blending a specific quantity of biofuels with the respective transport fuel. Such policies have boosted the utilization of biofuels in the transport sector, covering around 3% of the global road transport fuels in 2010 (IEA, 2011). Figure 1 shows the evolution of global biofuel production, as well as the evolution of those biofuels used in the transport sector. Despite the evident increase in biofuels production and use of the last years, various claims of land use changes, deforestation and food insecurity have thereafter undermined the sustainability rationale that was the original motivation for the adoption of biofuels as an alternative transport fuel (Tomei & Helliwell, 2016).

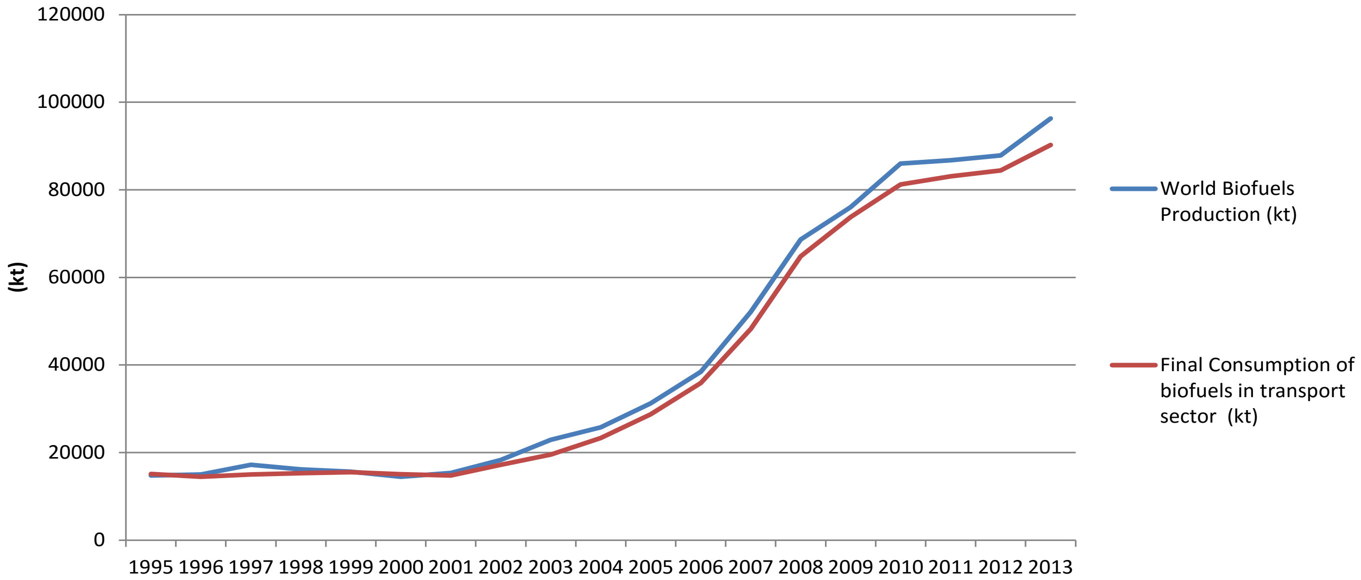

Figure 1: Evolution of world biofuels production and consumption for transport in the period 1995-2013 (source of data: IEA).

In terms of **categorization**, biofuels are usually distinguished in first, second and third generation biofuels, while the IEA categorizes them according to their maturity into conventional (coinciding with first generation) and advanced biofuels. The conventional or first generation biofuels come from well-established production processes and are therefore commercially mature. The feedstocks used for their production vary from corn, sugarcane, sugarcane molasses, wheat, and other crops (used for the production of bioethanol) as well as rapeseed oil, soybean oil and animal fats and cooked oils (used for the production of biodiesel). Although conventional biofuels are commercially mature, there is still a high potential for cost-efficiency optimization. As regards the advanced or second and third generation biofuels, they are produced from non-edible and/or lingo-cellulosic biomass, hydrotreated vegetable oil, or even algae (mainly referred to as the third generation ones) and are mainly still in their demonstration phase.

The **benefits** of increasing the share of biofuels in transport expand to various fields with direct and indirect socioeconomic and environmental implications.

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One of the most important advantages in the deployment of biofuels relates to sustainability and security of energy supply for transport by reducing transport sector's dependency on fossil fuels. At the moment, fossil fuels and, in specific, oil products (gasoline, diesel oil, etc.) dominate the transport sector and therefore make it sensitive both to oil price fluctuations as well as geopolitical disputes. The increase of biofuels share can play a significant role ensuring energy security and at the same time reducing oil price volatility. Moreover, it is associated to economic development of rural areas with high biomass and feedstock potential, whereas it constitutes a key element for utilizing wastes and contributing to the establishment of a circular economy. A larger deployment of biofuels for transport would not signify any substantial changes to vehicle stocks, nor to distribution infrastructure.

In terms of **projections** for the future deployment of biofuels, IEA's ETP 2010 BLUE Map Scenario foresees that sustainable biofuels will be able to provide 27% of transport consumption by 2050 and will contribute by 23% to overall transport GHG emissions reduction (IEA, 2011). More specifically, OECD countries will have the highest biofuel consumption in the first years of the projected period to 2050, with non-OECD countries (esp. China, India and Latin America) depicting a boost of biofuels consumption accounting for almost 70% of total global biofuel demand in 2050 (IEA). In Non-OECD countries conventional biofuels will be dominating the markets because of lower costs and complexity than advanced biofuels. Based on the IEA's ETP 2010 BLUE Map Scenario biofuel demand will be 32 EJ (or 760 Mtoe) in 2050 (Figure 1).

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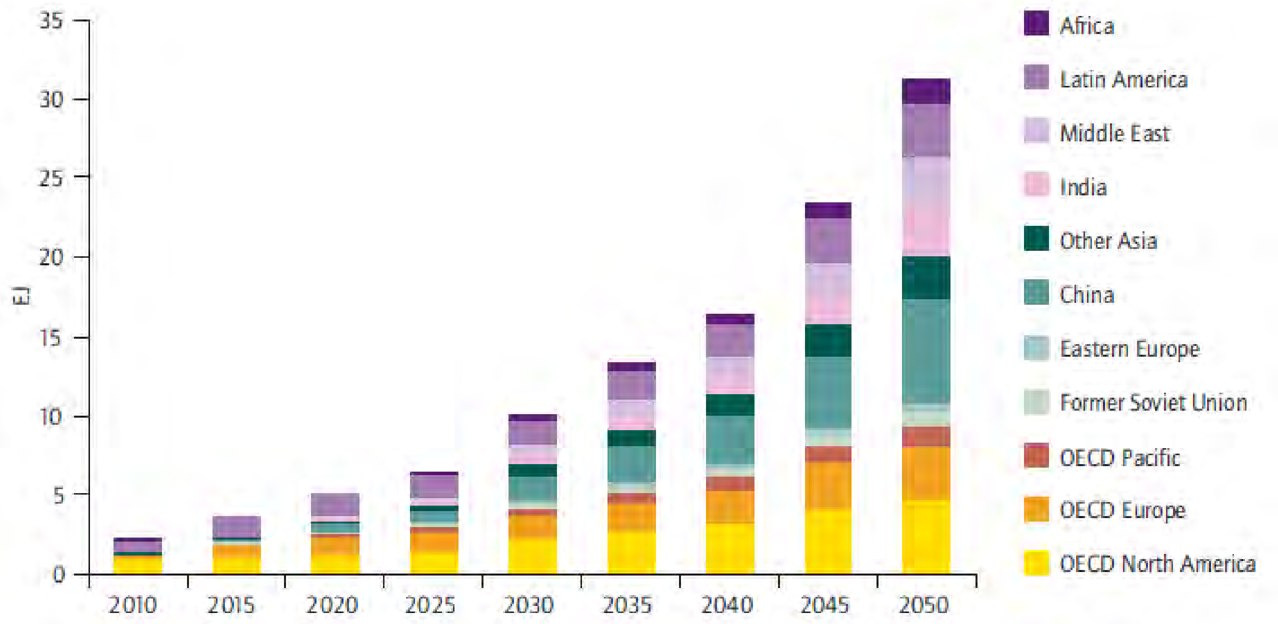

Figure 2. Biofuel demand by region in the period 2010 – 2050 according to IEA's ETP 2010 BLUE Map Scenario (IEA, 2011).

As depicted in Table 2, according to the New Policies Scenario of the World Energy Outlook 2013 the world demand for biofuels increases from 1.3 mboe/d in 2011 to 4.1 mboe/d in 2035. Correspondingly their share in road transport energy consumption rises from 3% to 8% (IEA, 2013).

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Table 2. Biofuels consumption in road transport according to the New Policies Scenario of the World Energy Outlook 2013 (mboe/d) (IEA, 2013).

	Ethanol		**Biodiesel**		**Biofuels total**		**Shares of road transport energy use**	
	2011	**2035**	**2011**	**2035**	**2011**	**2035**	**2011**	**2035**
OECD	**0.7**	**1.5**	**0.2**	**0.8**	**0.9**	**2.3**	**4%**	**12%**
Americas	0.6	1.3	0.1	0.3	0.7	1.6	4%	13%
United States	0.6	1.2	0.1	0.3	0.7	1.5	5%	15%
Europe	0	0.2	0.2	0.5	0.2	0.7	4%	12%
Non-OECD	**0.3**	**1.4**	**0.1**	**0.4**	**0.4**	**1.8**	**2%**	**5%**
E. Europe/Eurasia	**0**	**0**	**0**	**0**	**0**	**0**	**0%**	**2%**
Asia	**0**	**0.7**	**0**	**0.1**	**0.1**	**0.8**	**1%**	**4%**
China	0	0.4	0	0	0	0.4	1%	4%
India	0	0.2	0	0	0	0.2	0%	4%
Latin America	**0.3**	**0.8**	**0.1**	**0.2**	**0.4**	**1**	**10%**	**20%**
Brazil	0.2	0.6	0	0.2	0.3	0.8	19%	30%
World	**1**	**2.9**	**0.4**	**1.1**	**1.3**	**4.1**	**3%**	**8%**
European Union	**0**	**0.2**	**0.2**	**0.5**	**0.2**	**0.7**	**5%**	**15%**

Biofuels will play an important role in the future, as efforts are carried out to penetrate air transport and all other heavy-duty modes that cannot be electrified. Moreover, the transition to 3rd generation biofuels will be quite promising, although challenging. Algae is characterized by high productivity per hectare, whereas it can be grown on non-arable land and by means of different water sources, varying from fresh water to saline and wastewater (IEA, 2011).

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In order to exploit the full potential of biofuels in the future there are many barriers that need to be overcome, including the commercialization process of advanced biofuels and the establishment of an appropriate market structure and the elimination of controversies such as food security, management of natural resources (land, water and emissions) and social conditions, especially those of local communities.

3. Food security

The debate on food versus fuel has been one of the earliest controversies to oppose the deployment of biofuels. Land and biomass resources are an extremely decisive factor for the mass deployment and commercialization of biofuels, which inevitably leads to an increase of the respective feedstock demand. The major challenge, in this respect, is to be able to cover this demand without putting at risk food security, biodiversity and access to arable land.

Initially biofuels have been promoted as a tool for agricultural development that would support farmer's income, help to improve farm gate prices, encourage farmer education and technology transfer and would therefore increase the productivity and competitiveness of the whole sector. Nevertheless, this biofuels contribution to the agricultural sector has been vividly argued, and one of the most disputed aspects has been their impact on food production and availability (Tomei & Helliwell, 2016).

Many studies have been carried out to examine how biofuel can impact agricultural commodity markets, energy's role in the food price determination process, and how the current energy policies in the OECD countries carry the risk of generating food insecurity in low-income countries.

As mentioned earlier, a large part of the biofuels production is currently driven by mandates and subsidies implemented by the major biofuels production countries. However, according to FAO (Alexandratos & Bruinsma, 2012), if the conditions change and fossil fuel prices (especially oil prices) exhibit a dramatic increase in the future, biofuels may become competitive without support policies. Moreover, FAO controvert

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the possibility of biofuels expanding only into land not suitable for cultivating crops when we are talking of an environment of laissez-faire markets.

The main speculation expressed is that considering the relative importance of the energy markets compared to food markets, as well as the relative economic power of the consumers demanding more energy compared to the ones demanding more food, the increasing production of biofuels could eventually lead to increase of food prices and subsequently to imperiling access to food by vulnerable consumers. Nevertheless, it is recognized that if biofuels expand in a relatively prudential way, biofuels could form a significant driver for economic development in countries with rich resource potential for the production of biofuel feedstocks. According to their projection (see Table 4) approximately 180 million tons of cereals (mostly maize) will be used in 2050 for the production of biofuels riding from 61 million tons in the base year (average 2005/2007) (Alexandratos & Bruinsma, 2012).

Table 3. World use of crops for biofuels (Alexandratos & Bruinsma, 2012)[1].

FAO, 2012	**2005**	**2030**	**2050**
Cereals (million tonnes)	65	182	182
Cereals (percent of total use)	3.2	6.7	6.1
Veg. oils (million tonnes)	7	29	29
Veg. oils (percent of total use)	4.8	12.6	10.3
Sugar (equiv. of sugar cane) (million tonnes)	28	81	81
Sugar (percent of total use)	15.1	27.4	24.3
Cassava (fresh) (million tonnes)	1	8	8
Cassava (percent of total use)	0.4	2.3	1.8

[1] The projections presented in this study refer to a baseline scenario which is not meant to address explicitly biofuels

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In their study (Enciso, Fellmann, Dominguez, & Santini, 2016) also claim that the implemented policies for biofuels support are somewhat responsible for both high prices and increased price variability in agricultural markets.

They quantitatively assess the potential future impact of biofuel policies on agricultural price levels and price variability as well as global food security, by means of the partial stochastic analysis Aglink-Cosimo model[2]. They analyze two scenarios, the Reference one (REF) and the "No biofuel policy" one (NBP), which assumes that all biofuel policies are removed in the top five biofuels consuming regions for the examined period 2015-2024 (EU, US, Indonesia, Brazil and Argentina for biodiesel and US, Brazil, EU, China and India for ethanol). The results indicate that world agricultural commodity prices are indeed affected by biofuel policies, with higher price levels in the reference scenario compared to the NBP scenario, as seen in the following figure.

Table 4. Average crop prices for 2024 in the two scenarios studied by (Enciso, Fellmann, Dominguez, & Santini, 2016).

Commodity	**Reference scenario (USD/tonne)**	**NBP scenario (USD/tonne)**	**Change (%)**
Coarse Grains	194	182	-0.1%
Wheat	272	262	-3.5%
Oilseeds	460	446	-2.9%
Protein Meals	411	417	1.4%
Vegetable Oils	839	772	-8.1%
Sugar	364	353	-2.9%

[2] Aglink–Cosimo global economic model has been developed by the OECD and FAO Secretariats, with the aim of projecting the medium-term agricultural market conditions in all the main agricultural traded commodities by integrating the expertise of national agencies and market experts.

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However, as Enciso et al. (2016) claim, it would be more meaningful to examine the change in domestic commodity prices instead of global prices, when discussing food security and food access in general. The following illustration (Figure 2) depicts this change on prices for major crops in world regions caused by the abolishment of biofuel policies.

The impact of abolishing biofuel policies on commodity prices varies significantly from region to region. The most affected region is the EU, where biofuel policies strongly link the consumption of biofuel to fossil fuel use, through the mandate in place.

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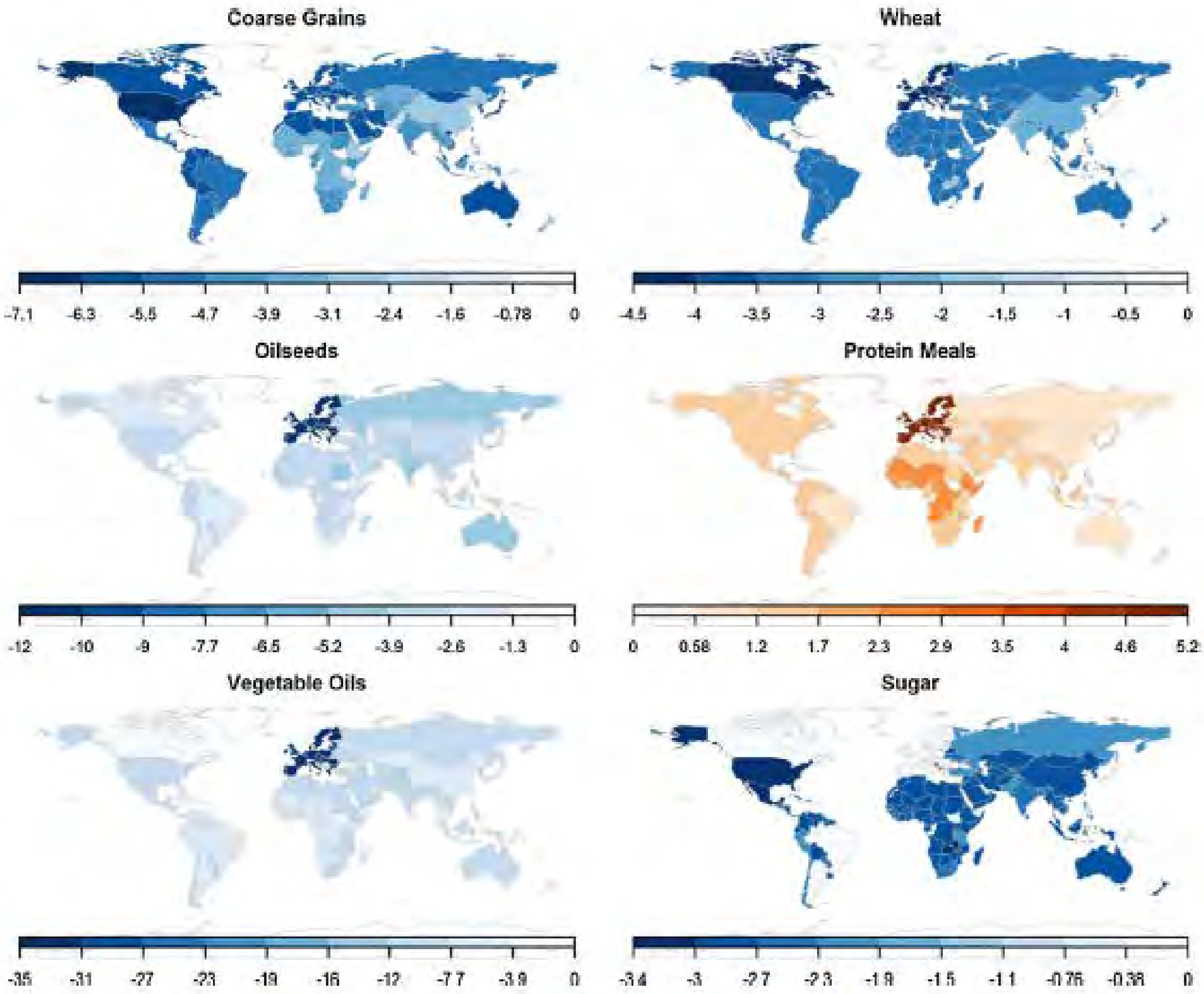

Figure 3. Percentage change in domestic agricultural prices (in local currency) in 2024 after the abolishment of biofuels policies (Enciso, Fellmann, Dominguez, & Santini, 2016).

What can be concluded, based on the aforementioned analysis, is that the reduction of commodity prices, through a presumed abolishment of biofuel policies, would also reduce the feedstock quantities required for the production of biofuels. Considering the above, it would lead to more affordable food for the population and subsequently an increase of food security.

However, given the fact that these commodities are not only used for food, but have other uses as well (e.g. feed or industrial use), the Enciso et al. (2016) NBP scenario has only led to marginal increases of food use.

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Koizumi (2015) also claims that the increase in biofuel production will inevitably have an impact on world agricultural commodity prices and food security. Figure 4 illustrates in a flow diagram, how the increase in biofuels demand and production can lead to a threat on food security.

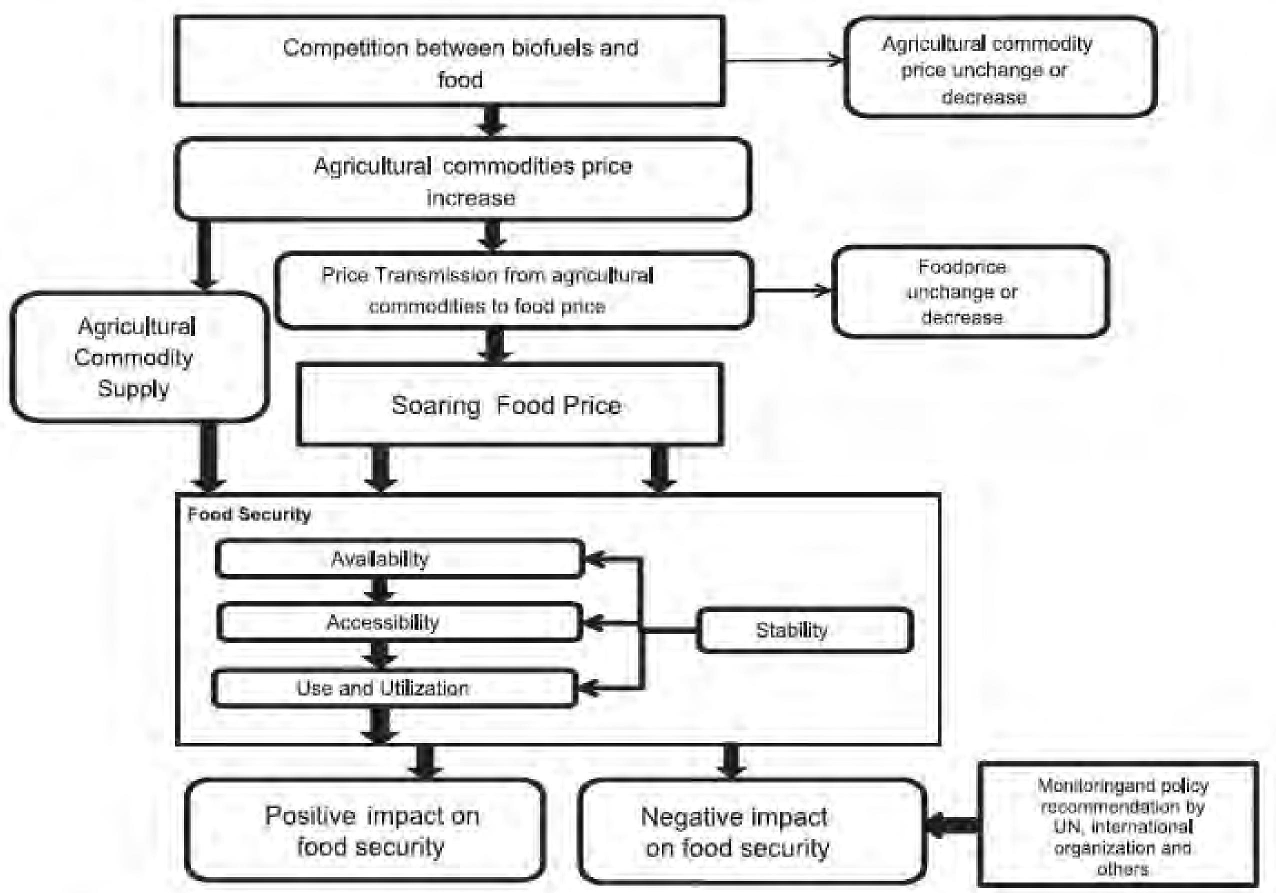

Figure 4. The relationship between biofuels and food security (Koizumi, 2015).

Table 5 shows the evolution of agricultural commodity shares used for biofuels production. It is clear that the total share of agricultural commodities used for the production of biofuels by 2013 was five times higher than only ten years ago, with the greatest shares observed for rapeseed oil, sugarcane, soybean oil and corn.

Table 5. Biofuel use ratio for agricultural commodity demand/production (Koizumi, 2015).

	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Sugarcane (%)	13.6	14.6	14.3	16.8	19.6	21	20.5	16.6	16.5	18.4
Corn (%)	5	5.6	8	10.6	12.7	15.2	16	15.8	15	15.3
Rapeseed oil (%)	0	0	21.1	23.2	29.7	27.9	29.3	27.7	25.8	22.4
Soybean oil (%)	–	4.8	6.1	8.3	10.1	12.2	14.3	18.1	16.8	15.5
Palm oil (%)	0	0	1.8	2.7	4.7	3.7	4.9	7.2	8.7	10.3
Coconut oil (%)	0	0	0.1	1.4	2	3.5	3.4	3.8	3.7	5.4
Sugar beet (%)	0	0	1.2	2.1	4.6	4	4.7	3.7	4.3	4.3
Cassava (%)	0	0	0.1	0.1	0.2	0.4	0.5	0.6	0.9	1
Wheat (%)	0	0	0.5	0.6	0.6	0.8	1	1	0.9	0.7

In his work, Koizumi performs an economic analysis for estimating the degree at which food security is affected by the increasing production of biofuels. In his analysis, he points out that biofuel production may have either a negative impact on food security, by contributing in the increase of feedstock and food price or it can create opportunities for the development of agricultural sector. The feedstock price elasticity is a key – although not the only - factor to determine how the increase in biofuel production will impact the agricultural sector and food security.

As an example, Koizumi investigates the case of sugarcane in Brazil. Due to the increasing demand for bioethanol production, a respective increase in sugarcane area harvested has occurred, which in turn contributed to an increase in its production.

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According to Koizumi, Brazilian sugarcane is elastic to price change, which means that it is actually quite efficient at responding to price changes with rapidly increasing its supply. Moreover, although sugar is considered as food in a large part of the world, it is not considered staple food and therefore cannot have a tremendously negative impact on food security. In Brazil, the national bioethanol program, has not only contributed to an abrupt increase of sugarcane production to meet the corresponding demand for bioethanol production, but it has been also deemed responsible for the creation of approximately one million direct jobs since 1975 when it was first launched. On the other hand, palm oil in Indonesia and Malaysia as well as corn in China, indicated that they lack the required price elasticity, to attain the price stability desired for ensuring food security in these countries.

4. Land use and GHG emissions

Although food security is a critical parameter for the socioeconomic acceptance of biofuels, the most controversial debate in the past years has been related to the consequences of land use and land use change as well as the associated release of GHG emissions.

The following figure (Figure 5) illustrates the sectors which are competed by the biofuels production, as depicted in the analysis of Koizumi. As elaborated previously, biofuels compete with food and food-related commodities, meaning that the same feedstock is used for both and affects the respective prices and food access. Analogously, it is important to apprehend the fact that biofuels also compete with the necessary natural and agricultural resources, such as land, water, fertilizer, etc.

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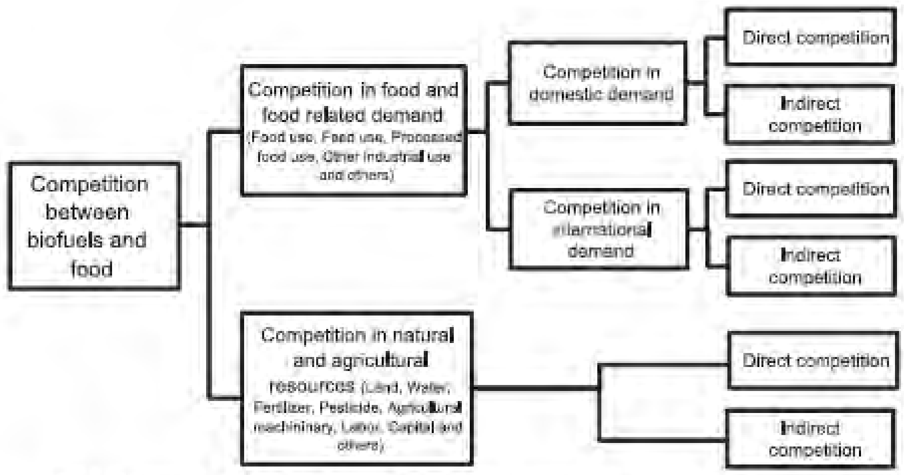

Figure 5. The concept of competition between biofuels and food data source (Koizumi, 2015).

Land use change, which can be also considered as an indirect impact on food security, occurs when the increasing demand for biofuel feedstock imposes a direct change of the primary use of a land (e.g. deforestation), or, alternatively, forces their cultivation on existing agricultural land, causing the dislocation of food (or feed) production to non-agricultural land such as forests. That way food production becomes in turn responsible for the land use change. Since forests act as an absorber of CO_2 from the atmosphere, removing them for biofuel production may actually result in increasing the total GHG emissions instead of decreasing them.

In this context, the land use changes occurred by the increase in biofuel production and demand have caused a long debate on the environmental impact and in specific the associated GHG emitted. It is considered imperative to take into account both GHG emissions and land use change, when assessing the environmental balance of biofuels.

The EU has already set rigorous sustainability criteria for biofuels, in order to promote biofuels that are able to reduce greenhouse gas emissions without adversely affecting the environment or social sustainability.

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In specific, to be considered sustainable, biofuels must achieve greenhouse gas savings of at least 35% in comparison to fossil fuels. This savings requirement rises to 50% in 2017. In 2018, it rises again to 60% but only for new production plants.

All life cycle emissions are taken into account when calculating greenhouse gas savings. This includes emissions from cultivation, processing, and transport. Furthermore, biofuels cannot be grown in areas converted from land with previously high carbon stock such as wetlands or forests and lastly they cannot be produced from raw materials obtained from land with high biodiversity such as primary forests or highly biodiverse grasslands.

As a result, in the EU, the production and use of biofuels can only be supported and/or counted towards mandatory national renewable energy targets when the biofuels comply with the EU sustainability criteria. Their compliance is proven by means of the respective national systems or the so-called voluntary schemes recognized by the European Commission (EC, 2016). Moreover, to combat indirect land use change, the EU launched new rules in 2015 which amending previous legislation on biofuels (EC, 2016).

In 2008 modeling work carried out by Searchinger et al. (2008) has shown that, contrary to previous studies which claimed that using biofuels instead of oil for transport would reduce GHG emissions, corn-based ethanol, instead of achieving 20% GHG savings, actually leads to almost doubling of GHG emissions over a 30-year period. Respectively, biofuels produced from switchgrass, which is cultivated on U.S. corn lands, would lead to an increase of GHG emissions by 50%. The reason lies to the fact that farmers respond to higher prices created for biofuel feedstocks and convert forest and grassland to new agricultural land in order to replace the one diverted to biofuels. *Table 6* compares GHG produced or absorbed with and without land-use change during each different stage of ethanol and gasoline production and use, as resulted by implementation of the GREET model.

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Table 6. Corn ethanol GHG produced or absorbed with and without land-use change per stage of production and use and comparison with gasoline GHG (in g-CO2eq/MJfuel) (Searchinger, et al., 2008).

Source of fuel	Making feedstock	Refining fuel	Vehicle operation (burning fuel)	Net Land-use effects		Total GHGs	% Change in net GHGs versus gasoline
				Feedstock carbon uptake from atmosphere (GREET)	Land-use change		
Gasoline	4	15	72	0	-	92	-
Corn ethanol (GREET)	24	40	71	-62	-	74	-20%
						135 *without feedstock credit	47% *without feedstock credit
Corn ethanol plus land use change	24	40	71	-62	104	177	93%
Biomass ethanol (GREET)	10	9	71	-62	-	27	-70%
Biomass ethanol plus land use change	10	9	71	-62	111	138	50%

5. Production costs and competitiveness

The cost competitiveness of biofuels is one of the main constraints against its vast deployment and the successful substitution of oil products. Although advanced biofuels are seen as rather promising for becoming economically competitive in the future, not all factors that define their competitive are clear-cut. For example, factors such as the energy input, the GHG emissions and the production costs of biofuel plants are very sensitive to feedstock, processes, co-products and local conditions (IRENA, 2013). Moreover, their commercially competitiveness largely depends on the fluctuating prices of gasoline and diesel, a fact that makes any projections highly sensitive to market conditions.

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Both conventional and advanced biofuels, with the exception of Brazilian sugarcane ethanol, cannot currently compete with gasoline and diesel, which is the reason why until now, biofuels are mainly supported by national policies, mandates, etc.

The main cost component of conventional biofuels is the feedstock price, which varies from 50-60% of the total cost for Brazilian sugarcane ethanol to 80-90% of the total cost for palm oil biodiesel, corn ethanol and rapeseed oil biodiesel (IRENA, 2013). Since the cost of feedstock exhibits an upward tendency, it is rather unlikely that the cost of conventional biofuels will decrease in the future.

To understand the large variations in the cost components forming the final cost of biofuels, it is important to examine local conditions as well. Table 7 below shows an example from IRENA (2013).

Table 7. Examples of cost components variations for the final cost of biofuels (IRENA, 2013).

	Sugarcane price (USD/t)
Brazil	3-8
Thailand	8-15
India	20-30

	Biomass transportation cost (US¢/t-km)
Ocean shipping	0.1
Road transport	10

Moreover, according to (IEA, 2013) conventional biodiesel is unlikely to face further cost reductions since it is produced through well-established industrial processes. Adding to that, biodiesel usually has a rather low yield per unit of land compared to other biofuels, which means that it is highly sensitive to increases in oil prices, independently of its maturity in the market.

Considering the above, it is not expected that conventional biofuels will become commercially competitive, unless a significant increase of the oil price occurs.

As concerns the advanced biofuels, they are currently much more expensive than conventional ones, but in their case the main cost component is the capital cost.

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Indicatively, the capital cost accounts for 40-50%, feedstock cost for 35-40% and O&M cost for the rest. The capital cost for a commercial biofuels plant producing 50-150Ml/year ranges from 235-250 million USD, which corresponds to 10 times higher than a conventional biodiesel plant (IRENA, 2013).

The expected technological advancements in the transformation processes of biofuels can ensure a significant cost reduction. Improving conversion efficiency can make biofuels not only economically more competitive but will also increase land-use efficiency and environmental performance.

In IEA's report on the production costs of alternative transportation fuels, two scenarios, namely the current technology and the mature technology scenario, were examined for differing costs of crude oil, with the aim to investigate the competitiveness of alternative fuels against gasoline and diesel. Table 8 presents the results for biofuels driving costs compared to gasoline and diesel, when crude oil is USD60/bbl and USD 150/bbl. As seen in the table (highlighted cells), rapeseed oil biodiesel becomes competitive to diesel only in the mature technology scenario and for crude oil at USD 150/bbl, whereas sugarcane ethanol is already competitive to gasoline in the current technology scenario. On the other hand, it is evident that all biofuels need quite high crude oil prices in order to prove their economic competitiveness.

Table 8. Driving costs (in USD/100km) for different types of biofuels, two scenarios of technological maturity and different prices of crude oil, compared to gasoline and diesel (IEA, 2013).

Driving costs (USD/100km)						
	Current Technology Scenario			**Mature Technology Scenario**		
Final Energy type	**USD 60/bbl**	**USD 150/bbl (Petroleum Intensity Method)**	**USD 150/bbl (Historical Trend Method)**	**USD 60/bbl**	**USD 150/bbl (Petroleum Intensity Method)**	**USD 150/bbl (Historical Trend Method)**
Gasoline	6.05	15.13	15.13	4.31	10.76	10.76
Diesel	5.63	14.06	14.06	3.88	9.71	9.71

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Biodiesel (rapeseed)	10.4	21.49	16.95	5.54	7.27	10.62
Corn ethanol	9.78	17.75	14.73	4.45	6.12	9.34
Sugarcane ethanol	6.91	14.01	10.95	4.09	5.39	6.69
BTL	10.1	26.34	13.88	5.36	11.63	7.89
Lignocellulosic ethanol	11.82	29.43	14.51	5.5	12.41	7.96

It is worth mentioning that economics also depend a lot on the value of co-products from the production of conventional biofuels, which can reduce their cost by up to 15-20%.

6. Supply chains and logistics

Many constraints arise in regards to the collection and transportation of the feedstock required for the production of biofuels, when it comes to wastes and residues. These constraints may lead to an unprofitable biofuels production from wastes and residues and in some cases the need for extending the share of energy crops, and therefore increase the land use required. However, given the anticipated advancements in the production of advanced biofuels, the, so-called, efficiencies of the respective feedstock will allow a more moderate increase of the required land (IEA, 2011).

A report completed in 2010 by the Feedstock Logistics Interagency Working Group in the US (Feedstock Logistics Interagency Working Group, 2010) has identified the most important barriers to the commercialization of biofuel feedstock logistics systems. In specific:

1. Low mass and energy density of biomass feedstocks from agricultural and forest resources, considering the currently available technologies for harvest and collection. Research and development is required to achieve higher bulk and/or energy densities, for transportation and storage to be economically viable.

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2. The higher than desired moisture content of biomass could cause aerobic instability during storage and therefore reduce the efficiency of transportation.
3. Inefficient capacity of the equipment for biomass feedstock logistics systems to economically harvest, store and deliver feedstocks. Innovative equipment is required.
4. Variability and inconsistency of biomass feedstocks quality can make conversion processes inefficient. Development of logistics operations is required which will maximize uniformity and consistency of feedstocks in terms of quality, particle size and moisture content.
5. Costly transportation through truck traffic, risk of damaging roadways and bridges and questionable social acceptance are factors that need to be addressed through the development of new transportation technology.

Most of the implemented studies on optimizing supply chains for biofuels start from the assumption that all decisions are taken at a centralized level, with all involved stakeholders cooperating closely to achieve the minimization of the total cost of the entire supply chain. However, this is not the case in reality, as farmers, biofuel producers and intermediate parties usually have individual targets and sometimes conflicting objectives with the aim to maximize their own profit. At the same time, other factors are to be taken into account, such as local regulations, interaction with land use and food supply, etc.

Since the complicated nature of designing cost competitive supply chains for biofuels is evident, it is important to consider all the involved uncertainties and particularities and some more recent studies have tried to capture this pluralism as reviewed in Bai et al. (2016).

The following figure (Figure 6) shows an indicative schema of how supply chains for second generation biofuels are formed and it refers to a model developed by (Hombach, Cambero, Sowlati, & Walther, 2016). It starts with the types and sources of biomass as well as land used to supply the biofuels production plants. Then it

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moves to the production plants which vary according to their number, type, capacity, location and stage of production (i.e. intermediate or final) conversion facilities for the production of second generation biofuel, the demand in first generation biofuel in case the second generation biofuels do not suffice, as well as all the annual flows of biomass, intermediate product and produced biofuel of the entire supply chain.

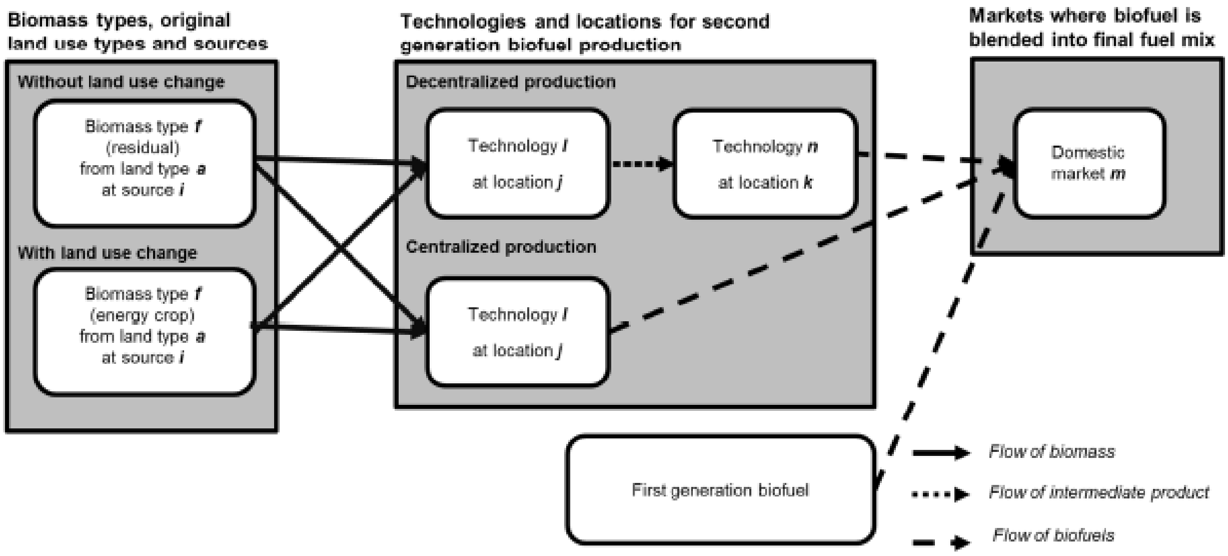

Figure 6. Exemplary schema of a second generation biofuel supply chain (Hombach, Cambero, Sowlati, & Walther, 2016).

The model developed by Hombach et al. (2016) minimizes the net present value (NPV) of the entire supply chain for the production of second generation biofuels.

The model is applied in a case study in the Rhineland-Palatinate region of Germany, a highly dense forestry area with significant agricultural potential as well.

Two different types of production routes exist, each of which can be fed from 36 potential sources, with several combination of biomass and type of land uses. Moreover, two concepts of production plants are studied; one large centralized and several smaller decentralized plants are available. Finally, different options for the location of the plants are integrated together with 36 different markets. The model is

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implemented on the basis of the current European regulatory framework for biofuels[3] as well as the proposed regulatory modifications[4]. Figure 6 presents the results of a sensitivity analysis performed in this study, which shows the impact that 20% changes in various parameters have on the NPV of the entire supply chain.

What is more striking is that the NPV of second generation biodiesel supply chain is very sensitive to diesel price and the capital and production costs, whereas it is rather insensitive to the transportation costs.

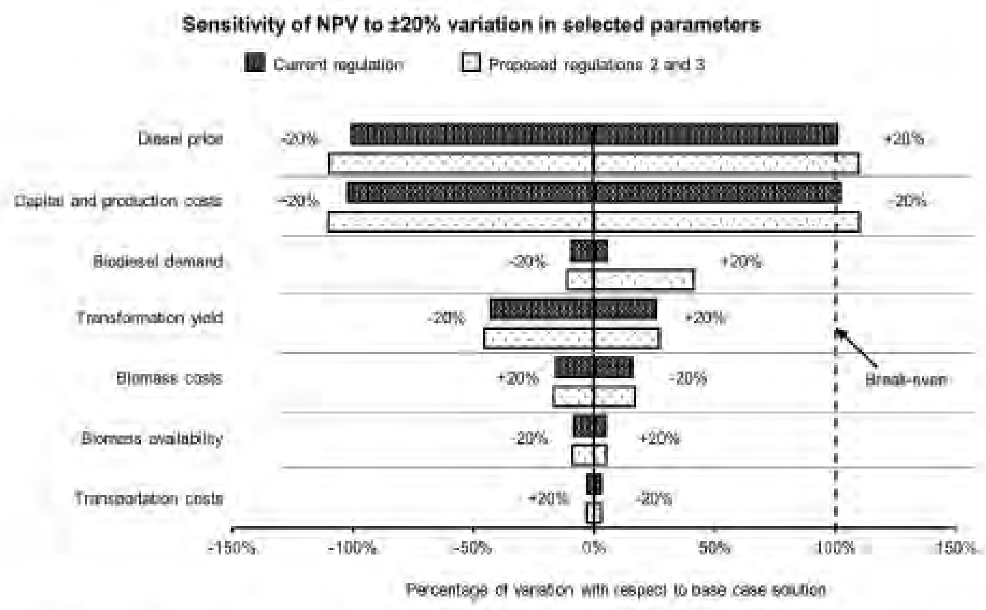

Figure 7. Sensitivity analysis of the supply chain model developed by (Hombach, Cambero, Sowlati, & Walther, 2016) to examine the impact of various model parameters in the NPV of the entire supply chain.

A special mention needs to be made on global feedstock and biofuel trade which will need to be enhanced in order to meet the corresponding biofuel production as well as the national targets for increasing biofuel share in transport. According to the projections of IEA, the global trade in biofuels increases from 0.2 mboe/d in 2012 to

[3] Directives 2009/28/EC and 2009/30/EC

[4] COM(2012)595 and 2012/0288(COD)

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0.7 mboe/d in 2035. However, this means that trade should become economically sensible and the associated advancement in logistics should play a significant role.

7. Conclusions

As described in the aforementioned paragraphs biofuels have been introduced in the global market as an alternative transport fuel with the initial scope of supporting the agricultural sector and later as a vehicle for strengthening energy security and mitigating GHG emissions as opposed to conventional fuels.

Despite the initial sustainability rationale, claims of land use changes, deforestation and food insecurity have restrained their full deployment and challenged their contribution to energy security, environment and social prosperity.

The main debated issues expressed in the last years that also form the most important constraints for their mass market deployment were summarized in this report.

The inevitable increase in the required feedstock demand for the production of biofuels brings about the challenge of covering this demand without putting at risk **food security**, biodiversity and access to arable land. The main questions relate to biofuels impact on agricultural commodity markets, their role in the food price determination process, and how the current biofuel policies carry the risk of generating food insecurity in low-income countries. The main speculation expressed is that considering the relative importance of the energy markets compared to food markets, as well as the relative economic power of the consumers demanding more energy compared to the ones demanding more food, an increased production of biofuels could eventually lead to increase of food prices and subsequently to imperiling access to food by vulnerable consumers.

On the other hand, when the increasing demand for biofuel feedstock imposes a **direct or indirect change of the primary use of a land** (e.g. deforestation) and considering that forests act as an absorber of CO_2 from the atmosphere, removing them for biofuel production may actually result in increasing the total GHG emissions

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instead of decreasing them. It is therefore considered imperative to take into account both GHG emissions and land use change, when assessing the environmental balance of biofuels.

As regards the **competitiveness** of biofuels, both conventional and advanced (except for Brazilian sugarcane ethanol) are currently far from competitive to gasoline and diesel, which is the reason why until now, biofuels are mainly supported by national policies. Moreover, as various studies have shown, projections on the timing at which biofuels will become competitive are rather hard to assess, since this depends a lot on the prices at which gasoline and diesel will eventually settle. This makes biofuels very sensitive to oil prices and market conditions.

Another major factor of uncertainty regarding the future of biofuels relates to their **supply chain and logistics**. The rather complicated nature of biomass feedstocks and biofuels as transported goods, combined with the high associated costs and impacts on the transportation of feedstocks and final product (such as low mass and energy density of feedstocks, high moisture content, inefficient capacity of harvesting, transportation and storing equipment, variability and inconsistency of feedstocks quality, costly transportation and risk of damaging roadways) have made it quite difficult to develop economically efficient supply chains. Moreover, the different and often competing interests of the parties involved in the entire supply chain could potentially impede an optimal supply chain design.

Considering all the above, it is important to introduce national and regional policies that will incentivize the technological development of advanced biofuels, with increased yields and efficiencies. This will allow the significant reduction of costs for the production of biofuels, making them in turn more competitive to fossil fuels for transport.

Moreover, although numerous international initiatives are already in place to ensure a minimal negative impact of biofuels on the environment and society (e.g. binding sustainability criteria by EU, USA, Switzerland among others), an integrated global approach should be adopted. To be able to consider biofuels for the

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decarbonization of the transport sector, an analysis of environmental, economic and social implications has to be performed, taking into account the extensive and complicated impacts of biofuels production and supply on environment and society as well as on the associated sectors of agriculture and forestry.

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D2.1: *Report with an analysis of the main limitations of variables and indicators selected to represent the pathways and scenarios.*

Annex 5: *Thermodynamic assessment of mineral resources: the concept of exergy replacement costs and thermodynamic rarity*

Grant agreement: 691287

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TABLES AND FIGURES

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1. Scope

This document is part of MEDEAS Deliverable 2.1. The main aim of this report is to explain the thermodynamic methodology behind the assessment of raw materials developed by CIRCE and previously published in several publications such as Valero and Valero (2013, 2014, 2015) or Valero et. Al. (2013a). Two concepts are explained: the exergy replacement costs and thermodynamic rarity, which are used to reassess the PAVs associated with the use of raw materials in exergy terms, namely PAVs 108 - 112.

2. Introduction: Rationale for using exergy as the unit of measure

Man's accelerated technological development continues to cause an intensified use of minor and scarce elements, plus a massive use of conventional minerals, such as iron or aluminum ores, construction materials, etc. This, in turn, leads to a net reduction of the planetary mineral endowment. Since the Earth's crust is in no way homogeneous, mining focuses on the extraction of the best ore grades, leaving behind the sub-optimal ones. Declining ore grades imply greater ecosystem destruction and greater amounts of water, materials and energy employed per each additional ton of mineral extracted. The result is that mining is becoming all the more evasive, deeper, remote and resource intensive. If resources are to be preserved for future generations, it is of paramount importance to become aware of this issue.

Unfortunately, the total amount of mineral resources in the Earth is probably unaccountable. That said, the annual loss of the quality (higher grade) minerals that society extracts from the crust can and should be quantitatively considered. Therefore, if the mineral capital on Earth is declining year by year, by how much is it doing so? Assessing this annual loss is not easy. Money, a common unit of measure, cannot be used, because it depends on markets and political decisions that are far removed from the objective reality of a physical loss. Alternatively, the use of mass (tonnage of extracted commodities) turns, for instance, the addition of ounces of gold with millions of tons of iron into absurdity. Moreover, as is also the case for tonnage, energy is not

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sensitive to the quality (ore grade) of the extracted mineral (the energy or the mass of a mineral in a deposit is independent of its ore grade).

What could be used then as the yardstick? If the second law of thermodynamics applies to all physical systems, why not use exergy analysis?

Exergy is a measure of the degree of thermodynamic distinction a system has from the surrounding commonness, and in this sense, it is a measure of an object's rarity. The rarer something is, the greater it stands out. People value distinction and pay higher prices for it. Given that it is only perceived upon comparing something with its surroundings, distinction is deeply related to economic value and with physics. In fact, exergy accurately measures, in energy terms, the distinction of a piece of matter with respect to a given reference environment (R.E.), sometimes also known as the "dead state". Exergy of any natural resource is defined as the minimum energy required to produce it with a specific structure and concentration from common materials in the reference environment.

Choosing an appropriate reference environment is key to making exergy analysis suitable for systems. It may be chosen according to the properties of the system one wants to analyze. For instance, when analyzing a simple steam cycle, the reference may be pure water at 15 °C and 1 bar; in contrast, when analyzing the exergy variation of a river, an appropriate reference state is that of seawater. Even if pure water has exergy with respect to seawater, using seawater for analyzing a steam cycle is unreasonable, and it unnecessarily complicates the calculations. Pure water is a relative R.E., whereas seawater is an absolute one. Contrary to water or energy systems, the concept of the "dead state" becomes more complex when dealing with chemical substances.

Mankind converts the stored chemical exergy of the Earth into a degraded environment, which is progressively less able to support economic activities as they are currently understood and eventually will fail to sustain life itself. One can imagine a "commercially-dead" planet Earth as a possible end to the "Anthropocene" period (Crutzen and Stoermer, 2000). In this scenario, which Valero et al. (2011) have called Thanatia from the Greek "Θανατος" (death), all concentrated materials would have been extracted and dispersed throughout the crust and all fossil fuels would have been burned, leading to an increase in the atmospheric CO2 concentration and mean global temperature, due to the greenhouse effect. Using this as a reference point, every substance that is more concentrated or diluted, warmer or cooler, with a greater or a lower chemical potential, pressure, height or velocity, and so on, will have exergy.

Thanatia constitutes the starting point for assessing the loss of mineral endowment on Earth, but in no way represents the end of life on our planet. It only implies that abiotic resources are no longer available in a concentrated form. The model behind Thanatia is the "crepuscular Earth" and has been developed with current geochemical and geological information on the atmosphere, hydrosphere and crust in Valero et al. (2011, 2011a). The crepuscular atmosphere occurs once all conventional fossil fuel reserves have been depleted and is set to be reached by approximately 2200, with an atmospheric injection of about 2000 GtC. Accordingly, the crepuscular atmosphere has a carbon dioxide content of 683 ppm, a mean surface temperature of 17 °C (a peak carbon dioxide induced warming of 3.7 °C above pre-industrial temperatures), a pressure of 1.021 bar and a composition, on a volume basis of 78.8% N2, 20.92% O2, 0.93% Ar and 0.0015% of trace gases.

3. Methodology to assess the exergy of mineral resources

The exergy of a mineral resource has at least two components: one associated to its chemical composition and one associated to its concentration. The chemical exergy bch of the resource comes into play when the reference environment chosen does not contain the substance under consideration. Since Thanatia contains in principle most of the minerals found in the crust, the chemical exergy will not appear, and only the concentration exergy bc component is used to assess mineral resources. The concentration exergy represents the minimum amount of energy associated with the concentration of a substance from an ideal mixture of two components as in Eq. 1.

$$b_{ci} = -\bar{R}T^0 \left[lnx_i + \frac{(1-x_i)}{x_i} ln(1-x_i) \right] \quad (1)$$

where R is the universal gas constant (8.314 kJ/kmolK), T0 is the temperature of the reference environment (298.15 K) and xi is the concentration of the substance i. The exergy accounting of mineral resources implies to know the ore grade which is the average mineral concentration in a mine x_m as well as the average concentration in the Earth's crust (in Thanatia) x_c. The value of x [g/g] in Eq. 1 is replaced by x_c or x_m to obtain their respective exergies, $b_c(x = x_c)$ and $b_c(x = x_m)$ whilst the difference between them $\Delta b_c(x_c \rightarrow x_m)$ represents the minimum energy (exergy) required to form the mineral from the concentration in the Earth's crust to the concentration in the mineral de-posits (Eq. 2).

$$\Delta b_c(x_c \rightarrow x_m) = b_c(x = x_c) - b_c(x = x_m) \quad (2)$$

From the 2nd Law of Thermodynamics, Eq. 1 indicates that as the concentration of substance tends to zero, the exergy required to separate it from the mixture tends to infinity. So Thermodynamics provides the tendency of the behavior. The real energy required is several orders of magnitude greater than what the Thermodynamics of reversible processes dictates. In fact, mixing and separating are very irreversible processes. When salt and sugar are mixed, the energy that is liberated in the mixture is almost imperceptible. If the process were reversible, the same amount of energy would be required to separate the mixture. But that is obviously not the case in the real world and when this happens in everyday life, it is easier to throw out the mixture than trying to separate it. Hence, property exergy is required but it is not sufficient to assess in a realistic way the mineral capital. For this reason, the irreversibility factor needs to be included. This can be done through the so called exergy replacement costs.

The exergy replacement cost is defined as the total exergy required to concentrate the mineral resources from Thanatia, with the best available technologies (see Figure 1). It can be seen as a "natural bonus" provided freely by Nature, for having minerals concentrated in mines and not dispersed throughout the crust. It should be noted that

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these are not absolute and universal values, as opposed to property exergy. The exergy costs are a function of the extraction and separation technologies used, which in turn vary with time, with the type of mineral analyzed, and with man's ability to extract it, i.e. with its learning curve (Domínguez and Valero, 2013).

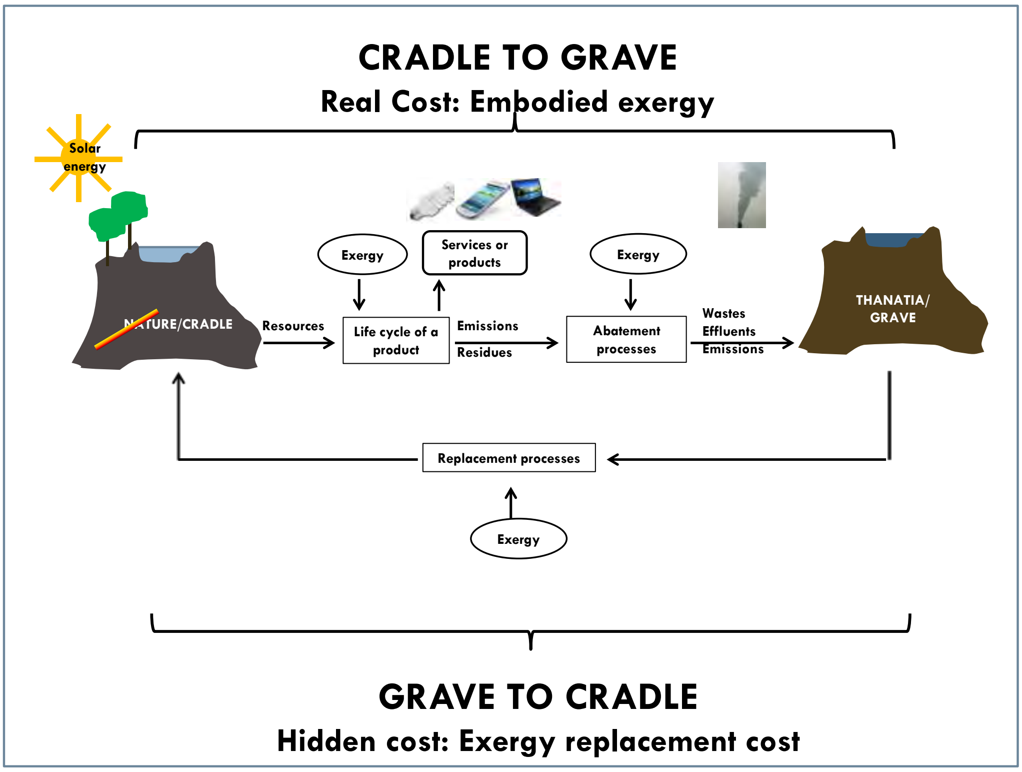

Figure 1. The concept of Exergy replacement cost with respect to embodied exergy. Valero and Valero (2013).

The concentration of a mineral from the ore grade of the deposit to its commercial grade implies an energy consumption completely different to that of concentrating the mineral from the dispersed state of Thanatia to the original conditions of the mine. In other words, from a theoretical point of view, the exergy cost of concentrating a mineral would require k times the minimum concentration exergy (Eq. 3).

$$b_{ci}^{*} = k \cdot b_{ci} \quad (3)$$

Where *k* is a constant called unit exergy cost and it is the ratio between the real cumulative energy required to accomplish the real process to concentrate the mineral

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from the ore grade x_m to the commercial grade x_r and the minimum thermodynamic exergy required to accomplish the same process (Eq. 4).

$$k = \frac{E_{(x_m \to x_r)}}{\Delta b(x_m \to x_r)} \quad (4)$$

Since the energy required for mining is a function of the ore grade of the mine and of the technology used, so it is the unit exergy cost. As Ruth (1995) states, both variables have an opposite effect on the energy used. The lower the ore grade, the more energy is required for mining. On the contrary, technological development usually improves the efficiency of mining processes and hence, decreases the energy consumption. In other words, the unit exergy cost depends on the ore grade (x) and the time (t) that is considered through the improvements in mining techniques, which in turn are reflected in the real energy consumptions.

$$k = k(x, t) \quad (5)$$

Hence, the temporal function *k* is only definable for the past and for each particular mineral. It is therefore difficult to extrapolate it towards the future for the practical impossibility to predict changes in the scientific and technological knowledge that will eventually appear.

The second problem with *k* is that it is not a continuous function. The technology applied can also vary with the concentration ranges of a particular deposit. And in turn, each mining technique (i.e. underground or open-pit mining), has a particular effect on the energy consumption due to different factors such as ore grade, grind size, nature, depth and processing route.

These factors have been analyzed for different commodities in other studies such as for copper, nickel aluminium and iron through the life cycle assessment methodology (Norgate and Jahanshahi (2010, 2011), Norgate and Haque (2010).

Bearing in mind these limitations and the kind of data available for mining (which is usually very scarce) it is assumed that the same technology is applied for the range of concentration between the ore grade x_m in the mine and the refining grade x_r, than

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between the dispersed state of the crepuscular crust xc and x_m. This way, an analysis of the average energy vs. ore grade trends for different minerals was carried out, in order to calculate the corresponding unit exergy cost values and extrapolate them to ore grades equal to those of the dispersed conditions of Thanatia.

4. Calculation of exergy replacement costs

The first step in obtaining the unit exergy replacement cost for the commodities analyzed is to obtain their real energy consumptions in the mining and concentrating processes (going from x_m to x_r) as a function of the ore grade (x_m). This information can be obtained from data published in literature. In a parallel way, the theoretical exergy of the same process is calculated as the difference in concentration exergy (Eq. 1) when $x = x_m$ and $x = x_r$. A calculation of the refining grade x_r requires a careful analysis of the different processes involved in the concentrating steps. Finally, unit exergy costs are calculated with Eq. 4 as a function of the ore grade. The latter can be extrapolated to obtain the unit exergy costs at the crepuscular grade x_c, which will eventually serve for calculating the exergy replacement costs of the mineral wealth on Earth with Eq. 3. The values used for the crepuscular grade are those x_c published in Valero et. Al. (2011). Average values for x_m have been obtained from several studies such as Mudd (2007, 2010). In the next section, as an example, the case of copper is presented. For more information about the remaining minerals can be found in Valero and Valero (2014) and Valero, Valero and Domínguez (2013).

4.1. Copper

Copper is always associated with other metals, commonly nickel, molybdenum and platinum group metals. Copper in mineral deposits is usually found in nature in association with sulphur, as chalcopyrite (CuFeS2). This ore has a crustal concentration of x_c = 6.64−05 g/g (Valero and Valero, 2011). The average ore grade assumed is x_m = 1.67− 02 g/g (Cox and Singer, 1992). Data sets for energy requirements as a function of the copper ore grade are obtained from the study of Mudd (2010) of sulphidic ores,

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which contain also cobalt and nickel. Energy is allocated among the minerals according to their tonnage. It is assumed that 60% of the whole energy recorded is used for the mining and concentration processes. Kennecott Utah Copper (2004) reports an average grade for Cu after beneficiation of x_r = 28.00− 02g/g. Figure 2 shows the trends for an ore grade range including the average value reported by Cox and Singer (1992).

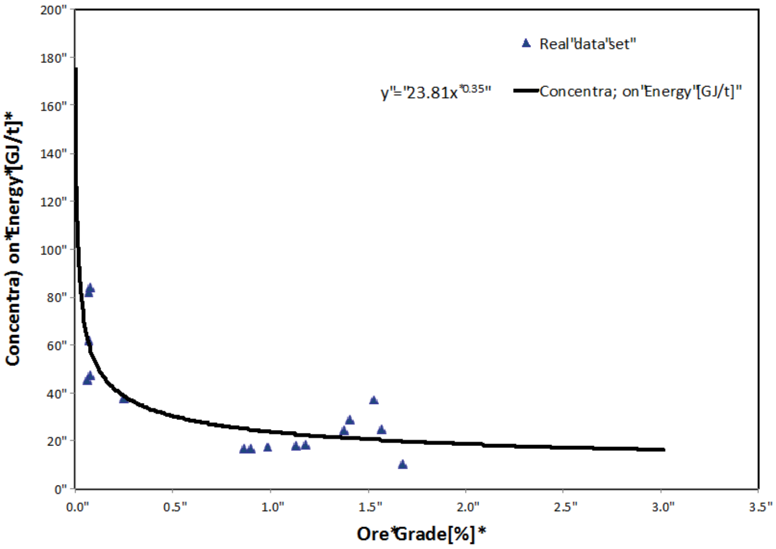

Figure 2. Energy requirement trends for copper production form sulphide ores as a function of the ore grade. Adapted from Mudd (2010).

From the observation that the energy consumption as a function of the ore grade shows expression varying from x−0.2 to x−0.9 and recognizing that empirical data for most of the minerals produced in the world is very limited, Valero and Valero (2013) proposed the following general expression for the exponential curve applied to estimate the energy consumption as a function of the ore grade:

$$E(x_m) = A \cdot x_m^{-0.5} \quad (6)$$

Coefficient A is determined for each mineral since generally, the average ore grade x_m and the energy required for concentrating and extracting the mineral at that grade $E(x_m)$ is known. It should be noted that x_m values are expressed in Eq. 6 as mass percentage of the element under consideration. This is a very rough approximation, but it is more in agreement with actual mining behavior than the equation proposed by

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Chapman and Roberts (1983), where the energy is inversely proportional to the ore grade.

5. Thermodynamic rarity

The idea of replacement cost allows one to move into another concept: "thermodynamic rarity". The Webster Dictionary defines rarity as "something that is valuable because there are few of its kind". Rarity therefore relates to the difficulty in attaining something. In the case of a mineral deposit, it is associated with the improbability of finding and accessing. Once accessed, it also relates to the effort of isolating it from undesired impurities, considering environmental conditions and the availability of water, energy and resources in general for its supply to market. Rarity thus prescribes the character of a natural resource to a given mineral deposit. If one considers all of these characteristics from a thermodynamic perspective, they are all rooted in entropy.

Mineral rarity, in turn, requires a definition. When one thinks of rarity generally, there is a tendency to express it in terms of unspecified quantities (i.e., whether there is a little or a lot). However, this concept, when applied to minerals, can be better described in quantified energy terms. Therefore, mineral rarity could arguably be defined as "the amount of exergy resources needed to obtain a mineral commodity from bare rock, using the best available technology".

Valero and Valero (2015) in their mineral resource assessment chose the common bare rock (Thanatia) as the reference baseline. Accordingly, the thermodynamic rarity of minerals is precisely defined as "the actual amount of exergy resources needed to obtain a mineral commodity from Thanatia to the market conditions using the current best available technologies". Consequently, a mineral's "thermodynamic rarity" equates to its natural bonus (measured in terms of exergy replacement costs) plus its mining and beneficiation and prior to the smelting and refining stages. Rarity becomes thus a quantifiable thermodynamic property measured in kJ. Moreover, as it is additive, indirect exergy costs related to water availability, environmental impact and transport from the mine to the customer can be incorporated into the definition.

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Thermodynamic rarity varies from mineral to mineral, as a function of absolute scarcity in Nature and the state of technological development. Generally speaking, if technology does not change, the thermodynamic rarity of a given mineral will remain constant, since it depends on fixed initial and final states, i.e., on Thanatia and on the commodity's quality following beneficiation, which is usually commercially imposed (see Figure 3). That said, as minerals are extracted, ore grades decline, and hence, mining and beneficiation costs increase. Yet, this "natural concentration bonus" with respect to Thanatia simultaneously decreases, and it becomes "easier" to replace low-quality resources or to find new ones (see Figure 4). In other words, at constant technological conditions, the hidden costs are converted into real ones. If, by way of contrast, technological improvements appear, thermodynamic rarity will decrease due to the reduction of both, hidden and real costs (mining and beneficiation) (see Figure 5).

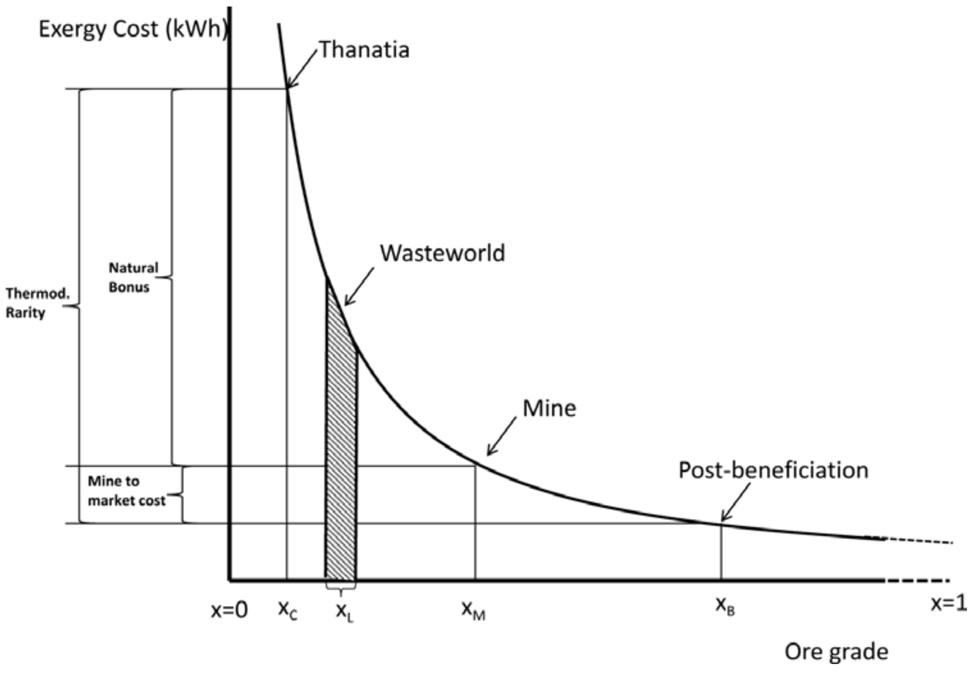

Figure 3. Thermodynamic rarity represents the exergy cost (kWh) needed for producing a given mineral commodity from bare rock to market, i.e., from Thanatia to the mine and then to post beneficiation. Valero and Valero (2015).

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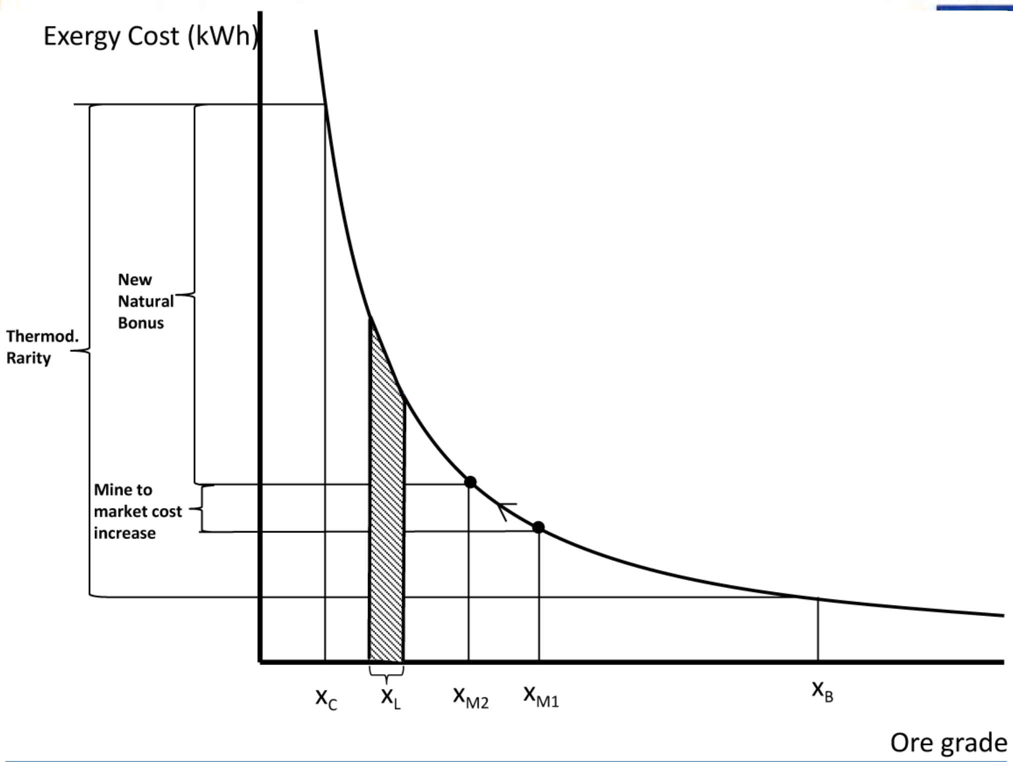

Figure 4. The influence of extraction on thermodynamic rarity, should technology remain constant. Valero and Valero (2015).

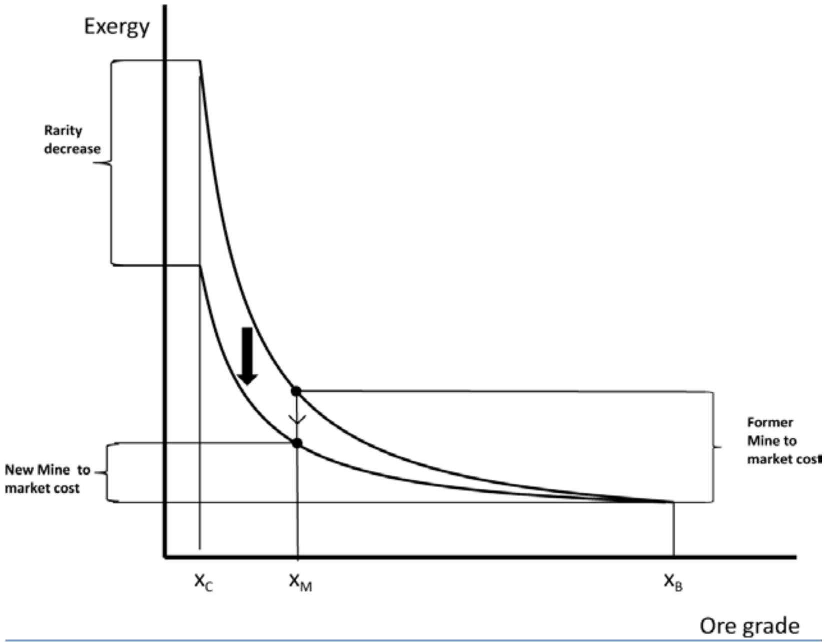

Figure 5. The influence of technological improvements on thermodynamic rarity. Valero and Valero (2015).

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One now may define rarefaction as an induced decline of the concentration of a given commodity, making thus its recovery costly. In the technosphere, rarefaction appears both at the mineral's beginning-of-life (BoL) and at its end-of-life (EoL). At the EoL, it occurs when a metal or mineral loses its usefulness and becomes landfilled, incinerated and, sooner or later, dispersed in Thanatia, i.e., it "rarefies". Its irreversible loss is accounted for by its exergy replacement cost from the concentration of the element in the wasted product to the concentration in landfill, x_L, or if dispersed in Thanatia, xc (see Figures 4 and 5). When this occurs, Man is irreversible converting highly concentrated substances into waste. The name "wasteworld" is used here to express all accumulated worldwide landfills showing a concentration range of around x_L. At the BoL, when the mineral is mined and beneficiated, what remains in the mine also rarifies, given that the concentration decreases, gradually approaching the limit of Thanatia. This process is the well-known "mining ore grade decline". As a consequence and as stated previously, the amount of exergy needed to extract the next ton of mineral in turn increases. The rarefaction process therefore appears twice, one at the BoL and the other at the EoL. In the authors' opinion, society should be aware of both processes in quantitative terms (kWh).

In summary, rarity is not a mere "yes or no" type question, but rather a cost (kWh) that depends on the given element's scarcity in the crust, the state of technology and the commodity's imposed quality. Furthermore, it is not only a matter of ore grade or geological scarcity, but of exergy costing. It has bearing on global energy consumption and the sustainability of planetary resources, because the greater the thermodynamic rarity, the more difficult it is to obtain a given commodity. In this respect, the economy of mine exploitation is better understood. This is because thermodynamic rarity can unify, into one continuous indicator, all of the following concepts usually found in geological surveys serving to identify resources and reserves data: recoverable, unrecoverable, hypothetical, proved, indicated, inferred, etc. This means that all such concepts are located in a specific interval of ore grade in the thermodynamic rarity function (Figure 6).

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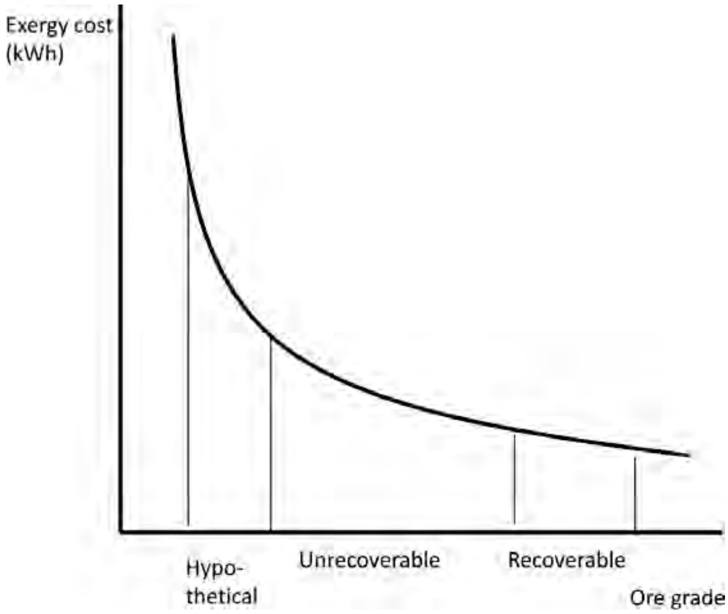

Figure 6. Resources classification as a function of the thermodynamic rarity of a given mineral deposit.

Moreover, thermodynamic rarity, as measured in energy terms, evidently relates to global energy consumption and the impact on the environment. The mineral depletion problem thus becomes not an absence of materials, but an insufficient provision of energy. Therefore, as there are no materials without energy and equally no energy without materials, the problem is two-fold or even three-fold if one considers the associated environmental consequences of mineral extraction.

This interpretation solves conceptual dilemmas in the classical mineral discourse, providing answers to questions, such as: are rare earths elements (REE) truly rare? REE are not geologically scarce, but dispersed and chemically challenging to isolate. Therefore, their depletion per se is not a problem, since there are more REE in the crust than, say, copper. The issue comes in their thermodynamic rarity, which is itself derived from several combining factors consisting of concentration, separation and chemical composition. Firstly, exploitable concentrations of REE-containing minerals, such as bastnasite, monazite or clays, are difficult to find, as they are highly dispersed. Secondly, REE occur all together. Some of them, like cerium and lanthanum, are relatively abundant in comparison to the remaining fifteen. Additionally, not all are

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equally demanded; for instance, dysprosium is a mass used component that prevents demagnetization at high temperatures in Nd-Fe-B permanent magnets. Thirdly, given that the chemical properties of all REE are very similar, their separation, mainly by ion exchange techniques, is complex and inefficient, as in the case of gadolinium. Finally, as with alkaline and alkaline-earth metals, REE need great amounts of energy in the reduction to their metallic state. Therefore, in a number of applications, to save energy, reactants and effort, mischmetal, rare earth oxide (REO) or even the naturally occurring total rare earth oxide (TREO) is commonly used instead of the pure metal. All of the above lead to REE having a very high exergy replacement cost and beneficiation cost, i.e., thermodynamic rarity, when compared to other metals. In short, rare earths are truly rare from a thermodynamic (exergy) perspective.

6. Conclusions

A summary of the exergy replacement cost and thermodynamic rarity values of all commodities analyzed is presented in Table 1. It contains the main values for each substance, such as x_c, x_m and x_r along with the equations to calculate the energy required to mining and concentrating a specific ore, the exergy replacement cost and thermodynamic rarity.

Table 1. Exergy replacement costs and thermodynamic rarity for various substances. Values of x_c, x_m and x_r are referred to the assumed mineral that represents the ores from which the metal is extracted.

	E(x)	x_c[g/g]	x_m[g/g]	x_r[g/g]	ERC - Bonus	Mining and conc.	Smelting and refining	Thermodynamic rarity (beneficiation)
Aluminium - Bauxite (Gibbsite)	$E=1{,}508x^{-0.5}$	1,38E-03	7,03E-01	9,50E-01	627,344	10,5	23,9	638
Antimony (Stibnite)	$E=2.72x^{-0.5}$	2,75E-07	5,27E-02	9,00E-01	474,489	1,4	12,0	476
Arsenic (Arsenopyrite)	$E=26.3x^{-0.5}$	4,71E-06	2,17E-02	9,00E-01	399,838	9,0	19,0	409
Barite	$E=7.099x^{-05}$	7,09E-04	9,50E-01	9,90E-01	38,338	0,9		39
Beryllium (Beryl)	$E=4.51x^{-0.5}$	3,22E-05	7,80E-02	9,00E-01	252,732	7,2	450,0	260
Bismuth (Bismuthinite)	$E=26.3x^{-0.5}$	5,10E-08	2,46E-03	9,00E-01	489,221	3,6	52,8	493
Cadmium (Greenockite)	$E=26.3x^{-0.5}$	1,16E-07	1,28E-04	3,86E-03	5.898,405	263,9	278,5	6.162
Cerium (Monazite)	$E=55.8x^{-0.5}$	1,03E-04	3,00E-04	9,00E-01	97,193	523,1		620
Chromium (Chromite)	$E=11.81x^{-0.5}$	1,98E-04	6,37E-01	8,10E-01	4,537	0,1	36,3	5
Cobalt (Linnaeite)	$E=2.24x^{-0.64}$	5,15E-09	1,90E-03	4,56E-02	10.871,925	9,2	129,0	10.881
Copper (Chalcopyrite)	$E=25.651x^{-0.366}$	6,64E-05	1,67E-02	8,09E-01	291,701	35,3	21,4	327
Fluorite	$E=7.25x^{-0.5}$	1,12E-05	2,50E-01	9,00E-01	182,657	1,5	-	184
Gadolinium-Monazite	$E=50.3x^{-0.5}$	1,30E-04	3,00E-04	9,00E-01	478,052	3607,3	-	4.085
Gallium (in Bauxite)	$E=4310x^{-0.5}$	1,76E-05	5,00E-05	9,00E-01	144.828,051	610000,0	-	754.828
Germanium (in Zinc)	$E=273x^{-0.5}$	1,41E-06	3,00E-03	9,00E-01	23.749,112	498,0	-	24.247
Gold	$E=169630x^{-0.275}$; x [g/t]	1,28E-09	2,24E-06	1,38E-04	553.044,197	110016,1	-	663.060
Graphite	$E=4.32x^{\wedge 0.5}$	2,41E-04	1,50E-01	8,70E-01	20,386	1,1		22
Gypsum	$E=1.81x^{-0.5}$	1,26E-04	8,00E-01	9,50E-01	15,410	0,2	-	16
Indium (in Zinc)	$E=704x^{-0.5}$	5,61E-08	4,50E-04	9,00E-01	360.597,516	3319,7	-	363.917
Iron ore (Hematite)	$E=5.97x^{-0.5}$	9,66E-04	7,30E-01	9,50E-01	17,751	0,7	13,4	18
Lanthanum-Monazite	$E=24.0x^{-0.5}$	1,30E-04	3,00E-04	9,00E-01	39,327	296,8	-	336
Lead (Galena)	$E=1.28x^{-0.5}$	6,67E-06	2,37E-02	6,35E-01	36,622	0,9	3,3	38
Lime	$E=2.09x^{-0.5}$	8,00E-03	6,00E-01	9,50E-01	2,616	0,4	5,8	3
Lithium (Spodumene)	$E=21.6x^{-0.5}$	3,83E-04	8,04E-01	9,50E-01	545,829	12,5	420,0	558
Magnesite	$E=21.6x^{-0.5}$	2,50E-02	4,20E-01	1,00E+00	25,555	9,5		35
Manganese (Pyrolusite)	$E=0.911x^{-0.5}$	4,90E-05	5,00E-01	6,71E-01	15,642	0,2	57,4	16
Mercury (Cinnabar)	$E=96.8x^{-0.5}$	5,73E-08	4,41E-03	9,00E-01	28.297,999	157,0	252,0	28.455
Molybdenum (Molybdenite)	$E=23.6x^{-0.5}$	1,83E-06	5,01E-04	9,18E-01	907,911	136,0	12,0	1.044
Neodymium-Monazite	$E=40.8x^{-0.5}$	1,30E-04	3,00E-04	9,00E-01	78,415	591,7	-	670
Nickel (sulphides) Pentlandite	$E=17.01x^{-0.67}$	5,75E-05	3,36E-02	4,68E-01	761,035	15,5	100,0	777
Nickel (laterites) Garnierite	$E=2.11x^{-0.5}$	4,10E-06	4,42E-02	8,04E-02	167,488	1,7	412,0	169
Niobium (ferrocolumbite)	$E=138.5x^{-0.5}$	8,10E-06	2,00E-02	6,00E-01	4.421,968	132,0		
Palladium	$E=2160x^{-0.5}$	3,95E-10	8,02E-07	9,00E-01	8.983.376,981	583333,3	-	
Phosphate rock (Apatite)	$E=0.373x^{-0.5}$	4,03E-04	5,97E-03	9,00E-01	0,352	0,3	4,6	1
Platinum	$E=2070x^{-0.5}$	3,95E-10	8,02E-07	9,00E-01	4.491.688,491	291666,7	-	
Potassium (Sylvite)	$E=8.38x^{-0.5}$	2,05E-06	3,99E-01	9,00E-01	664,922	1,7	N.A.	667
Praseodymium-Monazite	$E=10.8x^{-0.5}$	7,10E-06	3,00E-04	9,00E-01	577,078	296,3	-	873
Rhenium	$E=23.8x^{-0.5}$	1,98E-10	2,33E-04	9,00E-01	102.931,439	156,0	-	103.087
Silicon (Quartz)	$E=3.97x^{-0.5}$	2,29E-01	6,50E-01	9,80E-01	0,000	0,7	76,0	1
Silver (Argentite)	$E=24.7x^{-0.5}$	1,24E-08	4,27E-06	9,00E-01	7.371,408	1281,4	284,8	8.653
Sodium (Halite)	$E=8.13x^{-0.5}$	5,89E-04	2,00E-01	9,00E-01	44,073	3,3	39,6	47
Tantalum (Tantalite)	$E=429x^{-0.5}$	1,58E-07	7,44E-03	3,80E-01	482.827,991	3082,8	8,1	485.911
Tellurium-Tetradymite	$E=3540x^{-0.5}$	5,00E-09	1,00E-06	9,00E-01	2.235.698,904	589366,1	39,2	2.825.065
Tin (Cassiterite)	$E=10.6x^{-0.5}$	2,61E-06	6,09E-03	8,63E-01	426,354	15,2	11,4	442
Titanium (Ilmenite)	$E=8.16x^{-0.5}$	4,71E-03	2,42E-02	9,00E-01	4,511	7,2	128,1	12
Titanium (Rutile)	$E=6.32x^{-0.5}$	2,73E-04	2,10E-03	9,00E-01	8,824	13,8	243,8	23
Uranium (Uraninite)	$E=138.8x^{-0.28}$	1,51E-06	3,18E-03	7,50E-01	901,402	188,8	N.A.	1.090
Vanadium	$E=1.92x^{-0.5}$	9,70E-05	2,00E-02	9,00E-01	1.055,296	136,0	381,0	1.191
Wolfram (Scheelite)	$E=1.61x^{-0.5}$	2,67E-06	8,94E-03	9,00E-01	7.429,276	213,0	381,0	7.642
Yttrium-Monazite	$E=9.21x^{-0.5}$	1,30E-04	3,00E-04	9,00E-01	158,798	1198,3	-	1.357
Zinc (Sphalerite)	$E=4.49x^{-0.786}$	9,96E-05	6,05E-02	7,90E-01	155,031	1,5	40,4	157
Zirconium (Zircon)	$E=330.0x^{-0.5}$	3,88E-04	4,02E-03	9,00E-01	654,431	738,5	633,0	1.393

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D2.1: *Report with an analysis of the main limitations of variables and indicators selected to represent the pathways and scenarios.*

Annex 6: *Raw materials: production, reserves, resources, uses and recycling. Hubbert peaks and future production.*

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TABLES AND FIGURES

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1. Scope and introduction

This document is part of MEDEAS Deliverable 2.1. The main aim of this report is to explain in depth the availability of raw materials for supplying the potential future demand associate with renewables and green technologies. Accordingly, information on world production of non-fuel minerals from 1900 to 2015 is compiled. Additionally, information on reserves and resources for each commodity is compiled as well as an evaluation of future productions rates.

The results of this Deliverable will be implemented in MEDEAS model through the identified PAVs values as shown in Table 1.

Table 1. Links between raw materials and PAV list.

D2.1 Results	PAV	PAV description
Evolution of the production from 1900 to 2015 (in tonnes and Mtoe) of the minerals selected as critical.	108	Mineral production
Reserves (in tonnes and Mtoe) of the minerals selected as critical.	111	Total reserves
Resources (in tonnes and Mtoe) of the minerals selected as critical.	112	Total resources
Recycling rates (in %) of the minerals selected as critical.	113	Recycling rate
Recycling energy demand for select commodities (GJ/t).	114	Recycling energy demand
Material extraction energy for select commodities (GJ/t).	115	Material extraction energy demand
Material extraction emissions related to the energy needed for extraction and recycling.	116	Material extraction emissions

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2. Raw material production

Consumption of natural stock is a key element in current society, being economically, socially and culturally dependent. Minerals have become an ever-present component of our society and products that are used every day have mineral components that come from mining. There are virtually no products that contain no minerals or where minerals have not been used in their production. Base metals such as copper and zinc have a key role in those countries that are undergoing quick increases in social welfare, as they are essential to buildings, infrastructure, energy systems, automobiles, computers and mobile phones.

According to the Institute for Mineral Information, the average new born American in their lifetime (78.8 years) will consume approximately 1.4 million kilograms of minerals, metals and fuels (Minerals Education Coalition, 2015). Additionally, every year 17,940 kg of new minerals must be provided for every person in the United States to make the goods they use every day, including more than 2,600 kg of coal, 22 barrels of petroleum and 2,500 cubic meters of natural gas. Among others, 30 kg of aluminum are used to make buildings, beverage containers, cars and airplanes, 5 kg of lead are used for batteries, for communication and TV screen, as well as 3 kg of zinc are used to make rust resistant metals, various metals and alloys, paint, rubber or skin creams. Regarding industrial and construction minerals, more than 1,500 kilo-grams between stone, sand, gravel, cement and clays must be provided to make bricks, buildings, roads, houses, bridges and paper (Minerals Education Coalition, 2015).

In Europe, meanwhile, the average amount of extraction of resources during 2000 was around 13 tonnes per capita, or 36 kg per day (Friends of the Earth, 2009). When compared with North America, Oceania or Africa, being 68, 58, and 15 kg per person per day respectively, one can easily state that globally there is a great variation. When analyzing the consumption per capita, these numbers change drastically. In Europe, 43 kg are consumed per per-son per day, 88 in North America, 100 in Oceania and only 10 in Africa, meaning that an average European consumes as many as four times more re-sources than an average African. When observing European countries

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individually, differences in both material consumption per capita and material productivity can be observed, ranging from 3.8 tonnes of domestic material consumption per capita in Malta to over 50 in Ireland (European Environment Agency, 2012). With this consumption rate, we might be compromising the availability of natural resources for future generations; this is why it is critical to invest in research and exploration as well as in recycling and particularly in natural resources management and assessment techniques.

Due to this intensive consumption of mineral resources, on a worldwide scale there has been an exponential increasing trend of resource consumption in the last century. Studies that analyzed the growth in global material use in the 20th century have showed that the global total material extraction in-creased over the 1900-2005 period by a factor of eight, the strongest increase corresponding to construction minerals and ores and industrial minerals, which grew by a factor of 34 and 27 respectively (Krausmann et al., 2009).

The total world production from 1900 to 2015 of the 54 most common extracted mineral commodities is represented in Figure 1 (USGS, 2015).

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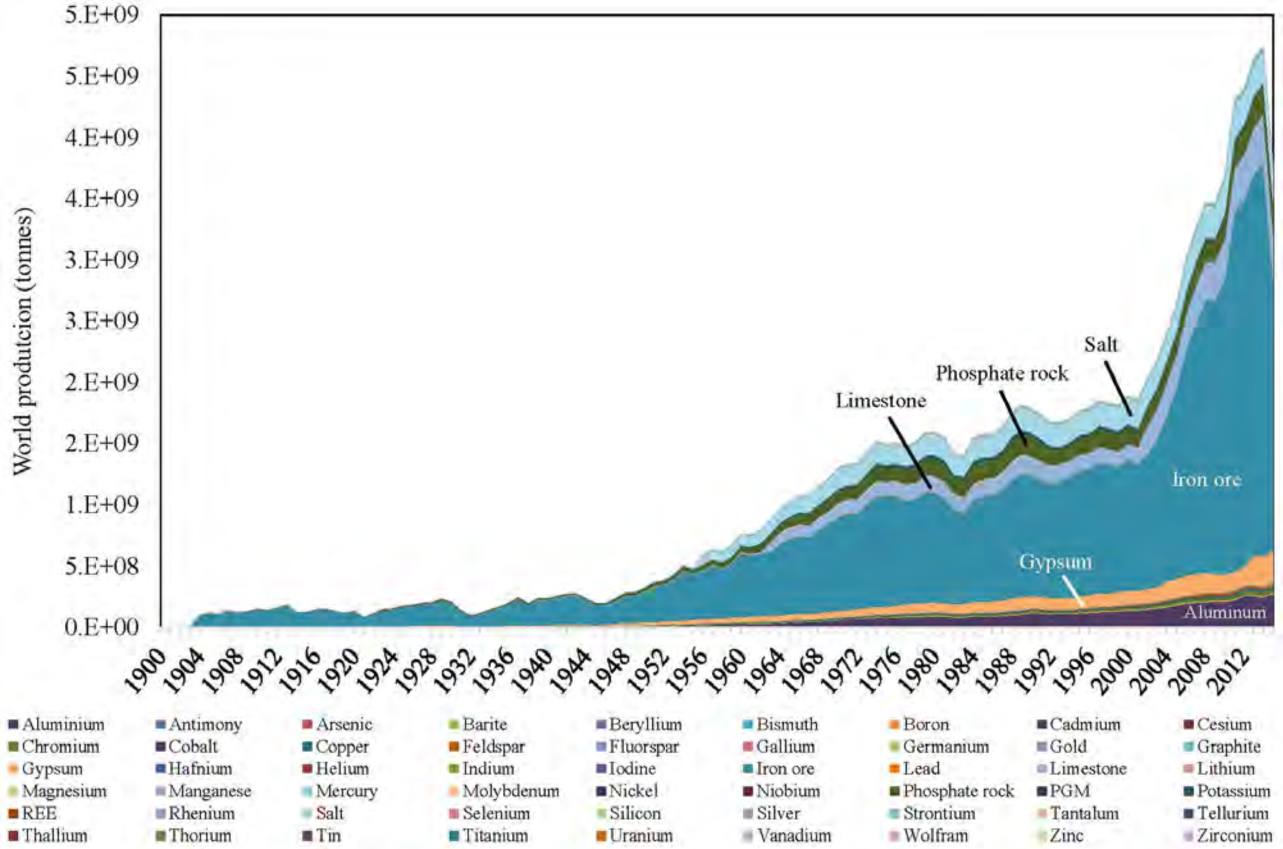

Figure 1. World production of main mineral commodities from 1900 to 2015 (in tonnes).

Of all of these commodities, aluminum, iron ore, gypsum, limestone, phosphate rock and salt extraction represent approximately 95% of the total world production in mass terms. When talking about the most extracted metallic minerals, the so-called "big six" (aluminium, chromium, copper, iron, manganese and zinc) they accounted for 67% of the total world production in 2015. In Figure 2 these commodities have been removed so the extraction of the other minerals can be better observed.

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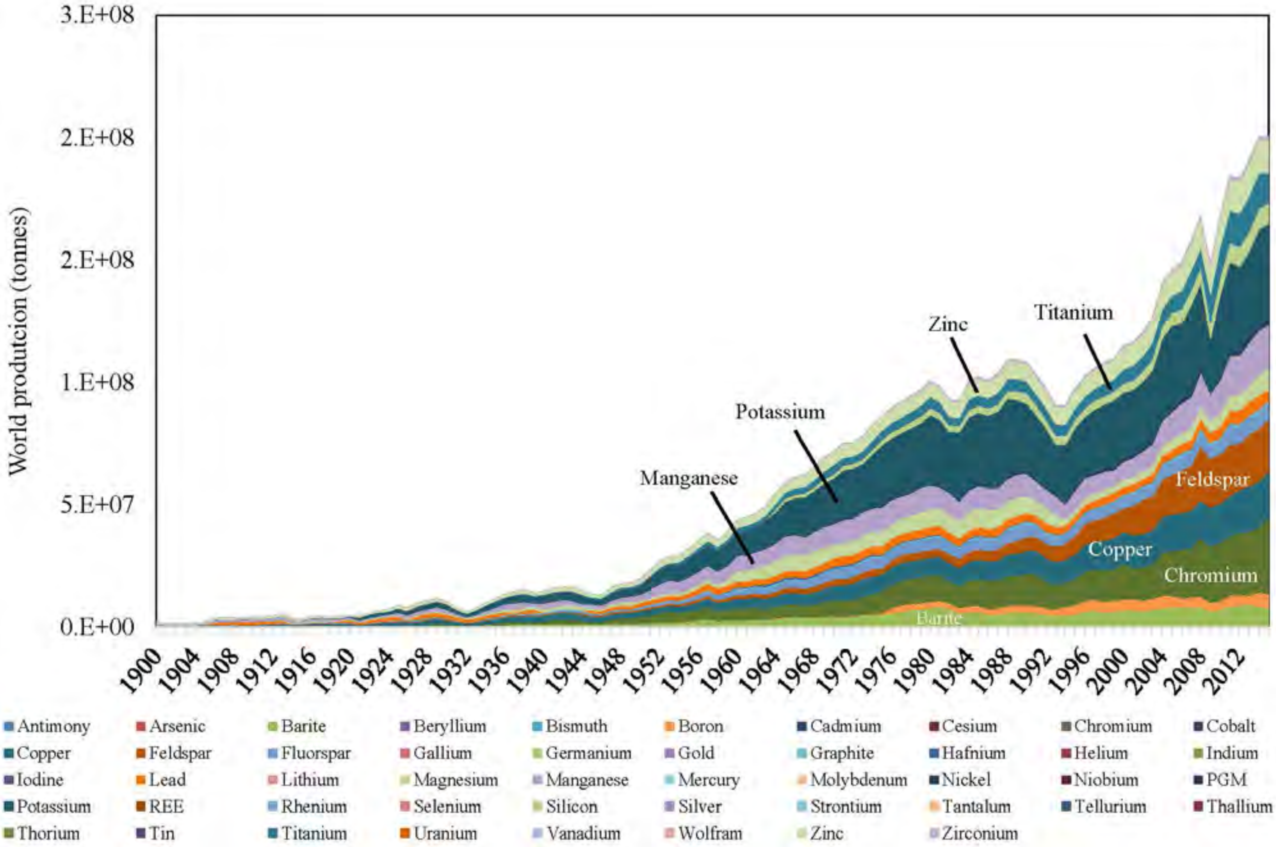

Figure 2. World production of selected mineral commodities from 1900 to 2015 (in tonnes).

In both cases, the tendency is quite clear, the world mineral production has been continuously increasing over time, reaching in the last few decades an exponential trend. The most striking and visual case is iron ore and gypsum production, which have increased by a factor of 3 in the last twenty years, but there are other commodities that have experienced highest increases during that same period of time. For instance, the world total gallium production increased from 62 tonnes in 1995 to 435 in 2015. The industrial usage in gallium began in the 1940s but it was not until 1970s when it was discovered that, when combined with other elements, it has semiconducting properties (Ullmann and Gerhartz, 2002). Since then a surge in demand has taken place to create gallium arsenide and gallium nitride compounds, widely used in LED's, in cell phone

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circuitry, in solar cells as semiconducting materials, among others. The same situation can be seen with the world production of germanium and indium, which increased more than 200% from 1995 to 2015.

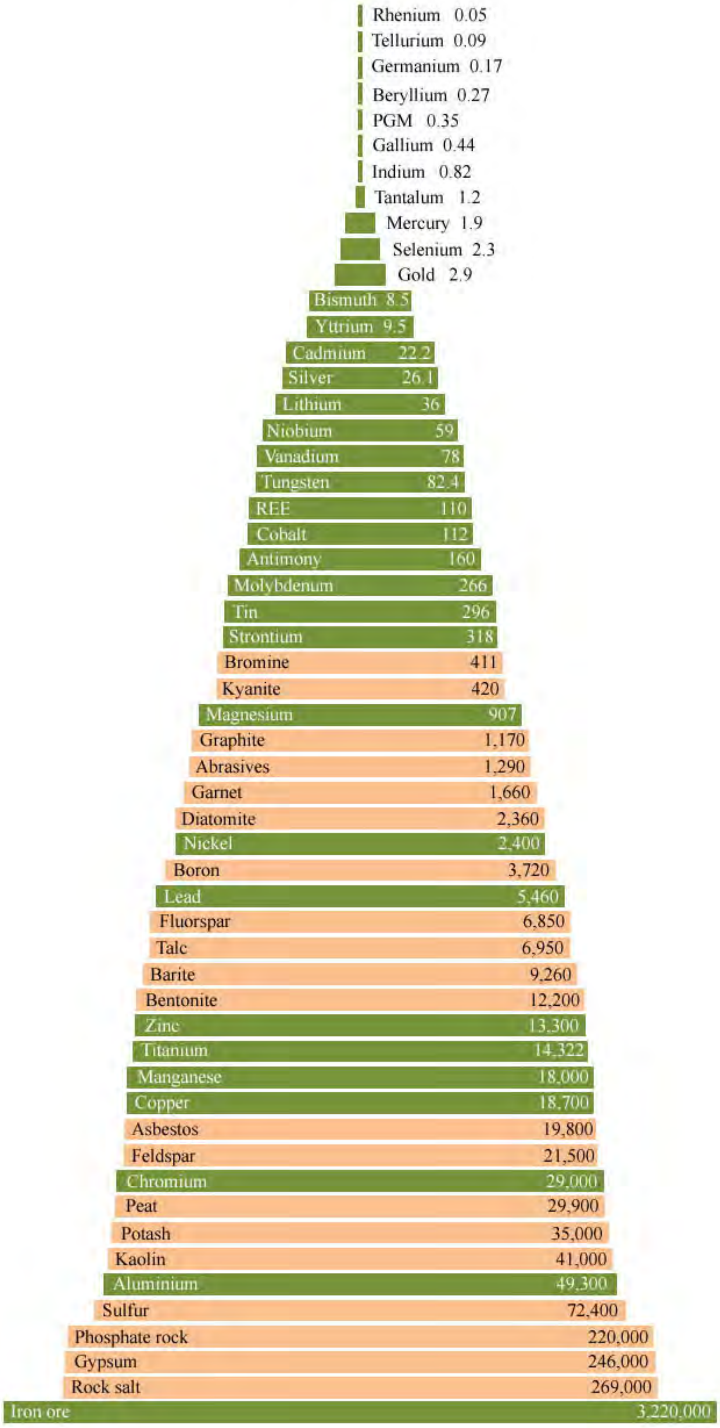

Figure 3. World primary production of mineral resources in 2014; production is in thousand metric tonnes.

Figure 3 represents the annual world production of mineral resources for 2014 (USGS, 2015). Metallic minerals, represented in green, are mainly in the upper half of the diagram, while industrial and construction minerals, represented in light orange, are in the lower part. In the base of the pyramid we can find the most extracted minerals, mainly industrial minerals, with the exception of iron ore, which is the most extracted commodity.

More than 4,700 million tonnes of non-fuel minerals were extracted during 2014, being produced in more than 90 different countries. The main countries that extracted non-fuel minerals were China, whose extraction accounted for almost 45% of the total world extraction, Australia, Brazil, United States and India, which accounted for 16, 8, 5 and 4%, respectively. According to the USGS (United States Geological Service), the production of rare earth elements (REE) in 2014 was 123,000 tonnes, measured in rare-earth oxides equivalent content, and 85% was produced in China. Additionally, half of the world reserves of REE are located in China and policies regarding tightening the REE exports were introduced in recent years, thereby increasing the trade value of these minerals (Mancheri, 2014).

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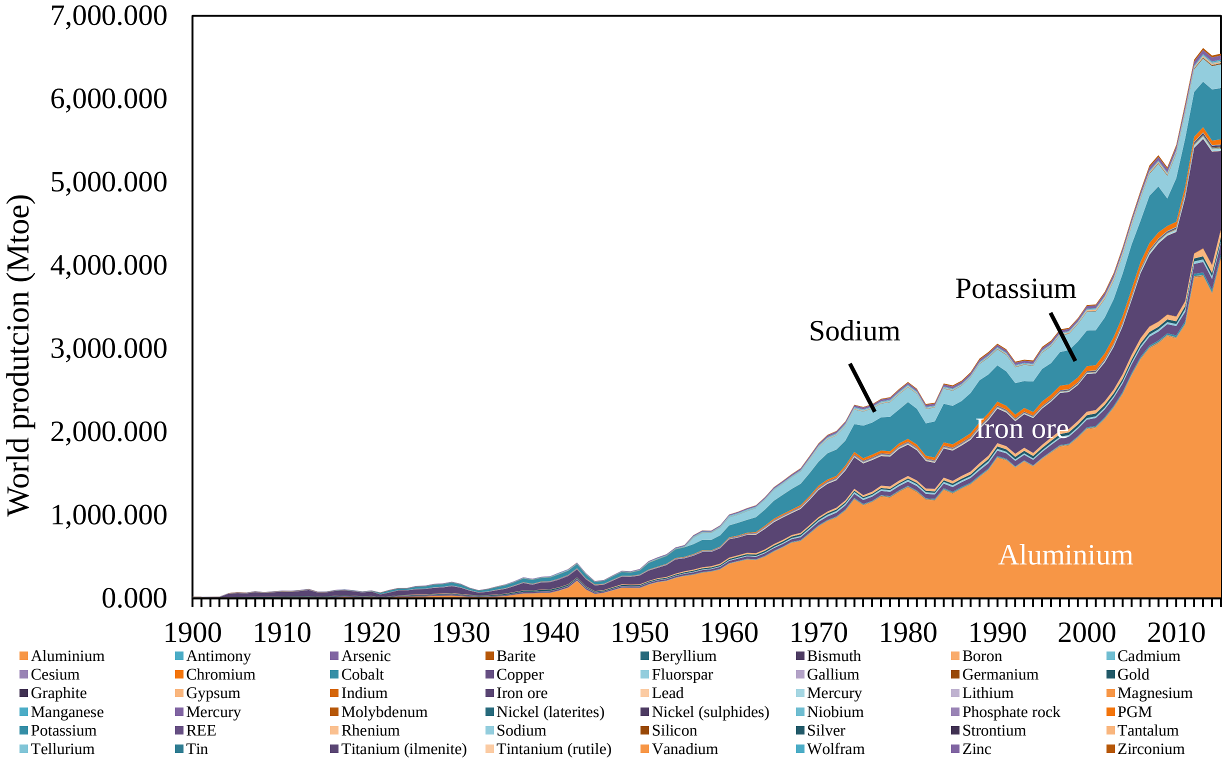

Figure 4. World production of the main mineral commodities from 1900 to 2015 (in Mtoe).

The production data can be additionally presented in exergy replacement costs (ERC) in Mtoe instead of in mass terms (Figure 4). The reason for this approach is explained in the corresponding Annex regarding the Methodology (*Thermodynamic assessment of mineral resources: the concept of exergy replacement costs and thermodynamic rarity).* As ERC take into account the scarcity of the materials and not only the weight in mass terms, as it is not the same to compare one tonne of PGM than one tone of limestone.

As in the previous case, the information regarding the most relevant commodities in weight, expressed in Mtoe, has been removed in Figure 5.

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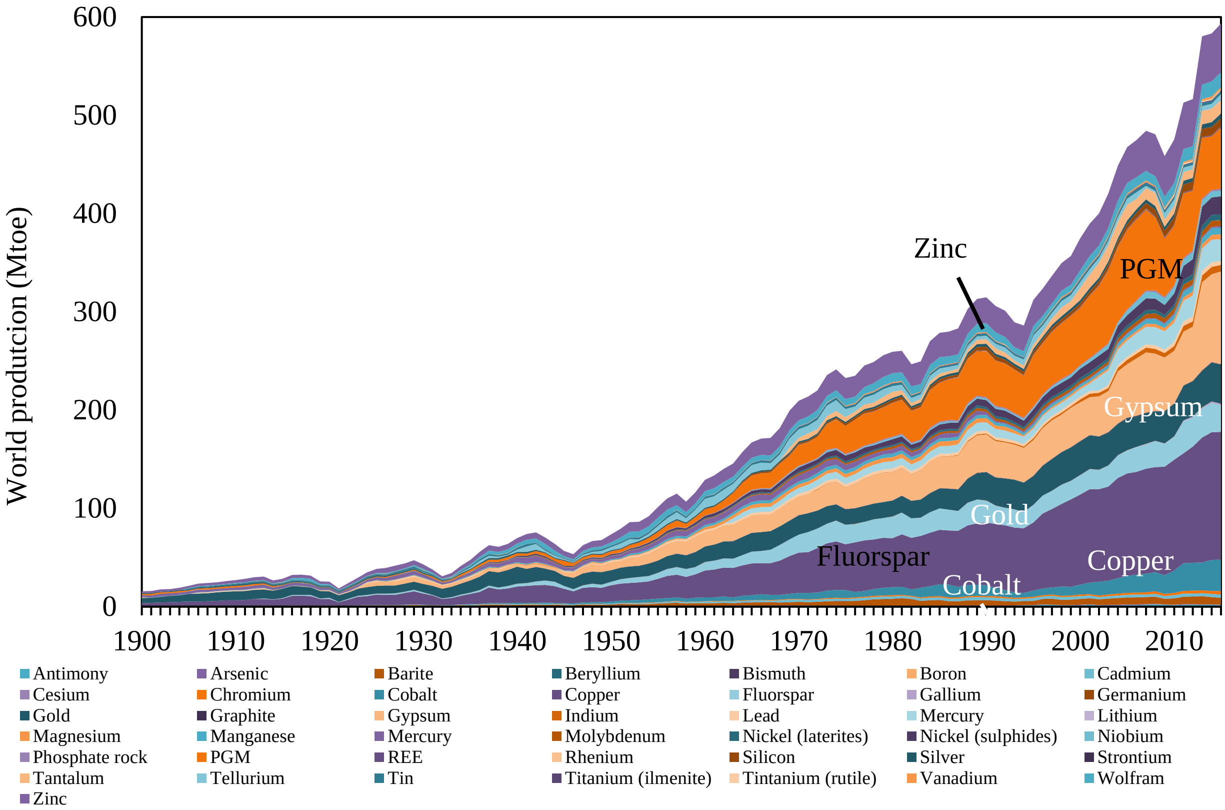

Figure 5. World production of selected mineral commodities from 1900 to 2015 (in Mtoe).

Bearing in mind this information, it becomes fundamental to assess the scarcity and criticality of each different commodity to ensure future availability for next generations. Another key point is to focus this study in the commodities that are going to be critical for the different sectors analyzed in MEDEAS. Combining these two factors, and taking into account the estimated demand of materials for green technologies, the substances selected for further studies are listed in Table 2 (American Physical Society and Materials Research Society, 2011; European Commission, 2014a; Moss et al., 2011; U.S. Department of Energy, 2011).

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Table 2. List of selected commodities for the MEDEAS model.

Aluminium	Iron ore	Phosphate rock
Chromium	Lithium	REE
Cobalt	Manganese	Silver
Copper	Molybdenum	Tantalum
Gallium	Nickel	Tellurium
Germanium	Niobium	Tin
Indium	PGM	Zinc

Some of these elements (gallium, germanium, indium, tellurium…) are extracted as byproducts of other main ores (aluminium, zinc, copper), therefore their production values, reserves and resources are conditioned by the values of the main ores (Figure 6).

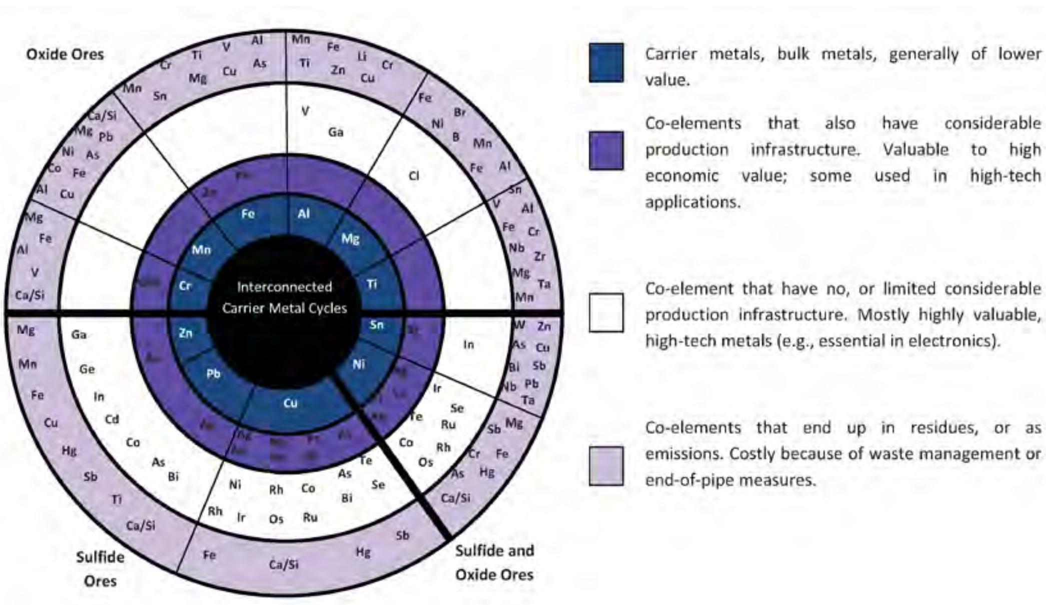

Figure 6. Metal Wheel. Redrawn from Reuter et al. (2005); Verhoef et al. (2004).

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3. Raw material reserves and resources

The scarcity of minerals is controlled by two terms, supply and demand. Usually 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.

The extraction is limited by the amount of minerals present in the crust, by the total resources, the identified resources, the estimated recoverable reserves and the reserves, as shown in Figure 7.

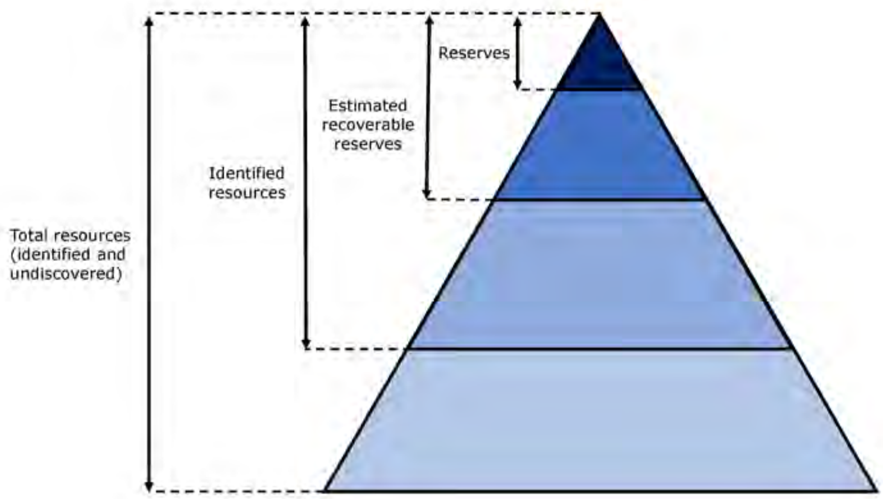

Figure 7. Mineral resource classification.

The *total resources* is the best estimate of the total availability of each commodity in the crust, included identified resources and undiscovered. The *identified resources* are resources whose location, quality and quantity are known or estimated. The *estimated recoverable reserves* includes the amount of material that can be mined with today's mining technology. *Reserves* are, last, that part of the estimated recoverable reserves which can be economically extracted or produced in a determined time. Therefore, as the technology and commodities prices change, the reserves varies as

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well. If new production technologies are developed, unattainable resources can be reachable or profitable.

Both reserves and resources are dynamic data. They may be reduced as ore is mined, as the extraction feasibility diminishes or increase as additional deposits are discovered or are more thoroughly explored. The estimations usually come from inventories of mining companies as well as from national geological services, and they are limited by many factors, such as price of the commodities, lack of exploration, geologic limitations and demand. Therefore, even if in this study we have used verified data from several sources, they must be taken as a first approach that can change over time.

The information on reserves and resources for each selected commodity is presented in Table 3, both in tonnes and in ERC (Mtoe). Different sources have been compared and the best and more accurate data have been used for the following steps of the process (Emsley, 2001; Frenzel et al., 2016, 2014; Sverdrup and Ragnarsdottir, 2014; USGS, 2015).

Table 3. Reserves and resources information for each selected commodity in tonnes and in Mtoe.

Commodity	Reserves (tonnes)	Reserves (Mtoe)	Resources (tonnes)	Resources (Mtoe)
Aluminium	28,000,000,000	418,229.33	75,000,000,000	1,120,257.14
Chromium	480,000,000	51.86	12,000,000,000	1,296.39
Cobalt	7,200,000	1,863.76	145,000,000	37,534.03
Copper	720,000,000	5,000.59	3,500,000,000	24,308.41
Gallium	5,200	17.93	1,000,000	3,448.29
Germanium	12,500	7.07	440,000	248.80
Indium	11,000	94.44	47,100	404.38
Iron ore	160,000,000,000	67,622.16	800,000,000,000	33,8110.78
Lithium	13,500,000	175.44	40,000,000	519.84
Manganese	570,000,000	212.28	1,030,000,000	383.59
Molybdenum	11,000,000	237.79	14,000,000	302.64
Nickel (sulphides)	32,400,000	587.08	52,000,000	302.64
Nickel (laterites)	48,600,000	193.81	78,000,000	311.05
Niobium	4,300,000	452.73	NA	-
PGM	66,000	10,587.55	100,000	16,041.74

Commodity	Reserves (tonnes)	Reserves (Mtoe)	Resources (tonnes)	Resources (Mtoe)
Phosphate rock	67,000,000,000	562.30	300,000,000,000	2,517.77
Silver	530,000	93.02	1,308,000	229.57
Tantalum	58,500	672.51	100,000	1,149.59
Tellurium	11,080	589.80	25,000	589.80
Tin	4,800,000	48.73	76,200,000	773.53
Zinc	230,000,000	848.98	1,900,000,000	7,013.29

Information regarding reserves and resources of rare earth elements (REE) is represented in Table 4 (Haque et al., 2014; USGS, 2015). Rare earth elements are a group of 14 chemically similar elements and are typically divided into heavy rare earth elements (HREE: Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu) and light rare earth elements (LREE: La, Ce, Pr, Nd, Sm). Additionally yttrium (Y), scandium (Sc) are usually also considered in this group.

Table 4. Reserves and resources information for rare earth elements (REE) in tonnes.

Commodity	Reserves (tonnes)	Resources (tonnes)*
Lanthanum	-	22,600,000
Cerium	-	31,700,000
Neodymium	-	16,700,000
Praseodymium	-	4,800,000
Samarium	1,755,000	2,900,000
Europium	234,000	244,333
Gadolinium	1,235,000	3,622,143
Terbium	156,000	566,104
Dysprosium	260,000	2,980,000
Erbium	39,000	1,850,000
Ytterbium	26,000	1,900,000
Scandium	13,000	15,400

* Data comes from Haque et al., 2014.

In the case of REE reserves and resources expressed in exergy replacement costs (Mtoe), the data are the following:

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- *Reserves*: according to USGS the total REE reserves are 130 million tonnes that in ERC represents **1,078.38 Mtoe**.
- *Resources*: USGS give an estimate of resources of 154 million tonnes that in ERC represents **1,277.47 Mtoe**. Using Haque *et al*. (2014) estimated resources, the corresponding ERC are **745.56 Mtoe**.

4. Energy use in the mining sector

Mining industry requires high amounts of energy to extract and process resources, including a variety of concentration and refining processes. According to the International Energy Agency, between 8 and 10% of the world total energy consumption is dedicated to the extraction of materials that the society demands, and that number does not take into account metallurgical processes, transport and other mining related activities (International Energy Agency, 2016).

The energy use, both in the mining and concentration stages and for smelting and refining, needed for each selected commodity for the MEDEAS model can be found in Table 5.

Table 5. Energy needed for mining selected commodities (Valero and Valero, 2014).

Commodity	**Mining and concentration (GJ/t)**	**Smelting and refining (GJ/t)**
Aluminium	10.5	23.9
Chromium	0.1	36.3
Cobalt	9.2	129.0
Copper	35.3	21.4
Gallium	610000	-
Germanium	498.0	-
Indium	3319.7	-
Iron ore	0.7	13.4
Lithium	12.5	420.0
Manganese	0.2	57.4
Molybdenum	136.0	12.0
Nickel (sulphides)	15.5	100.0
Nickel (laterites)	1.7	412.0

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Commodity	Mining and concentration (GJ/t)	Smelting and refining (GJ/t)
Niobium	132.0	228.30
Palladium	583333.3	-
Phosphate rock	0.3	4.6
Platinum	291666.7	-
REE	10.2	374
Silver	1281.4	284.8
Tantalum	3082.8	8.1
Tellurium	589366.1	39.2
Tin	15.2	11.4
Zinc	1.5	40.4

5. Raw material end-uses by sectors

Even if the MEDEAS model is focused on green and renewable technologies, all the mineral commodities are used for other sectors as well. Therefore, it is important to know the corresponding share of each sector for all the selected commodities. The principal end-uses by sectors of the big six are presented in Table 6.

Table 6. End-use and sector share for the "big six" metals (European Commission, 2014b).

Commodity	Sector	Share	Commodity	Sector	Share
Aluminium	Transport	37%	**Chromium**	Stainless steel	88%
	Construction	26%		Steel	9%
	Metals	16%		Other	3%
	Other	21%			
Copper	Electrical equipment and infrastructure	41%	**Iron**	Steel (construction)	26%
	Construction	13%		Steel (automotive)	16%
	Mechanical equipment	12%		Steel (metal and tubes)	24%
	Automotive	10%		Construction	11%
	Electronics	6%		Other	9%
	Other	18%			
Manganese	Construction	25%	**Zinc**	Galvanizing	50%
	Transport	14%		Brass and bronze	17%
	Mechanical equipment	34%		Alloys	17%
	Metals	16%		Chemicals	6%
	Other	5%		Other	10%

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The principal end-uses by sectors of the minerals selected as critical for the MEDEAS model are presented in Table 7.

Table 7. End-use and sector share for the minerals selected as critical for green and renewable technologies (European Commission, 2014b).

Commodity	Sector	Share	Commodity	Sector	Share
Cobalt	Batteries	30%	**Gallium**	Integrated circuits	41%
	Superalloys	19%		LED	25%
	Carbides, diamond tooling	13%		Alloys, batteries and magnets	17%
	Pigments	9%		Solar	17%
	Catalysts	9%			
	Magnets	7%			
	Other	13%			
Germanium	Fiber optic	30%	**Indium**	Flat display panels	56%
	Catalysts (polymers)	25%		Solders	10%
	Infrared optic	25%		Photovoltaics	8%
	Electrical and solar equipment	15%		Thermal interface materials	6%
	Others	5%		Batteries	5%
				Alloys/compounds	4%
				Compound semiconductors and LEDS	3%
				Others	8%
Lithium	Ceramics and glass	30%	**Molybdenum**	Oil and gas	18%
	Batteries	22%		Chemical/Petrochemical	15%
	Lubricating grease	11%		Automotive	14%
	Continuous casting	4%		Mechanical engineering	12%
	Gas and air treatment	4%		Power generation	8%
	Synthetic rubbers and plastics	3%		Process industry	8%
	Aluminium smelting	2%		Building/Construction	6%
	Pharmaceuticals	2%		Aerospace and defense	3%
	Other	22%		Electronics and medical	2%
				Other	14%
Nickel	Stainless steel	61%	**Niobium**	Steel (structural)	31%

	Nickel base alloys	12%		Steel (automotive)	28%
	Alloy steel	9%		Steel (pipeline)	24%
	Plating	7%		Steel (chemical industry)	3%
	Copper base alloys	2%		Superalloys	8%
	Other	5%		Other	6%
PGM	Autocatalyst	55%	**Phosphate rock**	Fertilizers and animal feed supplements	95%
	Jewelry	17%		Other	5%
	Electronics	10%			
	Chemical & electrochemical	7%			
	Medical alloys	3%			
	Petroleum production	1%			
	Other	7%			
REE (heavy)	Phosphors: lighting and displays	59%	**REE (light)**	Magnets	21%
	Magnets	12%		Glass polishing	17%
	Chemicals	10%		FCCs	14%
	Ceramics: electronics	7%		Metallurgy	12%
	Glass	4%		Batteries	9%
	Metallurgy	3%		Autocatalyst	7%
	Other	5%		Glass	7%
				Ceramics	2%
				Other	11%
Silver	Jewelry, coins and medals	37%	**Tantalum**	Capacitors	40%
	Electronics	22%		Superalloys	21%
	Photography	8%		Sputtering targets	12%
	Brazing alloys and solders	7%		Mill products	11%
	Photovoltaics	6%		Carbides	10%
	Ethylene oxide industry	3%		Chemicals	6%
	Other	17%			
Tellurium	Photovoltaics	40%	**Tin**	Solder (electronics)	45%
	Thermoelectric	30%		Tinplate (packaging)	16%
	Metallurgy	15%		Chemicals and pigments	15%
	Rubber formation	5%		Solder (industrial)	9%
	Other	10%		Brass and bronze	5%
				Float glass	2%
				Other	8%

6. Future estimated production using Hubbert peaks

6.1. Methodology

One of the aims of the MEDEAS project is to try to predict the raw material behavior production and evolution over time. Hubbert (1962, 1956), a geoscientist working for Royal Dutch Shell in Texas, found in the mid-fifties that trends in fossil fuel production almost always followed an identical pattern. All curves, regardless of the fuel's exact specification, started slowly before rising steeply and tending towards an exponential increase over time, until an inflection point was reached, upon which the shape became downward concave.

The observed trends that Hubbert saw were and remain to this day based on the fact that no finite resource can sustain beyond a brief period such a production growth rate; therefore, although production rates tend initially to increase exponentially, physical limits prevent their continuing to do so. So for any production curve of a fixed amount finite resource, two points on the curve are known on the outset, namely that at $t = 0$ and again at $t = 1$. The production rate will be zero when the reference time is zero and the rate will return to zero when the resource is exhausted, after passing through one or several maxima. The second consideration is that the area under the production curve must equal the quantity of the resource available (R). In this way, the production curve of a certain resource throughout history takes the ideal form of the bell as shown in Figure 8.

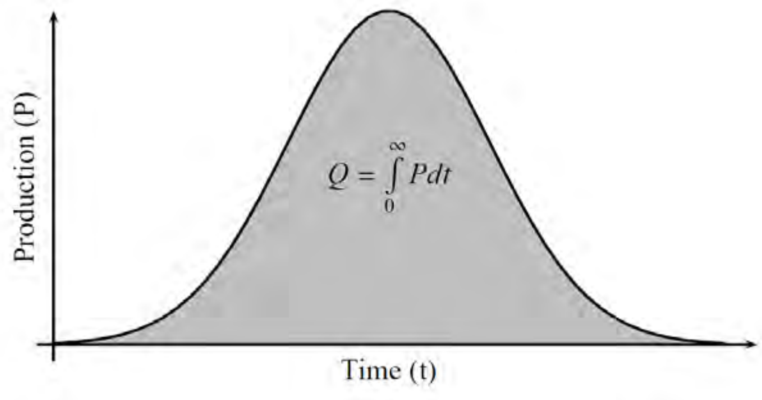

Figure 8. Hubbert's bell shape curve of the production cycle of any exhaustible resource (Hubbert, 1956).

The model of the curve to be adjusted is given by the following equation:

$$f(t) = \frac{R}{b_0\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t-t_0}{b_0}\right)^2}$$

Where R are the reserves or resources of the commodity and where the parameters b_0 and t_0 are the unknowns. The function's maximum is given by parameter t_0, and it verifies that:

$$f(t_0) = \frac{R}{b_0\sqrt{2\pi}}$$

It must be pointed out that any successful prediction obtained using the model (or its derivatives) depends on many factors, the reliability of the estimated reserves being a critical one (Höök et al., 2010). For instance, these curves can be asymmetric with the decline much sharper than the growth when several factors, such as economic, geological, political or technological, come into play, which may result in a deterioration of the quality of fit between the data and the Gaussian curves. Another critical issue is that recycling is not considered in the Hubbert model, a factor that in the case of critical metals, whose production is not very high but whose recycling rates are fundamental for supplying the market, could be essential to predict future extraction trends.

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Accordingly the possible deviations of the empirical data from the theoretical curves are classified into the following categories:

- *Political instability:* the political/economic intervention of OPEC in 1973-4 and again in 1980 following the Iran-Iraq War is for instance argued to have prevented the Hubbert global peak oil prediction of 2000 from being correct (Almeida and Silva, 2009). Thus, as economists tend to argue, the interaction of supply and demand determines the equilibrium price path in a market economy.

- *Investment niche:* gold is the most representative commodity whose production depends strongly on market speculation. Indeed with the global economic instability and market price fluctuations, investment in gold has increased, as investors seek safe-havens. Other precious metals such as silver or platinum follow similar patterns of behavior.

- *Environment and health factors*: certain minerals have proven to be dangerous for the environment and/or human health. Consequently, alternative and safer options have been sought to replace the original substance in its application, leading to sharp reductions in its extraction. Obviously if there is no commercial interest in a mineral, there is no investment wasted in its exploration. Hence, real or perceived mineral scarcity often has an economic origin rather than a geological one. A clear example of this is that of mercury. Its decline in consumption, except for in small-scale gold mining, forced companies to curve and finally stop production, as is the case for the Spanish Almadén mine, once the leading producer, where mining ceased in 2003. Consequently, production is said to follow an economic-driven bell-shaped curve. Commodities with similar stories are those of arsenic, beryllium, antimony or radioactive minerals (mainly uranium and thorium).

- *Concentration of supply:* as claimed by Moss et al. (2011), where the structure of supply is monopolistic or dominated by only a few players, individual large supplier countries have sufficient market power to affect global production

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and price thresholds as in the case of rare earths, antimony or fuel minerals, particularly oil and natural gas.

- *Byproduct character*: when the mineral is a byproduct, production decisions may be driven by the economics of the host-metal and hence the curves do not necessarily follow typical bell-shaped curves. This aspect is especially pronounced at the local scale.

- *Technological factors*: this category relates to the ability to substitute and recycle minerals. The general trend observed is that these factors only slightly affect a commodity's production pattern. For instance, in the case of Aluminium or iron, where recycling rates are high, the effect of recycling is imperceptible due to the continual growth in demand for new raw-material. Nevertheless, substitution and recycling could become more critical into the next decades when scarcity becomes more acute. Once the peak of a mineral has been reached (or when it is in sight), the sought for alternative materials and recycling is enhanced so as to reduce production costs. The result is that the curve is asymmetrical, given that the section right of the peak falls more rapidly than the left climbed.

Generally speaking, the Hubbert Peak Model can be rather satisfactorily applied to those minerals, where the concentration factor is not important, i.e. to liquid and gaseous fossil fuels. However, there have been a few prominent studies relating the application of the Hubbert model to non-fuel minerals applied exponential-like curves to the production of various different commodities. The bell-shaped curve is better suited to non-fuel minerals than fuels if exergy is plotted as a function of time instead of mass. This is because whilst fuel quality remains near constant with extraction, non-fuel mineral quality degrades as time goes on (as long as mining continues). Therefore exergy is a better unit of measure than mass, as it accounts not only for quantity but also for ore grades and composition.

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6.2. Hubbert peaks

Using the combined methodology of the Hubbert Peak Model and the exergy approach, the Hubbert curves for the selected commodities have been calculated. In each case, the accumulated production from 1900 to 2015 and the reserves and resources for each commodity have been introduced in the calculation system.

6.2.1. The "big six"

First, the Hubbert curves of the most extracted materials, the so-called "big six" (aluminium, chromium, copper, iron, manganese and zinc) have been represented in Figure 9 and Figure 10 using the available information on reserves, and Figure 11 and Figure 12 using the available information on resources.

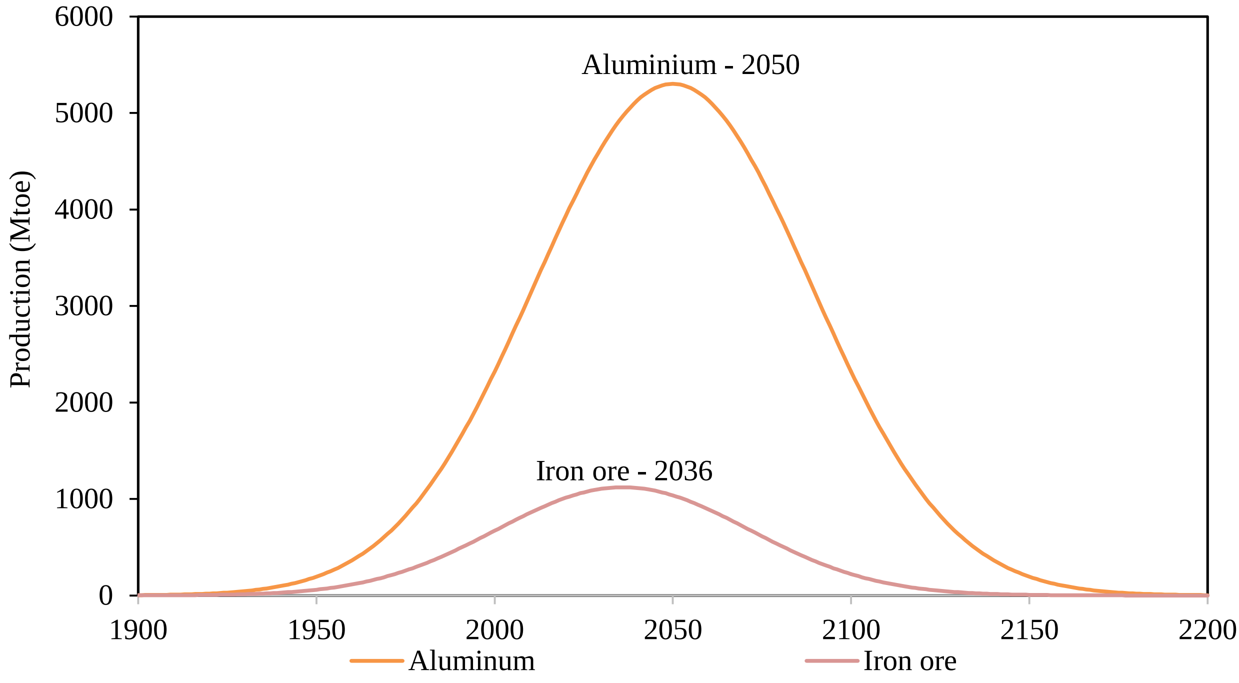

Figure 9. The Hubbert peak applied to the "big six" reserves (1).

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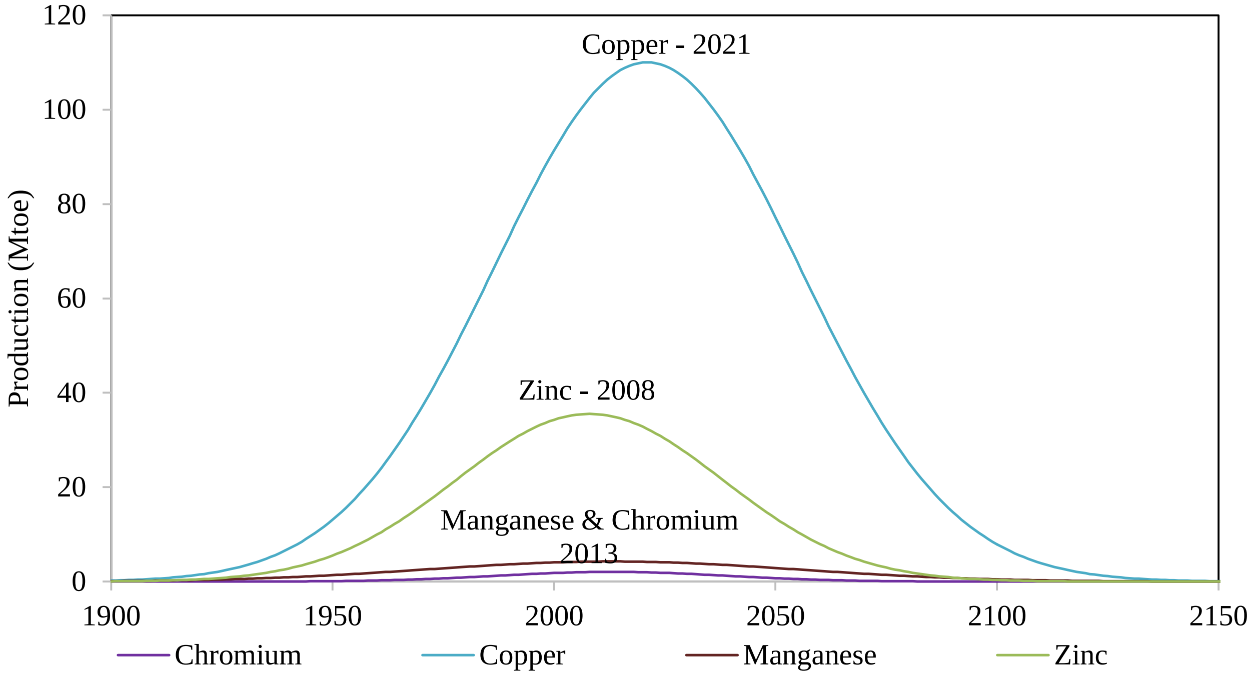

Figure 10. The Hubbert peak applied to the "big six" reserves (2).

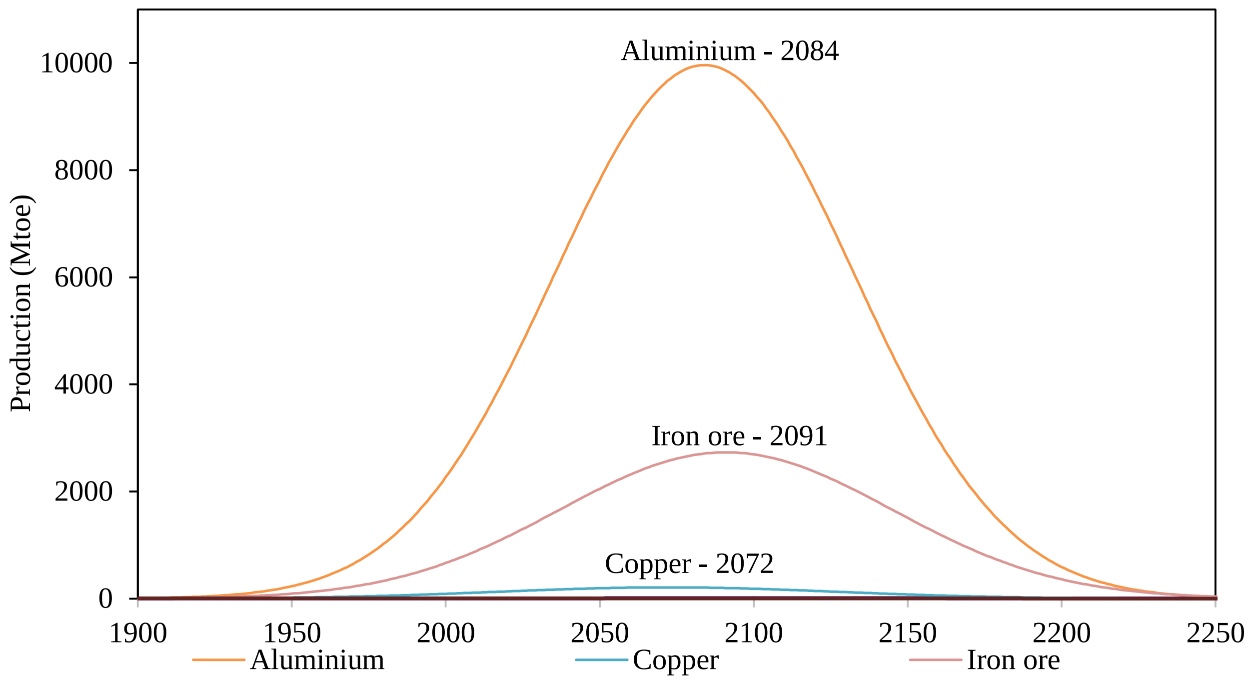

Figure 11. The Hubbert peak applied to the "big six" resources (1).

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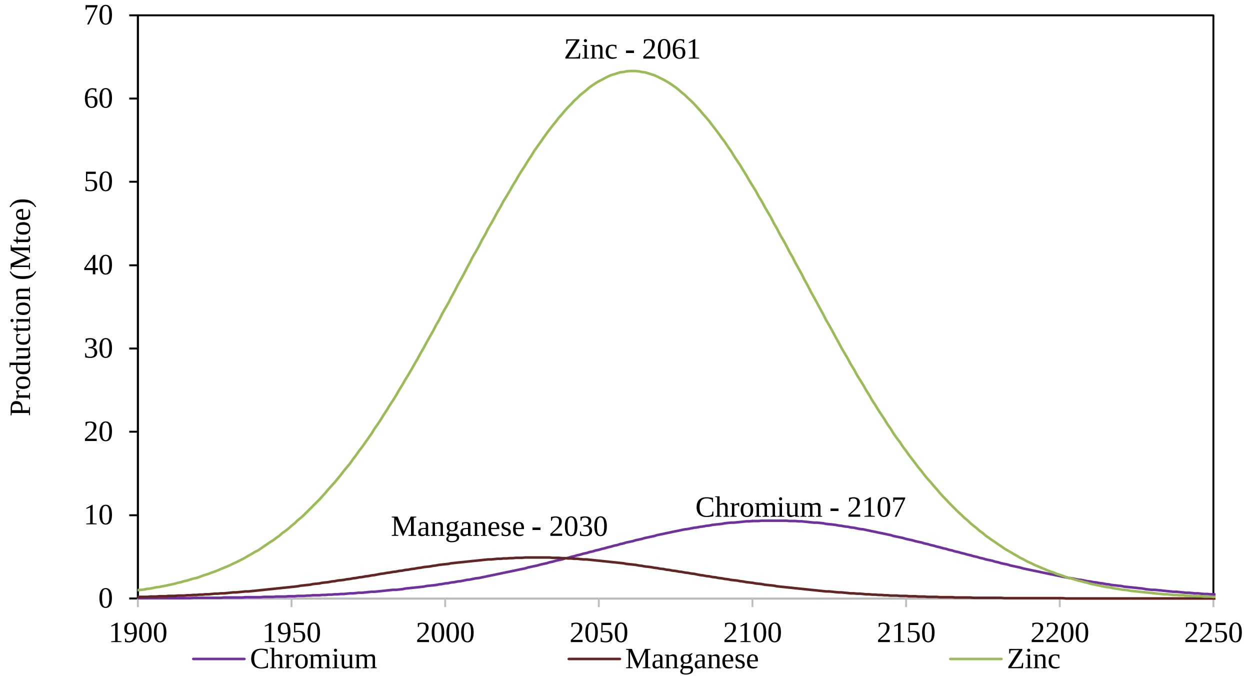

Figure 12. The Hubbert peak applied to the "big six" resources (2).

6.2.2. Critical minerals

For the rest of the selected critical commodities, the Hubbert curves are represented considering the available information on reserves. As the production and reserves, and their corresponding weight expressed in ERC is very variable according to the quality of each commodity, the Hubbert peaks have been represented in three different figures: Figure 13, Figure 14 and Figure 15.

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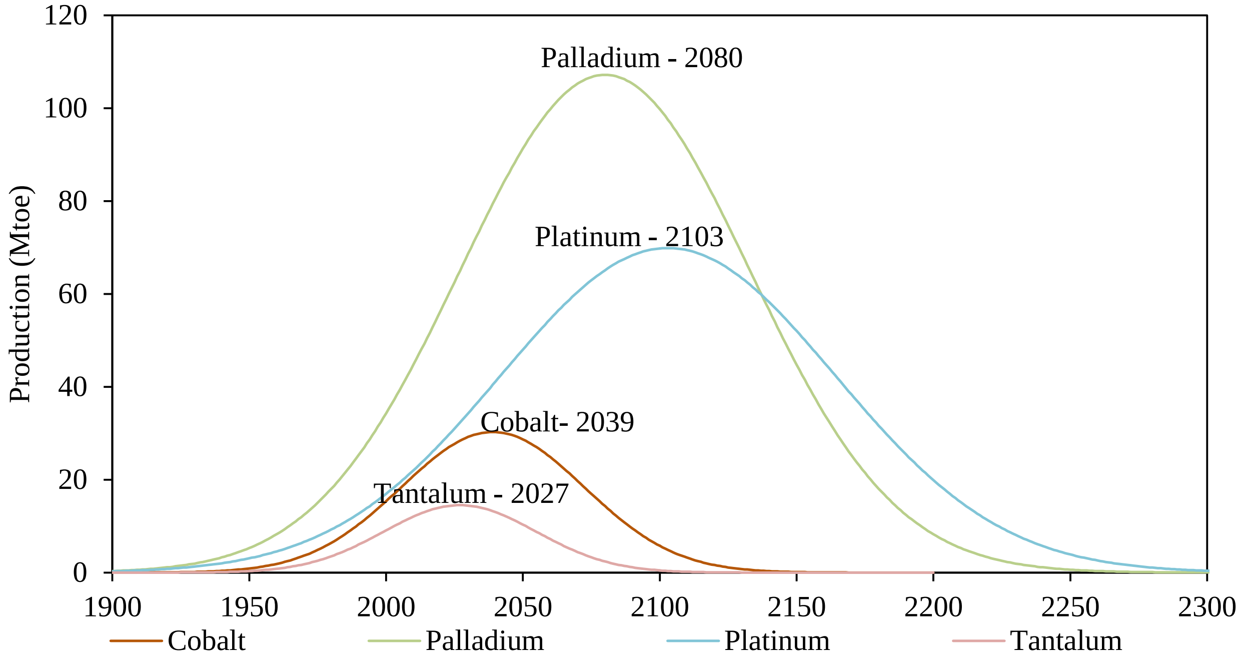

Figure 13. The Hubbert peak applied to selected critical minerals reserves (1).

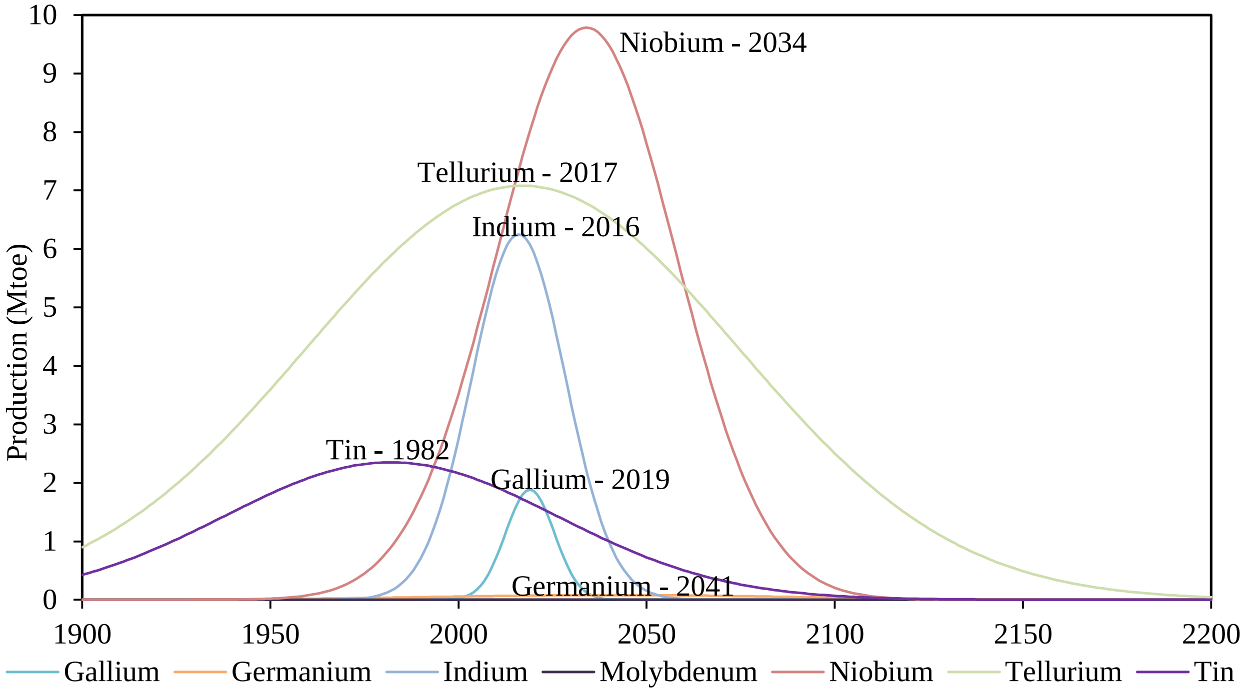

Figure 14. The Hubbert peak applied to selected critical minerals reserves (2).

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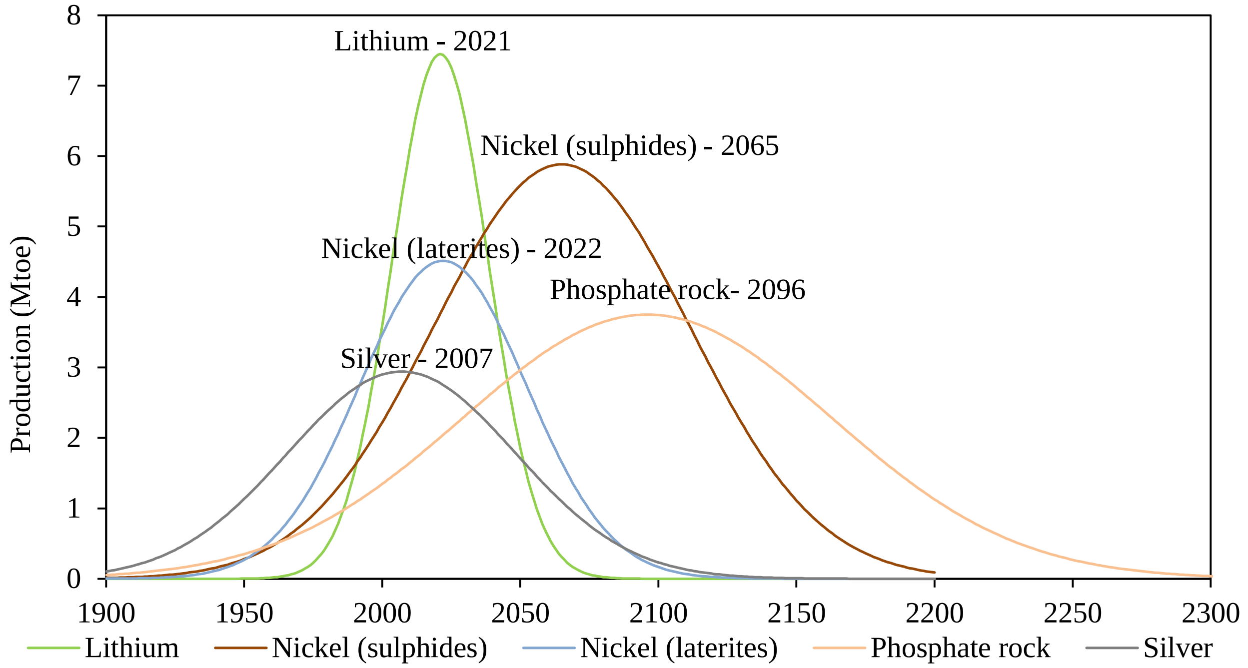

Figure 15. The Hubbert peak applied to selected critical minerals reserves (3).

In the case of the Hubbert peaks where the accumulated production and resources information is used, they can be found in the next three following figures: Figure 16, Figure 17 and Figure 18.

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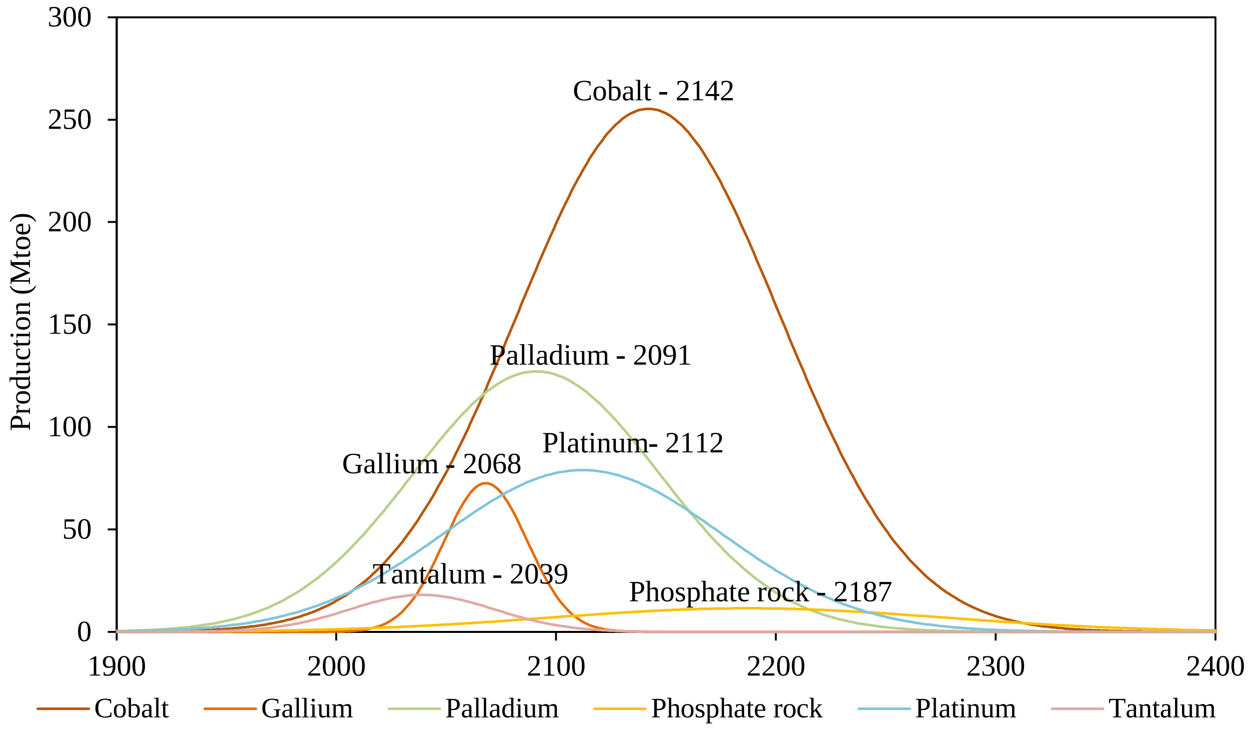

Figure 16. The Hubbert peak applied to selected critical minerals resources (1).

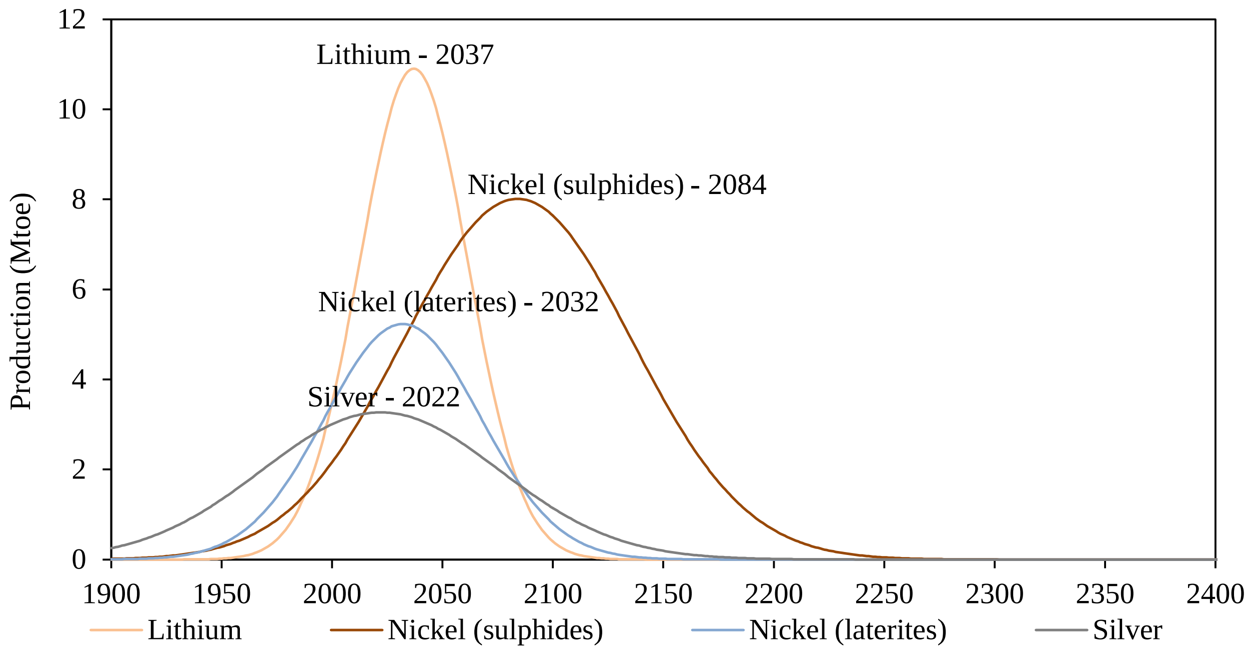

Figure 17. The Hubbert peak applied to selected critical minerals resources (2).

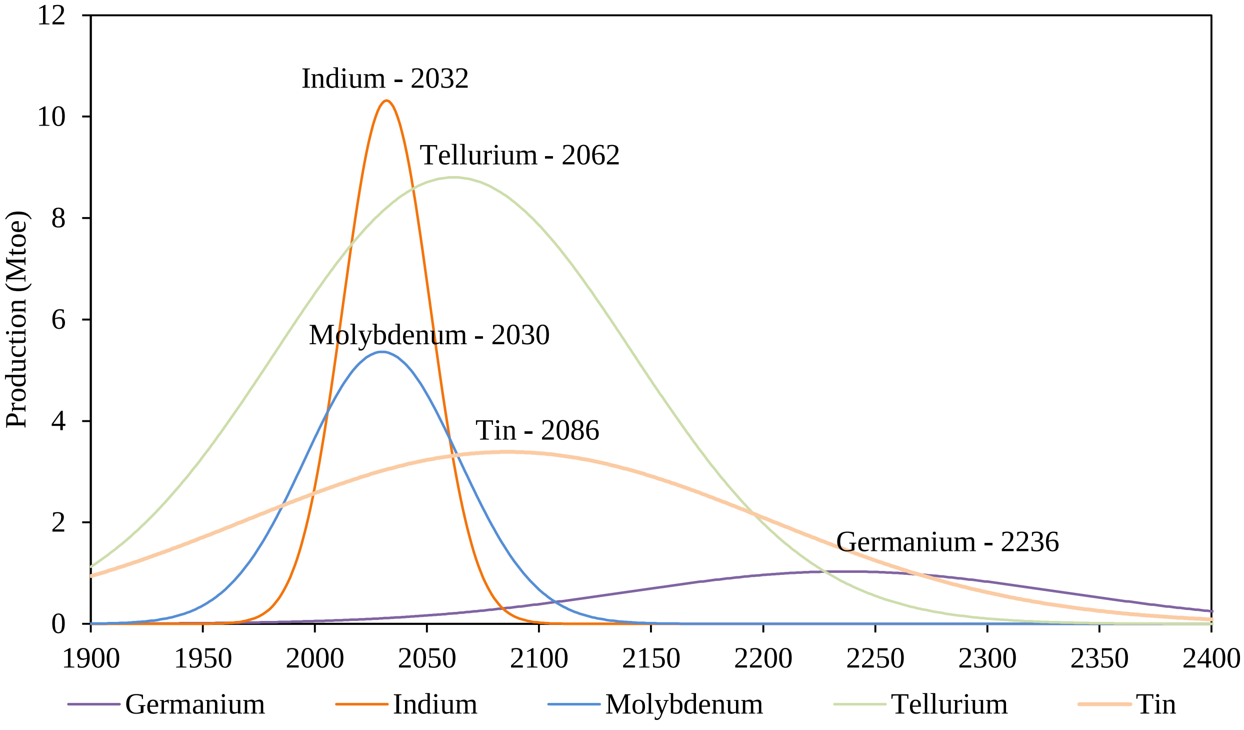

Figure 18. The Hubbert peak applied to selected critical minerals resources (3).

For the case of REE, the Hubbert peaks have been calculated using only information in tonnes as the ERC of all the different REE considered is not available. Additionally, as the most accurate data are resources information, only this graphic is going to be presented in the deliverable (Figure 19 and Figure 20).

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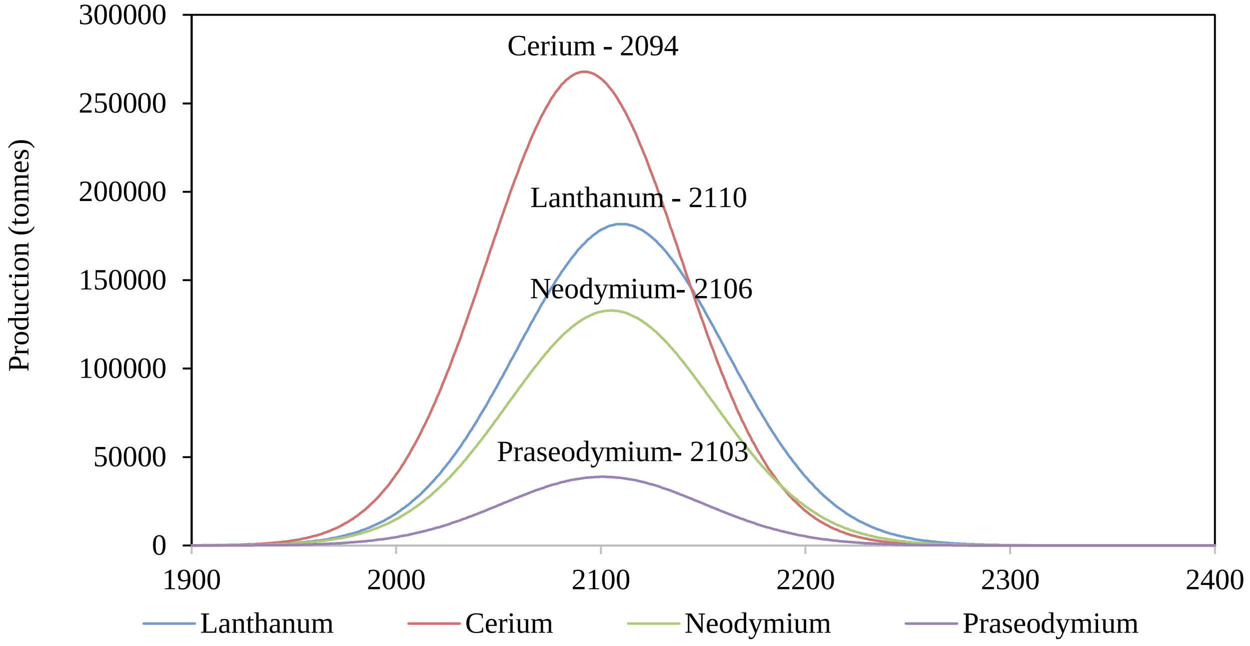

Figure 19. The Hubbert peak applied to REE resources (1).

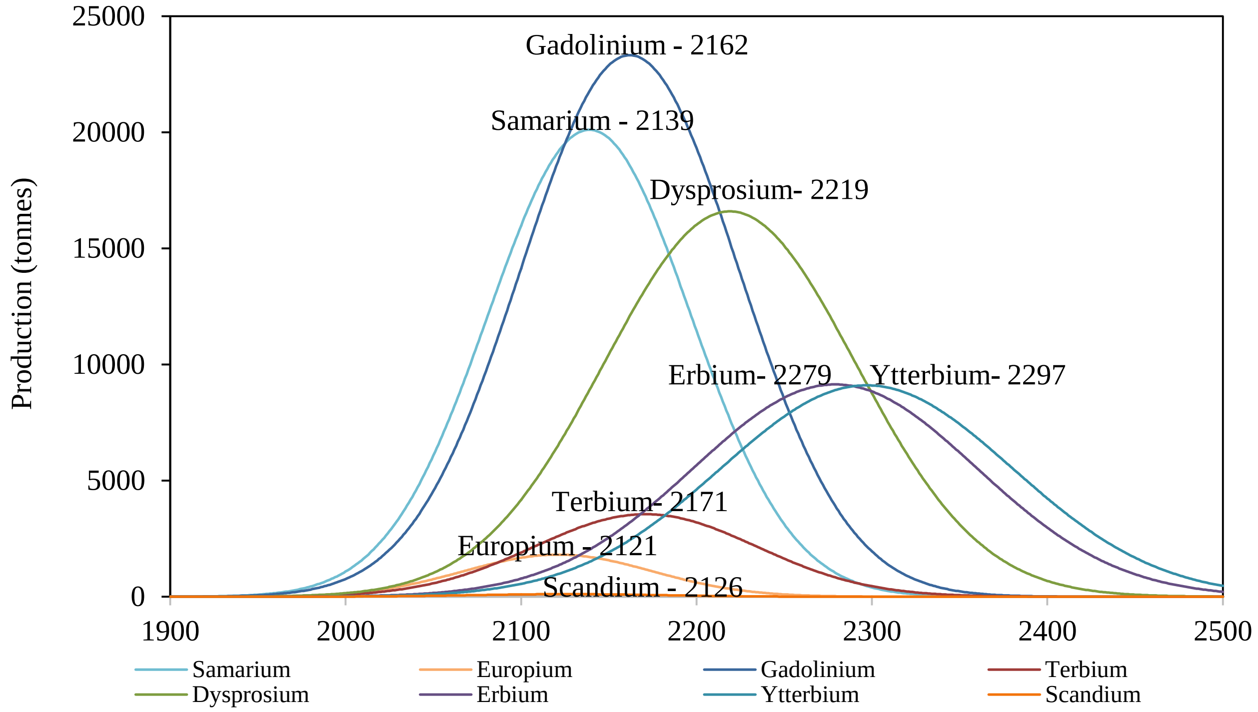

Figure 20. The Hubbert peak applied to REE resources (2).

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7. Recycling rates

Metals are used for a wide number of applications, as seen on Section 5 of this document, and they are inherently recyclable. They can be reused, minimizing the need to extract raw materials and saving important amounts of energy and water while minimizing as well the environmental impacts and degradation.

Recycling rates can be defined in many different ways and for different perspectives and stages, according factors such as product, metal, metal in product, among others.

According to the International Resource Panel created by UNEP (Graedel et al., 2011), *recycled content* is defined as the fraction of scrap metal in the total metal input to metal production (Figure 21). The difference between total metal input and metal production equates to the losses experienced throughout the entire life cycle. These include residues in mining and metallurgy derived from tailings, slags, effluents and dust. The *End-of-life recycling rates* (EOL-RR) refers to functional recycling and includes recycling as a pure metal (i.e. copper) and as an alloy (i.e. brass) (Figure 22). Last, the old scrap ratio (OSR) describes the fraction of old scrap in the recycling flows (Figure 23).

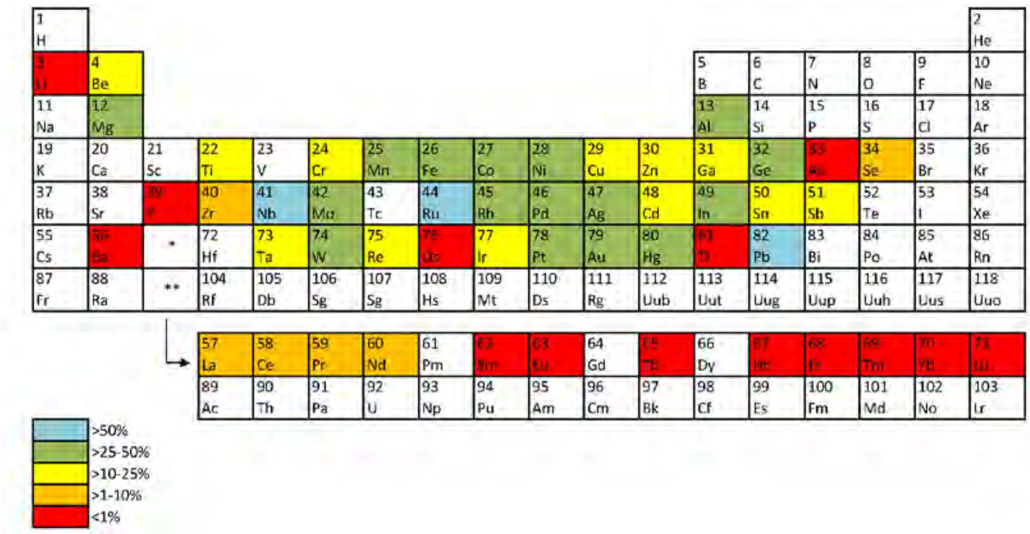

Figure 21. The periodic table of recycling content (RC) for sixty metals (from Graedel et. al, 2011).

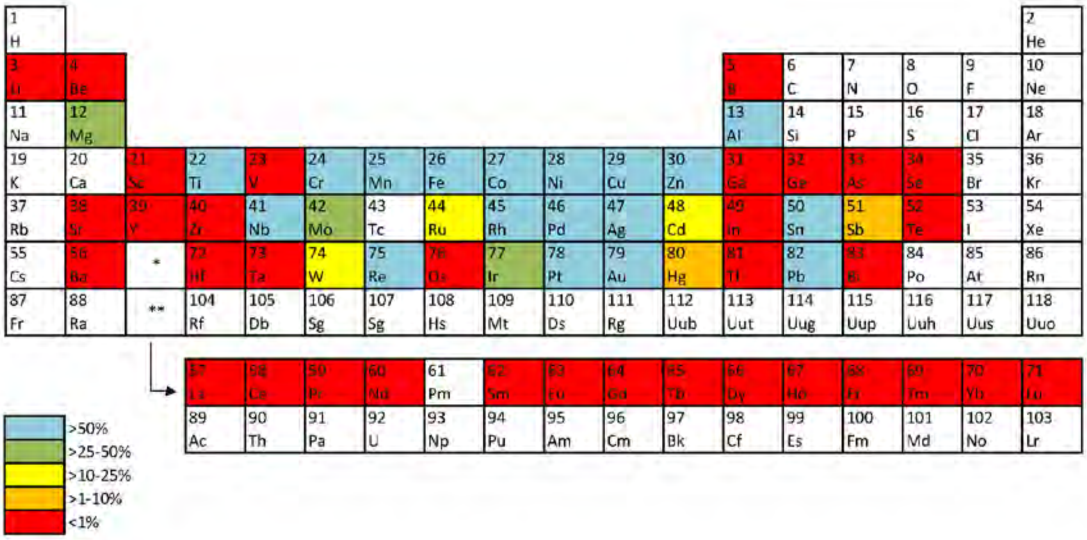

Figure 22. The periodic table of End-of-life recycling rates (EOL-RR) for sixty metals (from Graedel et. al, 2011).

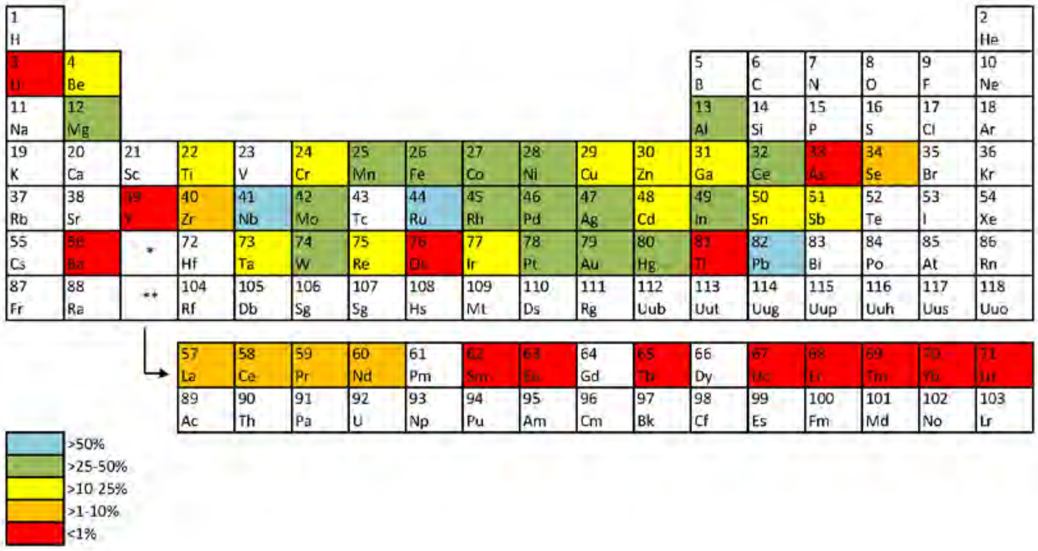

Figure 23. The periodic table of old scrap ratio (OSR) for sixty metals (from Graedel et. al, 2011).

The specific values of recycled content (RC), end-of-life recycling rate (EOL-RR) and old scrap ratio (OSR) for the commodities selected as critical for the MEDEAS model are listed in Table 8.

Table 8. Different recycling rates of the commodities selected as critical for the MEDEAS model according to the expected demand in green technologies.

Commodity	RC (in %)	EOL-RR (in %)	OSR (in %)
Aluminium	36	75	40-50
Chromium	20	87	60
Cobalt	32	68	50
Copper	30	60	78
Gallium	25	<1	<1
Germanium	35	<1	40
Indium	25-50	<1	<1
Iron ore	50	63	52
Lithium	<1	<1	<1
Manganese	37	53	33
Molybdenum	33	30-40	33
Nickel	29	58-63	66-70
Niobium	22	53	50
PGM	50	60-95	>80
Silver	30	30-50	>80
Tantalum	10-25	<1	1-10
Tellurium	-	<1	-
Tin	22	75	50
Zinc	18-27	35-60	34

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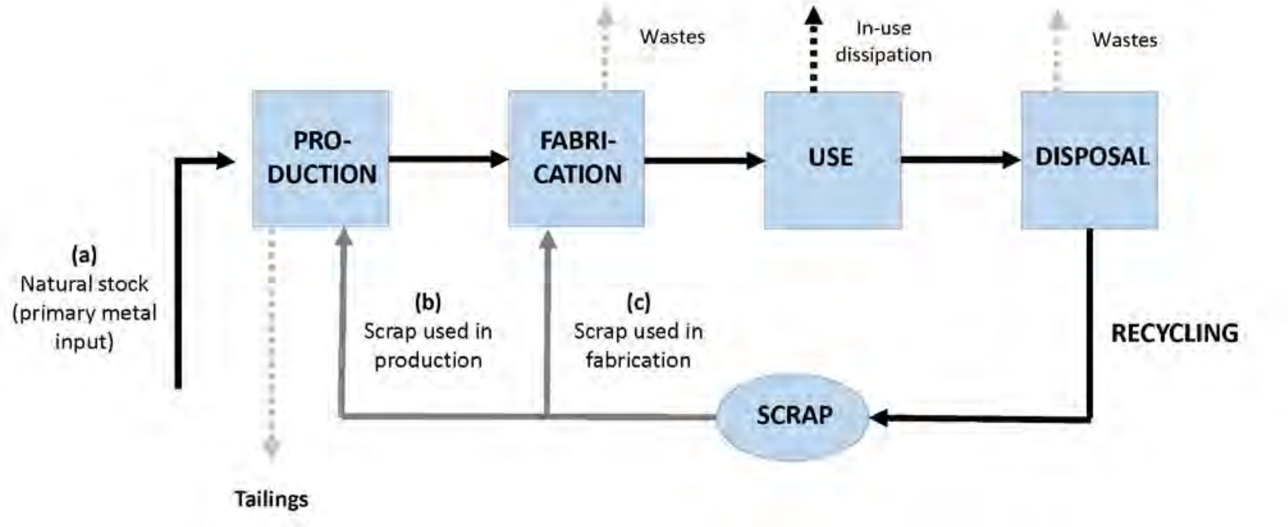

Figure 24. Simplified metal life cycle (modified from UNEP, 2011).

Recycled content as an indicator is absolute in that it measures the actual amount of metal that enters into the industrial lifecycle of an element. Being, according to Figure 24:

$$RC = \frac{b + c}{a + b + c}$$

The life cycle comprises of mining and metallurgical stages, product manufacture, use, end-of-life and scrap recycling. Any scrap metal contains both that was generated along the entire manufacturing chain and that recovered from products that upon reaching end-of-life were converted into secondary material. Therefore, the Recycling content (RC) is the recycling rate that is going to be implemented in the MEDEAS model.

8. Recycling energy

Secondary production can be fundamental to meet the demand of commodities, especially the most extracted ones. In Table 9 the energy needed to recycle several

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commodities and the energy savings compared to extraction are represented (Grimes et al., 2008, 2016).

Table 9. Energy needed for recycling and savings compared to extraction for the commodities selected for the MEDEAS model.

Commodity	**Energy needed for Recycling (GJ/t)**	**Energy savings compared to extraction (%)**
Aluminium	2.4	92-95
Chromium	-	75
Copper	6.3	85
Iron	-	47
Nickel	1.86	76
Tin	0.2	99
Zinc	18	60

9. Conclusions

The main conclusions of this study regarding the available information on reserves, resources, energy needed for extraction, energy needed for recycling, and the calculated Hubbert peaks for each commodity selected for MEDEAS are reflected in Table 10.

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Table 10. Summary of the reserves, resources, Hubbert peak, and energy for mining and recycling for selected commodities in the MEDEAS model according to the expected demand in green technologies.

Commodity	Reserves (Mtoe)	Peak (using reserves)	Resources (Mtoe)	Peak (using resources)	Mining and concentration (GJ/t)	Smelting and refining (GJ/t)	Recycled content (%)	Energy needed for recycling (GJ/t)
Aluminium	418,229.33	2050	1,120,257.14	2084	10.5	23.9	36	2.4
Chromium	51.86	2013	1,296.39	2107	0.1	36.3	20	-
Cobalt	1,863.76	2039	37,534.03	2142	9.2	129.0	32	-
Copper	5,000.59	2021	24,308.41	2072	35.3	21.4	30	6.3
Gallium	17.93	2019	3,448.29	2068	610000	-	25	-
Germanium	7.07	2041	248.80	2236	498.0	-	25	-
Indium	94.44	2016	404.38	2032	3319.7	-	25-50	-
Iron ore	67,622.16	2036	338,110.78	2091	0.7	13.4	50	-
Lithium	175.44	2021	519.84	2037	12.5	420.0	<1	-
Manganese	212.28	2013	383.59	2030	0.2	57.4	37	-
Molybdenum	237.79	2005	302.64	2030	136.0	12.0	33	-
Nickel (sulphides)	587.08	2065	302.64	2084	15.5	100.0	29	1.86 (for Nickel)
Nickel (laterites)	193.81	2022	311.05	2032	1.7	412.0	29	
Niobium	452.73	2034	-	-	132.0	228.30	22	-
Palladium	7,058.37	2080	10,694.50	2091	583333.3	-	50	-
Phosphate rock	562.30	2096	2,517.77	2187	0.3	4.6	-	-
Platinum	3,259.18	2103	5,374.25	2112	291666.7	-	50	-
REE	1,078.38	2120	1,277.47	2127	10.2	374	1-10	-

Commodity	Reserves (Mtoe)	Peak (using reserves)	Resources (Mtoe)	Peak (using resources)	Mining and concentration (GJ/t)	Smelting and refining (GJ/t)	Recycled content (%)	Energy needed for recycling (GJ/t)
Silver	93.02	2007	229.57	2022	1281.4	284.8	30	-
Tantalum	672.51	2027	1,149.59	2039	3082.8	8.1	10-25	-
Tellurium	589.80	2017	589.80	2062	589366.1	39.2	-	-
Tin	48.73	1982	773.53	2086	15.2	11.4	22	0.2
Zinc	848.98	2008	7,013.29	2061	1.5	40.4	18-27	18

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D2.1: *Report with an analysis of the main limitations of variables and indicators selected to represent the pathways and scenarios.*

Annex 7: *Passenger light duty vehicles based on electro mobility and physical constraints*

Grant agreement: 691287

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MEDEAS

MODELING THE RENEWABLE ENERGY TRANSITION IN EUROPE

European Commission

INDEX

TABLE AND FIGURE INDEX

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1. Scope and goal

This document is part of MEDEAS Deliverable 2.1. The main aim of this report is to explain in depth which physical constraints are expected in the passenger vehicle sector from 2015 to 2050 from the point of view of raw materials.

This activity is done through an assessment of the materials required to manufacture different types of vehicles from 2015 to 2050.

The results of this Deliverable will be implemented in MEDEAS model through PAVs database values. For this reason the following table shows the links between physical constraint identification and PAVs.

Table 1. Link between physical constraints in passenger vehicles and PAVs.

D2.1 Results	PAV	PAV description
European and World passenger fleet evolution from 2015 to 2050	61	Passenger light-duty vehicles fleet
BEV at EU and World level fleet evolution from 2015 to 2050	62	Electrical power train light duty vehicles share
BEV at EU and World level sales evolution from 2015 to 2050	63	Electrical powertrain light duty vehicles sales
PHEV at EU and World level fleet evolution from 2015 to 2050	64	Mechanical and Electrical power train light duty vehicles share
PHEV at EU and World level sales evolution from 2015 to 2050	65	Mechanical and Electrical power train light duty vehicles sales
ICE at EU and World level fleet evolution from 2015 to 2050	66	Mechanical power train light duty vehicles share
ICE at EU and World level sales evolution from 2015 to 2050	67	Mechanical power train light duty vehicles sales
GHG evolution of light duty vehicles	68	GHG evolution as a result of regulation evolution for different polluting (NOx, CO, CO_2, PM_{10}, HC)
Li, Ni, Nd, Ag, Co, Cu, Ta, Mn, Pt, V transport demand evolution from 2015 to 2050	110	Material intensity for transport

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2. Introduction

Around 75% of European population lives in urban and metropolitan areas (European Environmental Agency, 2013), causing not only a size increase of cities but also a mobility demand growth. As a consequence, 2.7 daily trips per person are made (European Metropolitan Transport Authorities, 2013) and as a result the urban mobility indicator passenger-kilometer has grown by 7% since last decade (European Comission, 2011). Nowadays, 49% of urban daily trips are made using private vehicles with the negative associated impact (European Metropolitan Transport Authorities, 2009). Some of the most known problems are:

- Traffic jams, which costs are estimated at 80,000 M€/year (European Comission, 2011).
- GHG emissions, where passenger cars and vans are responsible of 15 % of CO_2 emissions in the EU (European Comission, 2011).
- Traffic accidents, where urban mobility is responsible for 38% of fatal urban traffic collisions (European Comission, 2013).

In this global context, local authorities' efforts are being focused on encouraging a change in urban mobility through more sustainable transport systems fostered by Sustainable Urban Mobility Plans.

Nowadays, light duty vehicles around the world approximately account 47 % of transport energy use and the total stock of these vehicles is expected to grow to at least 2 billion by 2050 (International Energy Agency, 2009). Electro mobility is one of the proposed solutions to reduce some of these impacts. As Transport White Paper establishes, ICE vehicles fleet must be reduced at least 50 % before 2030 and must be avoided by 2050.

A commonly accepted way to assess the impact of electro mobility is by means of Life Cycle Assessment methodology. Life Cycle Assessment methodologies are the reference tools to study different sectors from cradle to grave; this approach is very useful to understand for instance how important eco-design practices are.

Nevertheless, a more comprehensive and rigorous analysis can be undertaken if not only the cradle-to-grave approach is taken into account, but also the grave-to-cradle, including the criticality of the mineral resources that come into play using thermodynamics and more specifically an exergy analysis (Valero and Valero, 2014).

Indeed, a thorough analysis of the resources required for a certain economic sector needs to include not only the energy used throughout its life cycle but also the materials required to manufacture the analyzed system. The supply of critical raw materials is an important issue that is currently regarded as a potential threat that may put at risk the so-called "Green Economy". Accordingly, a list of 20 raw materials considered as critical contemplating supply risk and their impacts on the economy, was recently published by the European Commission (2014). Some of these materials are Platinum Group Metals (PGM) and Rare Earth Elements (REE). However there are more materials which currently are not considered as critical in this list whose use must be also monitored. The term "critical", as defined by the EC, is not static and it changes with the socio-economic circumstances. This means that there is not a specific definition of the term, and hence there are more than 20 raw materials that must be considered when we talk about supply risk (Cullbrand and Magnusson, 2011).

Going back to the transport sector, the demand for materials used in passenger cars, such us catalyst converters, glass, flat panel displays, electronic equipment, electrical motors, batteries, super alloys or communication technologies, is rapidly increasing. As an example, global car sales have more than doubled over the past thirty years, from about 29 million in 1980 to 65 million in 2014 (International Organization of Motor Vehicles Manufacturers, 2014). Moreover, the expected renewal of current vehicles to electrical vehicles will, as will be seen later, requires even more scarce raw materials. Both issues make it critical to urgently analyze deeply the use of raw materials in the automotive industry to guarantee a real sustainable development of the sector.

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3. Passenger vehicles classification

A very significant change in current passenger vehicle fleet is expected in the near to medium term. According to Transport White paper, in 2050 there will not be allowed non-zero emission vehicles in urban areas so new technologies based on electro mobility will be applied. On the other hand, the European End of Life Vehicle Directive 2000/53/CE is aware of the problematic on the recycling approach in vehicles. This legislation stablishes a recycling target of 95 % of vehicle mass starting from 2015.

For these reasons there a big change in passenger vehicles is expected and possible physical constraints must be identified to guarantee the sustainability of the sector.

There are different types of vehicles from power train point of view. The following chart shows the classification (Figure 1).

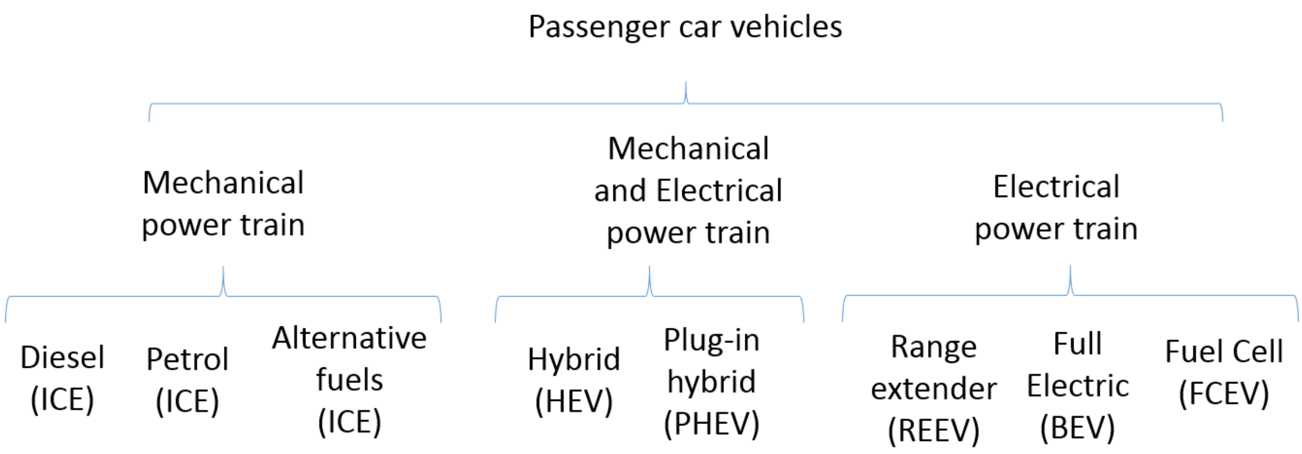

Figure 1. Passenger vehicle classification.

In turn, private vehicles can be classified according to the type of power train used:

- Mechanical power train (using different types of fuel).
- Hybrid power train (in different configurations like conventional or plug-in).
- Electrical power train (in different configurations like range extender, fuel cell or full battery electric).

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According to published sales projections (International Energy Agency, 2010) a world vehicle fleet based mainly on ICE, PHEV and BEV is expected from 2015 to 2050, while contribution of FCEV and ICE using alternative fuels such as biofuels are not so significant. Considering these facts, the following 3 types of vehicles are assessed:

- ICE in a medium family car.
- PHEV in a medium family car with 50 km[1] of autonomy and Li-ion based technology battery.
- BEV in a medium family car with 250 km[2] of autonomy and Li-ion based technology battery.

The following components have been considered: body, steering, suspension, power train, electronic components, infotainment, energy storage, brakes, exhaust pipe and catalytic converter.

Materials contained in tires and plastic are not included. Embodied materials from manufacturing processes like painting are also excluded.

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1 Common autonomy in current PHEV like Volvo V60 Twin Engine. http://www.volvocars.com/es/modelos/nuevos-modelos-volvo/v60/v60-hibrido

2 Common autonomy in current BEV like Nissan Leaf. http://www.nissan.es/ES/es/vehicle/electric-vehicles/leaf/discover/main-features.html

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4. Materials demand in passenger vehicles

To identify what materials are used in these types of vehicles, a state of the art analysis obtained from the bibliography has been undertaken. In the following table a list of critical raw materials identified by different authors is shown.

Table 2. Compilation of critical materials used in passenger car vehicles (in g).

Material	(Cullbrand & Magnusson, 2012)		(Du & Graedel, 2013)			(Du et al., 2015)	(Alonso et al., 2012)	(Grandell et al., 2016)	
	ICE	PHEV	max	min	ave			PHEV	BEV[3]
Cerium	12.91	0.31	80	6	6	0.02	81		
Cobalt			160	5	6				
Dysprosium	1.96	129.66	25	5	6	0.03	27.45	210	336
Erbium	0	0.18							
Europium	<0.01	<0.01					0.45		
Gadolinium	<0.01	<0.01	0.36	0.01	0.12	0.05	0.36		
Gallium	0.42	0.57	11	0.1	0.25			1.05	1.68
Germanium								0.05	0.08
Gold			0.21	0.01	0.15			0.2	0.32
Indium	0.38	0.08	0.42	0.01	0.15			0.05	0.08
Lanthanum	0	6.68	12	0.8	5.2	12	8.1		
Lithium	1.36	6,256.55							
Molybdenum			170	5	5				
Neodymium	27.6	531.88	300	5	7	2.16	297	360	576
Niobium	89.81	109.14	150	5	10				
Palladium	1.24	1.81	10	0.1	0.25				0.12
Platinum	7.85	5.51	5.5	0.1	0.25				

[3] Original values are published for a 50 kW motor. In the present study, values are adapted for 50 kW and 80 kW motors in PHEV and BEV cases respectively.

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Material	(Cullbrand & Magnusson, 2012)		(Du & Graedel, 2013)			(Du et al., 2015)	(Alonso et al., 2012)	(Grandell et al., 2016)	
	ICE	PHEV	max	min	ave			PHEV	BEV[3]
Praseodymium	2.47	4.01	25	5	6	0.07	30.6	120	192
Rhodium	<0.01	<0.01							
Samarium	0.73	1.4	3.2	0.1	0.25	0	3.24		
Scandium							1.13		
Silver	17,5	50						6	9.6
Strontium			180	30	140				
Tantalum	6.99	10.83	6	0.1	0.25				
Terbium	0	19.86	0.01	0.01	0.01	0.01	0	21	34
Wolfram			3	0.1	0.2				
Ytterbium	0	0.16					0		
Yttrium	0.02	0.23	0.58	0.08	0.4	0.08	0.59		

Nevertheless to cover all expected physical constrains it is necessary to analyze not only critical materials as defined by the EC, but also more conventional materials like Fe, Al or Cu due to their mass use in vehicles.

The following table shows the quantity of materials demanded in different vehicles through several authors' approaches:

Table 3. Common materials used in passenger car vehicles through different authors (in kg).

Author	Al	Steel	Copper	Cast iron	Others
Gonzalez et al. (2012)	100 (FCHEV) 200 (BEV) 50 (ICE)	760 (FCHEV) 770 (BEV) 740 (ICE)	25 (FCHEV) 150 (BEV) 25 (ICE)	20 (FCHEV) 20 (BEV) 50 (ICE)	225 (FCHEV) 210 (BEV) 135 (ICE)
Spielmann and Althaus (2007)	52.41				
Castro et al. (2003)	31.24				
Schmidt et al. (2004)	198				50

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Author	Al	Steel	Copper	Cast iron	Others
Wells (1998)	88.4				40.3
Amatayukul and Ramnas (2000)	96	624			
Lewis et al. (2014)	90 (ICE) 100 (HEV) 100 (PHEV)	710 (ICE) 710 (HEV) 750 (PHEV)	50 (HEV) 50 (PHEV)	20 (ICE) 20 (HEV) 20 (PHEV)	100 (ICE) 12 (HEV) 130 (PHEV)
USGS (2006)	88.45	975.22			

Since the storage system is one of the most critical components in PHEV and BEV, a deeper study of materials demanded in different types of batteries has been undertaken. In the following table a classification of current types of batteries is shown (Table 4).

Table 4. Different battery types and vehicle applications (EUROBAT, 2014).

	Conventional vehicles	Hybrid vehicles	Full electric vehicles
Lead – Based Batteries	Only as auxiliary battery	Only as auxiliary battery	Only as auxiliary battery
Nickel – Based Batteries	Non expected	Expected	Non expected
Lithium – Based Batteries	Non expected	Expected	Expected

It can be summarized that lead based batteries will continue to be used in passenger cars for a long time to supply the energy for auxiliary devices. NiMH batteries will compete in the market of hybrid vehicles with lithium-ion batteries and the last ones will be mainly used in full electric vehicles and plug hybrid vehicles, due to their high energy density and because their relatively greater cost is less of a barrier in these higher-end vehicles (EUROBAT, 2014).

Although Li:ion technology is expected to be the reference in the following years, from a material point of view there are different types of Li:ion batteries. The following table shows an example of materials demand in different Li:ion batteries:

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Table 5: Metal requirements in Kg of different types of batteries (Simon, Ziemann, & Weil, 2015)[4].

	Battery types				
	NMC/C	**NCA/C**	**LFP/C**	**Li/S**	**Li/air**
Nickel	8	31	0	0	0
Lithium	2.8	4.8	3.6	8.4	3
Cobalt	4.2	6	0	0	0
Iron	0	0	25	0	0
Manganese	8	0	0	0	0
Aluminium	0	1	0	0	0

In Li-ion batteries, NMC/C technology represents the current market availability. Nevertheless an increase of NCA/C is expected due to its higher energy density besides NCA batteries are used by the main electrical vehicle manufactures like TESLA (Nitta et al, 2015) so it is expected to become the most important technology for electrical vehicles in the following years.

LFP/C, Li/S and Li-air batteries are not considered since the implementation of this technology is not clear in the following years as they are currently on an early development phase. Taking into account these facts, a deeper study of NCA chemistry batteries has been done. In Table **6** are shown Li, Co and Ni content of NCA batteries by different authors[5].

Table 6. Material demand by type of vehicle in gr, own elaboration through (Gaines et al 2010), (Simon et al., 2015) and (U.S. Department of Energy, 2011)

	(Gaines et al 2010)	**(Simon et al., 2015)**	**(U.S. Department of Energy, 2011)**	**Average**
Li	9.01	7.2	9.3	8.50
Ni	57.40	46.5	58	53.97
Co	10.91	9	12	10.34

[4] Values adapted from kg/kWh to an estimated battery of 20 kWh.

[5] Values adapted to a battery autonomy of 200 km.

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Considering all previous bibliographic revision, the following table summarizes the materials used in ICE, PHEV and BEV and their vehicle allocation (Table 7). It is made considering average value from Table **6** for BEV and in PHEV case these values are adapted for a battery with an autonomy of 50 km.

Table 7. Studied materials in vehicles, contribution in Mass (gr) per unit of vehicle analyzed and component where it is installed.

	Type of vehicle			Type of component				
	ICE	**PHEV**	**BEV**	**Body**	**Powertrain**	**Chemical Storage**	**Electrical and Electronic**	**Infotainment**
Ag	17.50	28	29.8				X	
Al	110,544	115,544	200,000	X	X			
Au	0	0.2	0.32				X	
Ce	51.29	49.67	0		X			
Co	32.50	2,734.21	10,711.87		X	X	X	
Cr	12,789	12,789	11,850	X				
Cu	28,5	59,166	105,000				X	
Fe	806,144	806,144	746,945	X	X			
Ga	0.32	0.81	1.12				X	
Gd	0.18	0.18	0.18				X	
Ge	0	0.05	0.08				X	
In	0.10	0.10	0.10				X	X
La	5.36	7.38	7.38		X		X	
Li	7.63	2,126.09	8,504.37			X	X	
Mn	12,468.28	14,468.28	19,530	X		X		
Mo	4,007.94	4,007.94	4,007.94	X				X
Nb	484	484	484	X				
Nd	210.760	552.79	797.76				X	
Ni	4,335.46	17,863.81	58,025.59	X		X		
Pb	6,000	0	0			X		
Pd	1.38	0.94	0.03		X			
Pr	16.89	51.48	98.05				X	
Pt	6.78	5.51	0		X			
Rh	0.01	0.01	0		X			
Ta	8.38	10.83	10.83	X			X	

V	852.61	852.61	790	X				
Y	0.41	0.41	0.41	X				X

In the case of ICE the highest contribution is attributed to Al and Fe, while other materials such as Cr, Mn, Ni and Mo are demanded as alloys in the steel body. On the other hand, REE are demanded for electronic applications and PGM in catalytic converters (Figure 2).

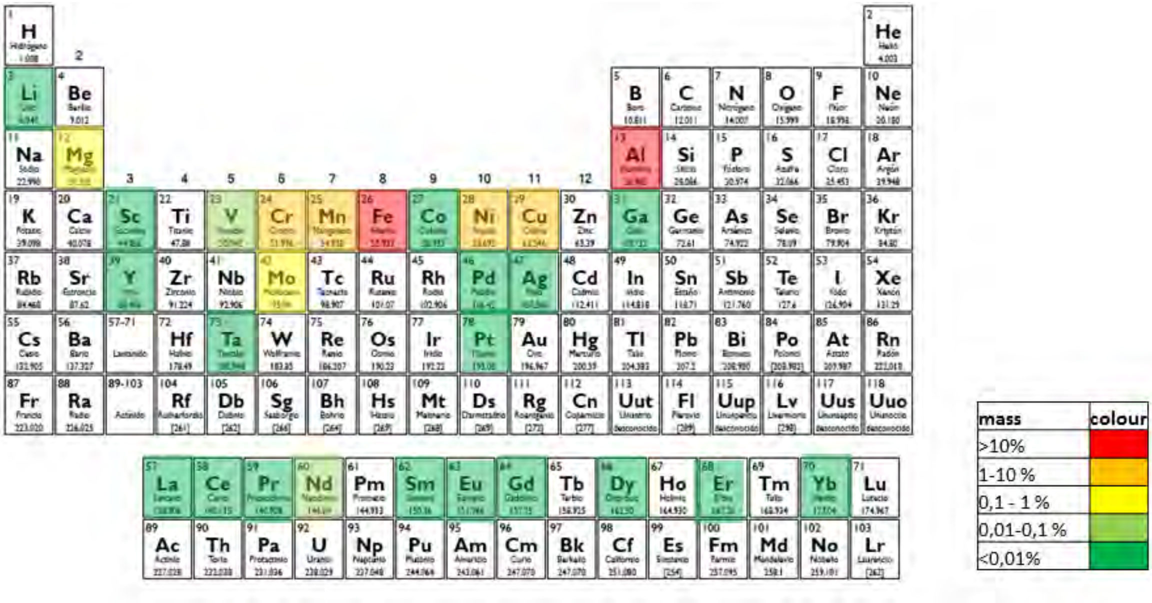

Figure 2. Studied materials in ICE vehicles.

In the case of PHEV, Li, Co, Mn, Ni and Nd demand are higher than in the previous case as a consequence of the storage system and permanent magnets in the motor (Figure 3).

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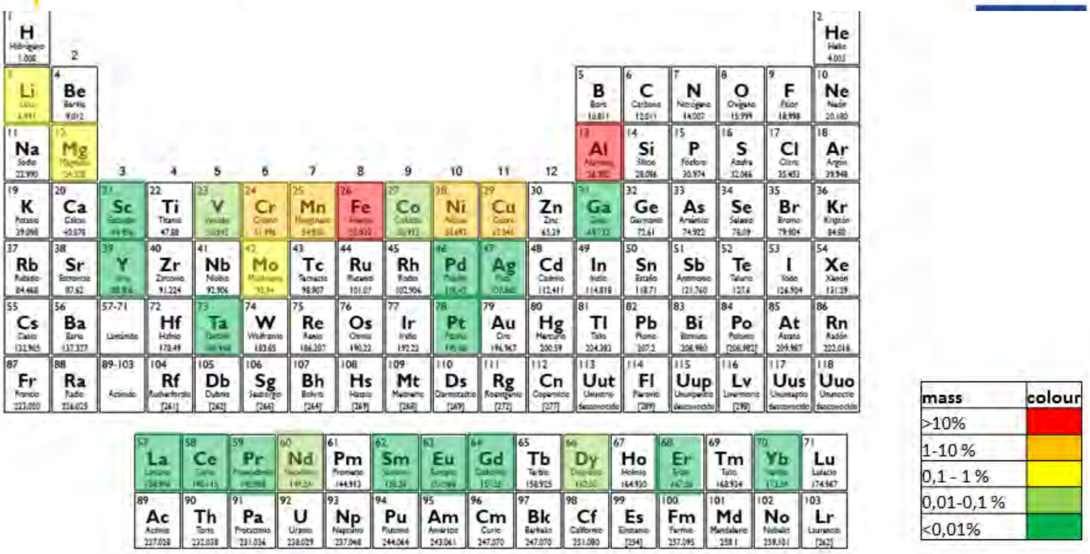

Figure 3. Studied materials in PHEV vehicles.

In BEV, PGMs are not used since this vehicle does not need catalytic converters. However the demand of materials needed to storage electricity is significantly greater than in the previous cases (Figure 4).

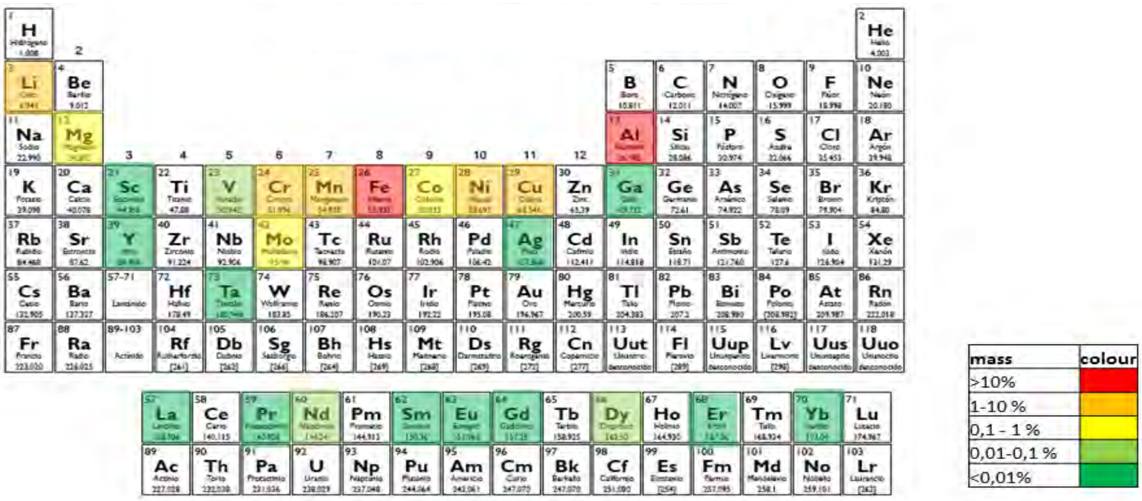

Figure 4. Studied materials in BEV vehicles.

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5. Evolution of the passenger vehicle fleet

To assess the impact of passenger vehicle material demand in reserves the expected sales projections from 2015 to 2050 by the different types of vehicles is required. To do so, sales projection values from European Environmental Agency (2010), International Energy Agency (2010), John Dulac (2013) and ANFAC (2014) have been consulted. Considering these data, the following market sales and world fleet have be used.

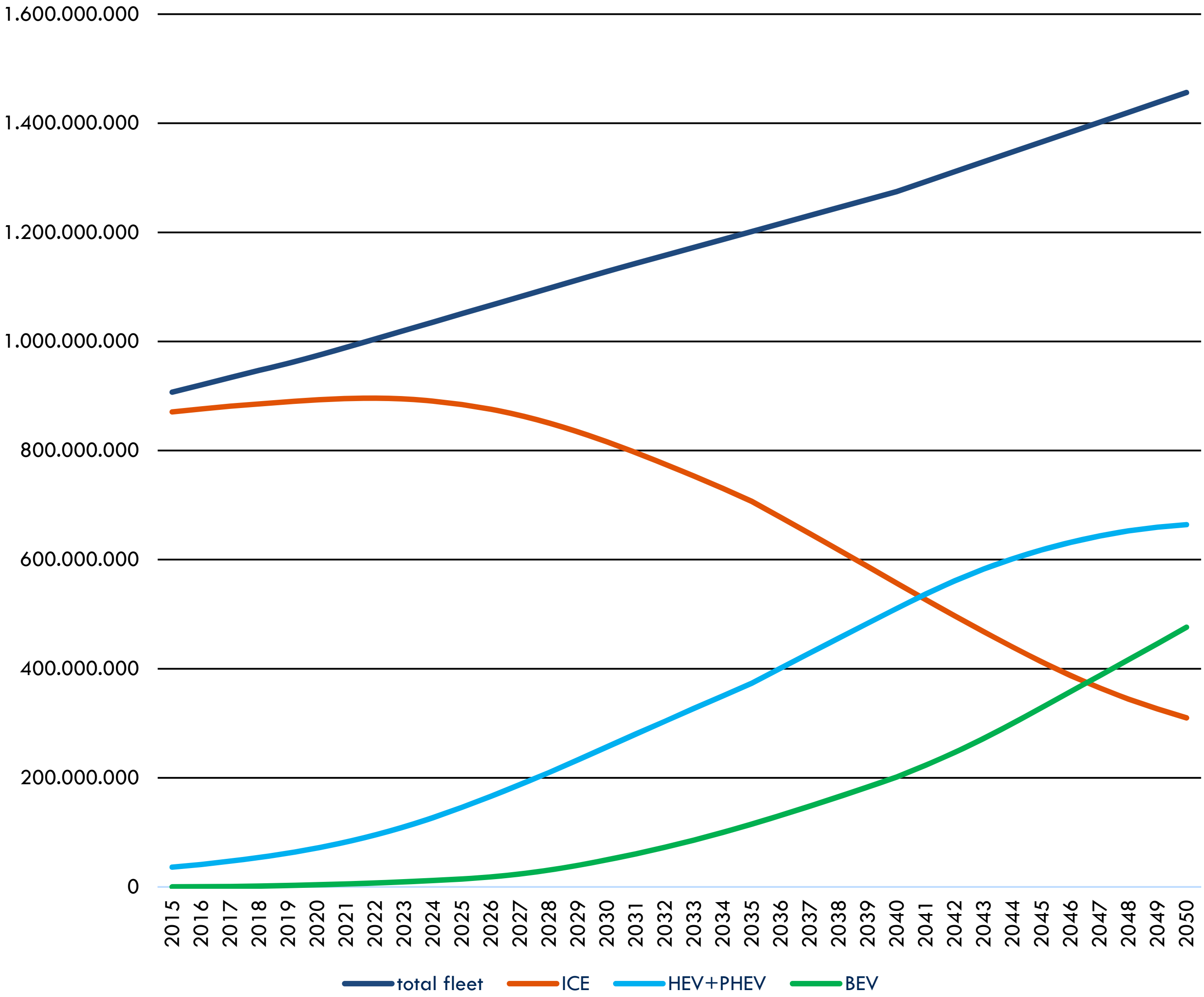

Figure 5. World passenger car fleet evolution.

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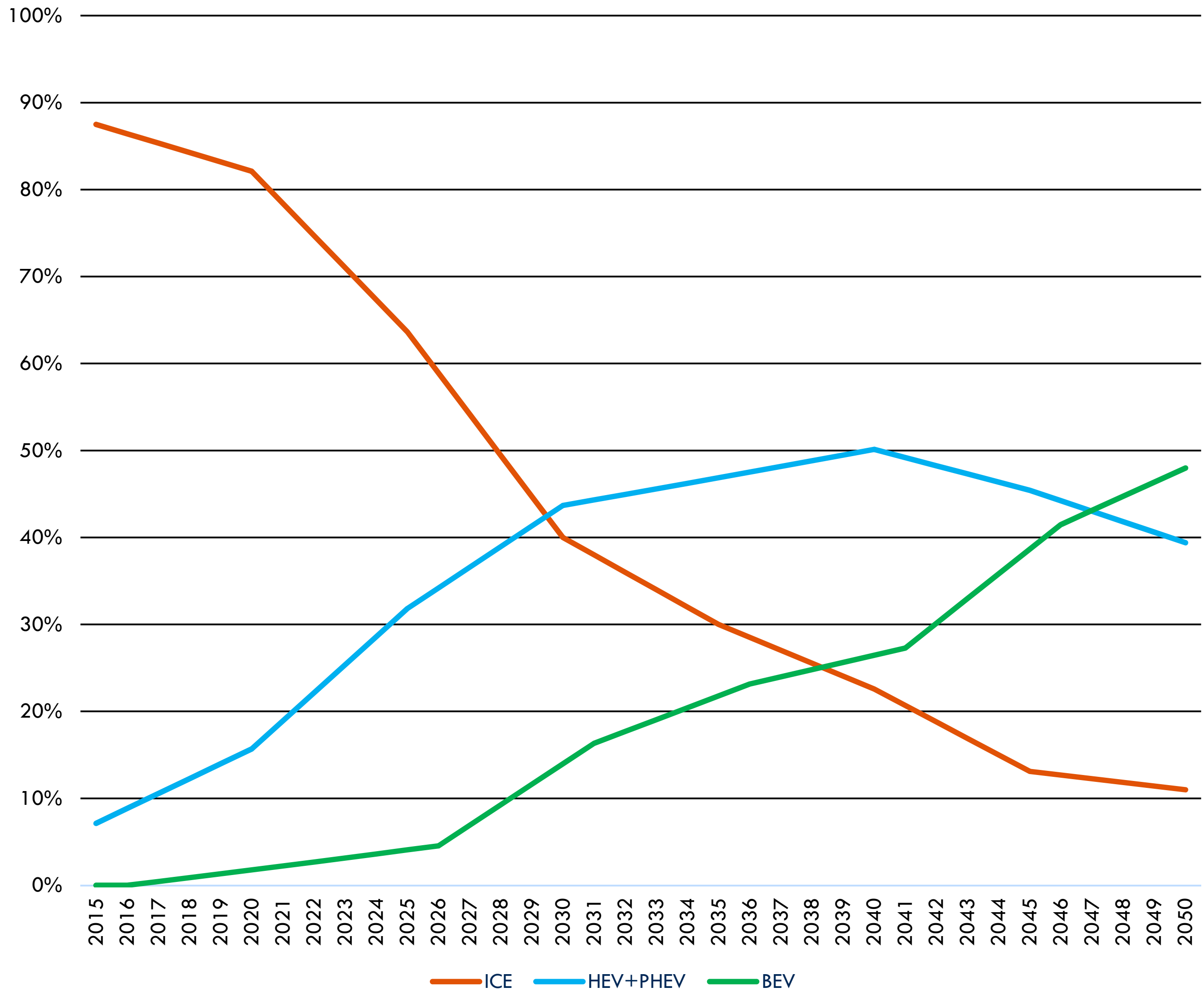

Figure 6. World passenger car sales evolution.

As it can be seen in Figure 5 and Figure 6, ICE sales will decrease from 2016 in favor of PHEV. BEV sales will mainly grow from 2025 and in 2045 they will be even greater than PHEV world sales. Considering these forecasts, PHEV and BEV share in world fleet will be even higher than ICE in 2045.

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6. Methodology

To assess the impact of different used materials, the methodology developed by Valero and Valero (2014) is used. This methodology covers the total life cycle, from cradle to gate including the grave to cradle approach.

- **Cradle to Gate approach:** assess the exergy cost to produce a refined metal from the mine to be used in industrial applications.
- **Grave to Cradle:** assess the exergy replacement cost to return raw materials from a dispersed state (i.e.: landfills) to the initial state in mines.

This methodology uses the concept of thermodynamic rarity (Valero and Valero, 2014). The thermodynamic rarity indicator is a rigorous exergy measure of a mineral´s quality considering physical aspects of the minerals such as natural concentration, chemical composition, comminution and energy requirements to beneficiate the given mineral.

This approach gives an additional dimension to the criticality of minerals taking into account physical aspects (scarcity in the crust and energy intensity to mine and beneficiate the mineral). Note that this new dimension is not yet included in current criticality assessments which are focused on supply risk and economic importance. Whereas the thermodynamic rarity concept is universal and absolute, the socio-economic criticality assessment is country-dependent and variable.

To identify physical constraints for the vehicle sector a combination of bottom-up and top-down approaches will be used:

- **Bottom-up**: assess the estimated evolution of material production according to current reserves and past production values. This method uses the Hubbert curve methodology traditionally used to assess peak oil. Reserves and production data comes from (Calvo, 2015).
- **Top-down**: assess the estimated demand of materials from different studied vehicles according to material´s demand and expected sales by type of vehicle and recycling current figures of different studied materials.

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The values used to assess material rarity are included in the following table:

Table 8. Exergy values used (GJ/ton).

	(A) Grave-Cradle	(B) Cradle-Gate	(A)+(B) Rarity
Ag	7,371.00	1,281.4	8,652.4
Al	627.24	10.5	637.74
Au	553.044	110.016	663.060
Ce	97.19	523.1	620.29
Co	10,872.00	9.2	10,881.2
Cr	4.5400	0.1	4.64
Cu	291.70	35.30	327.00
Fe	17.75	0.70	18.45
Ga	144,828.00	61,000	205,828
Gd	478.05	3,607.30	4,085.35
Ge	23,749	498	24,247
In	360,598.00	3,319.70	363,917.70
La	39.33	296.80	336.13
Li	545.83	12.50	558.33
Mn	15.64	0.20	15.84
Mo	907.91	136	1,043.91
Nb	4,421.97	228.30	4,650.27
Nd	78.42	591.70	670.12
Ni	523.61	9.98	533.59
Pb	36.62	4.2	40.82
Pd	8,983,376.98	583,333.3	9,566,710.28
Pr	577.08	296.3	873.38
Pt	4,491,688	291,666.7	4,783,354.70
Rh	102,931	156	103,087
Ta	482,828	3,082.8	485,910.80
V	1,055	136	1,191

Considering these values and from a rarity point of view, it can be seen for instance that it is not the same to use 1kg of Fe (with a rarity of 18 MJ) than the same quantity of Li (558 MJ).

The values of current recycling rates are included in the following table:

Table 9. Recycling rates by element (UNEP, 2011)

Element	Recycling rate	Element	Recycling rate
Ag	30.0%	**Li**	1.0%
Al	36.0%	**Mn**	37.0%
Au	50.0 %	**Mo**	33.0%
Ce	1.0%	**Nb**	50.0%
Co	32.0%	**Nd**	5.0%
Cr	20.0%	**Ni**	29.0%
Cu	30.0%	**Pd**	50.0%
Fe	50.0%	**Pr**	5.0%
Ga	25.0%	**Pt**	50.0%
Gd	5.0%	**Rh**	40.0%
Ge	25.0 %	**Ta**	17.5%
In	37.5%	**V**	0.0%
La	5.0%		

7. Results

7.1. Rarity analysis per type of vehicle

Figure 7 shows a comparison between a mass and exergy (rarity) analysis for an ICE. From a mass point of view, Fe and Al constitute around 95 % of the vehicle. However in rarity terms, Fe and Al only account for 55 %. This is because more valuable metals (led by Pt and Pd contained in catalytic converters) have a greater exergy content.

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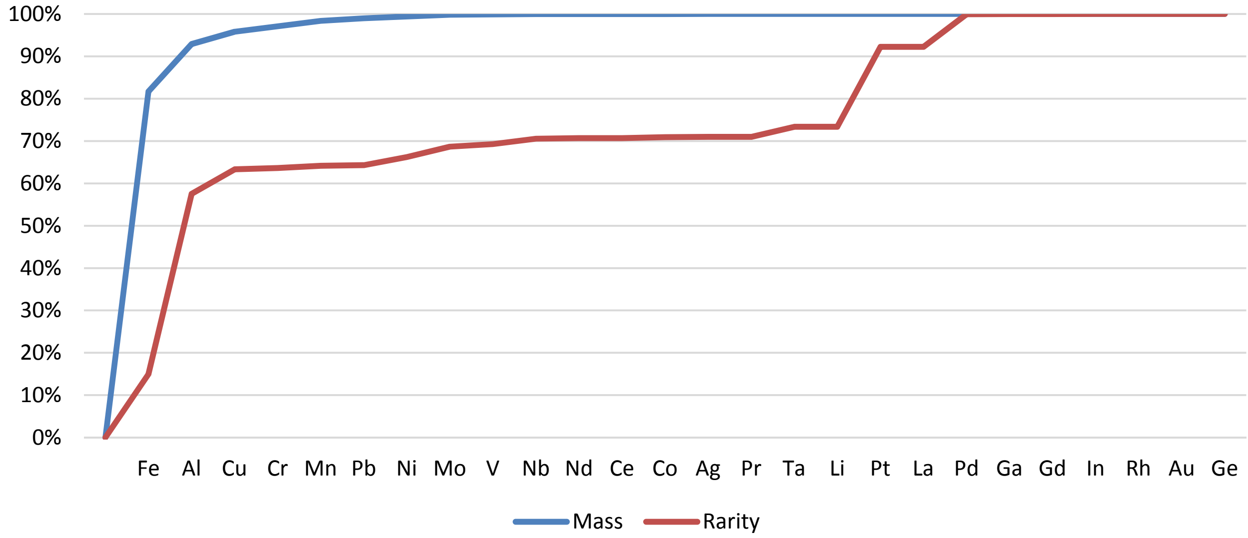

Figure 7. Mass and Exergy-rarity comparison in an ICE.

Figure 8 shows the results for a PHEV-type vehicle. Cu contribution in mass is greater than in the ICE case. Li and Co have an important rarity contribution since they are needed to manufacture batteries. As in the previous case, Pt and Pd for catalytic converters have a relevant rarity contribution.

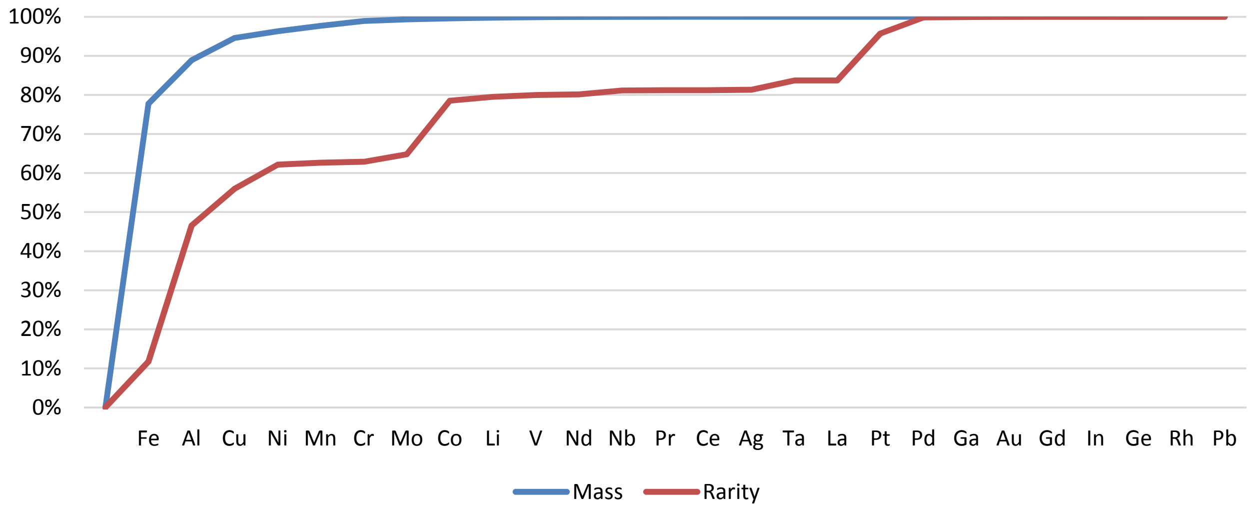

Figure 8. Mass and Exergy-rarity comparison in a PHEV.

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Figure 9, shows the result for BEV. Here Li, Ni, Mn and Co acquire a more relevant role in exergy (rarity) terms compared with previous vehicles. The highest exergy demand of BEV is ascribed mainly to materials needed to manufacture Li-ion batteries.

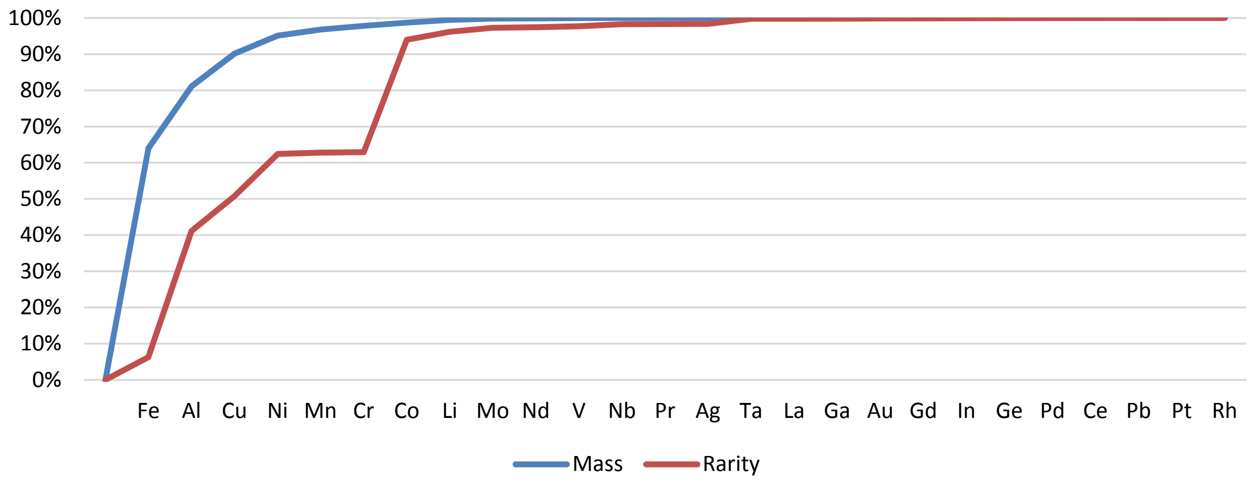

Figure 9. Mass and Exergy-rarity comparison in a BEV.

Figure 10 summarizes the rarity values for each analyzed vehicle type. It can be seen how materials demanded by BEV have an exergy content of over 379 GJ while ICE and PHEV have only 171 GJ and 219 GJ, respectively.

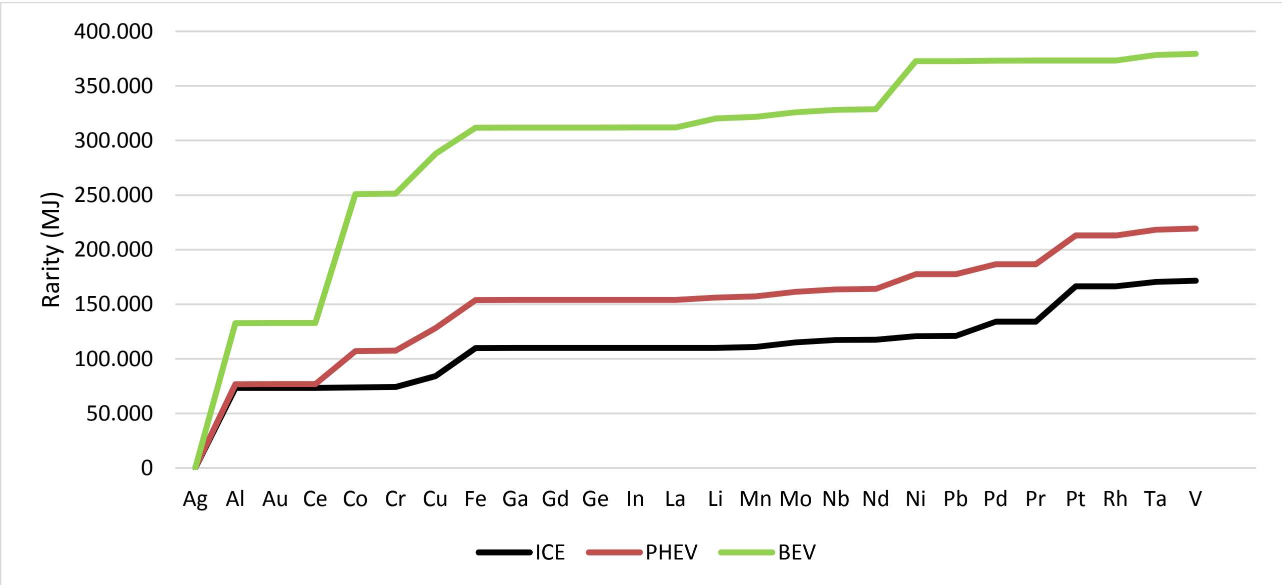

Figure 10. Rarity comparison (MJ) between studied vehicles.

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7.2. Stock in use per type of vehicle

In this stage the importance of assessing stock in use materials is analyzed with the aim to encourage recycling polices. The following figures show stock in use evolution measured in Exergy of the main studied materials.

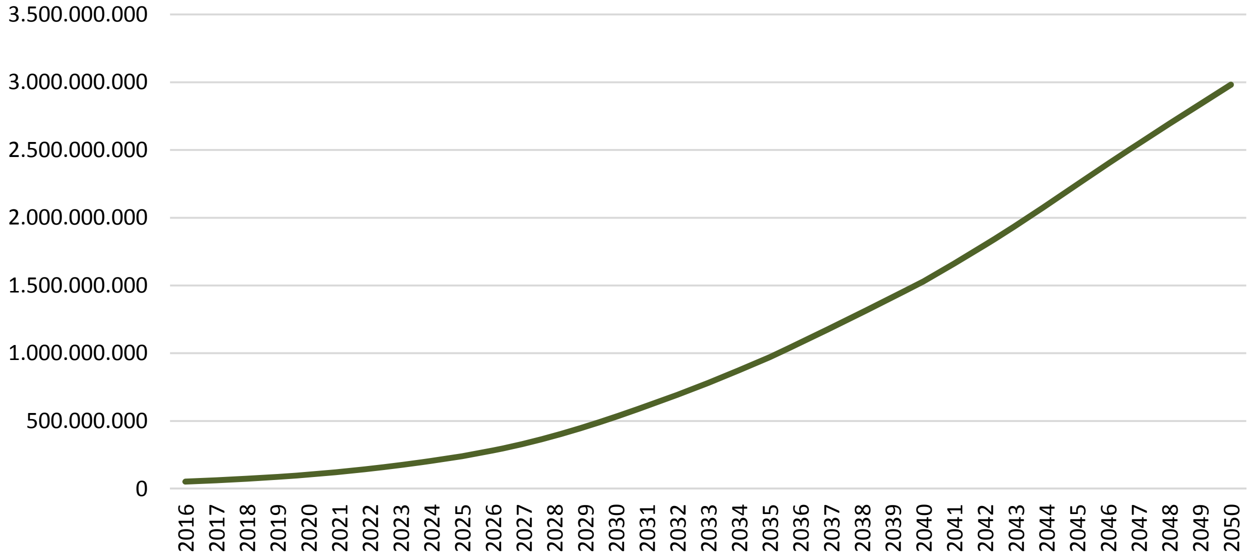

Figure 11. Li stock in use evolution (GJ).

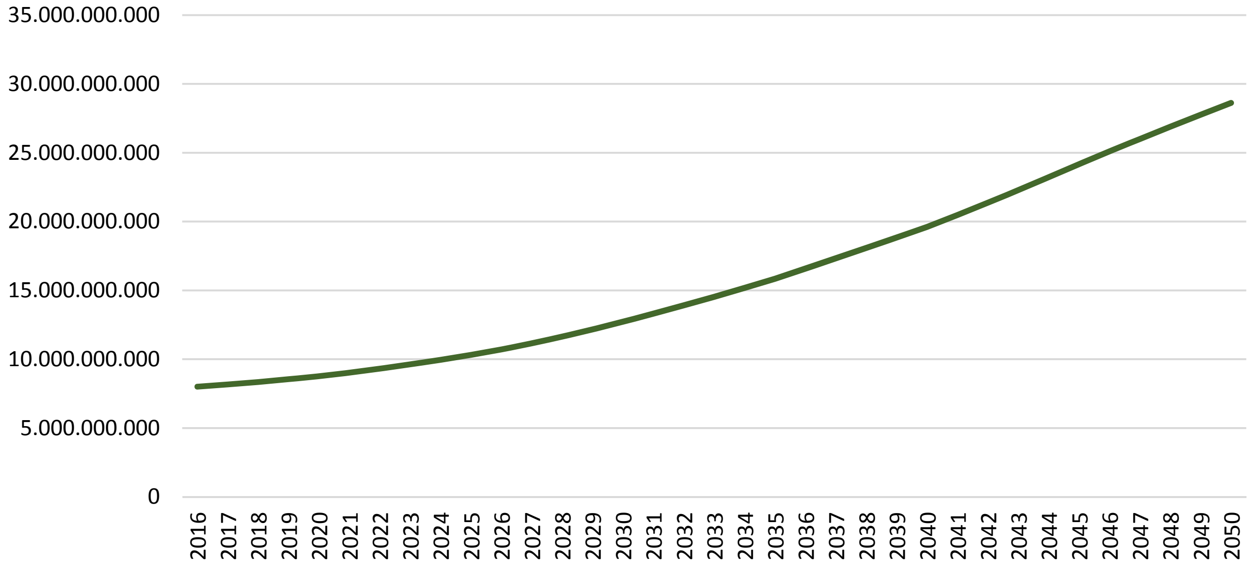

Figure 12. Cu stock in use evolution (GJ).

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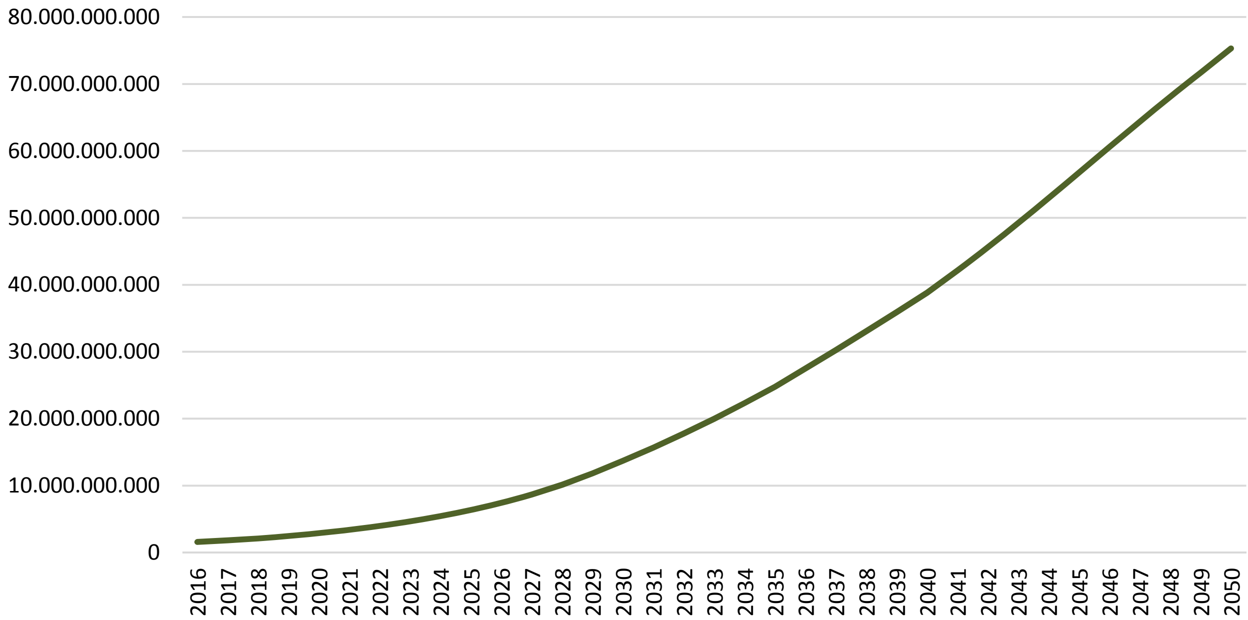

Figure 13. Co stock in use evolution (GJ).

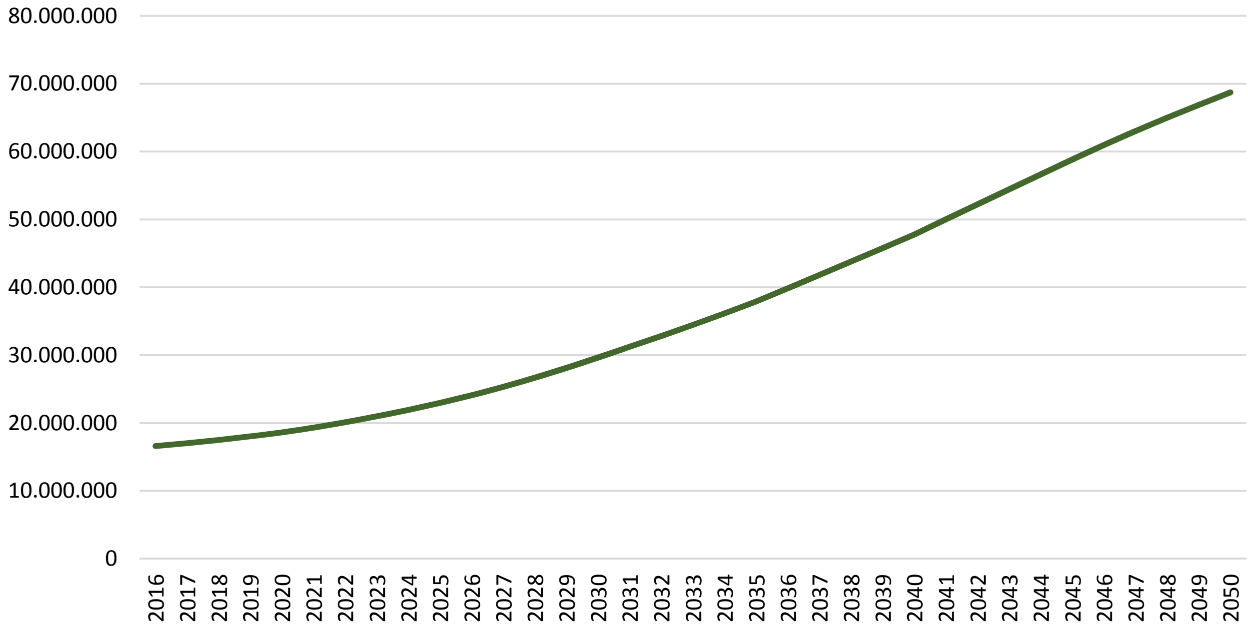

Figure 14. Nd stock in use evolution (GJ).

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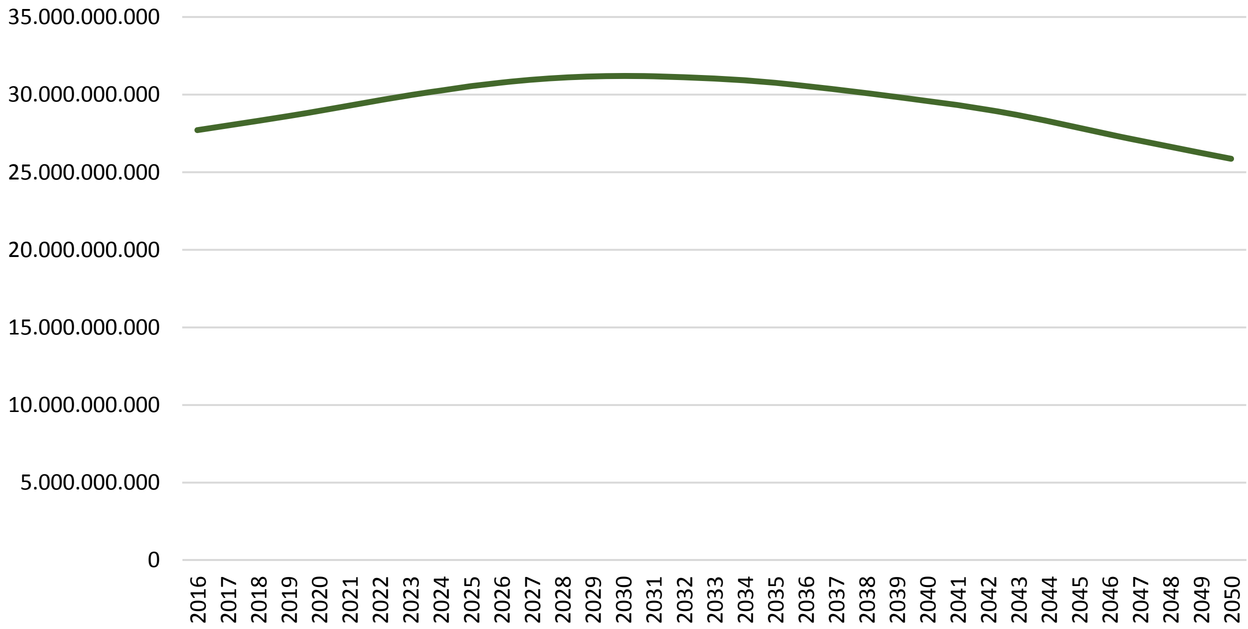

Figure 15. Pt stock in use evolution (GJ).

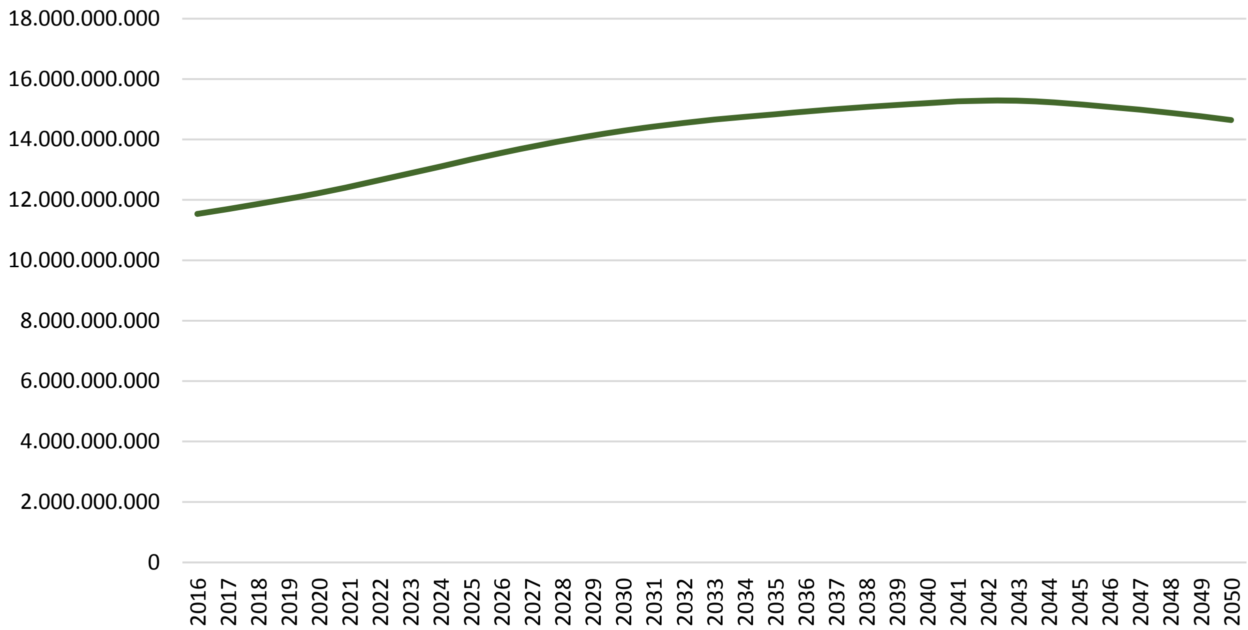

Figure 16. Pd stock in use evolution (GJ).

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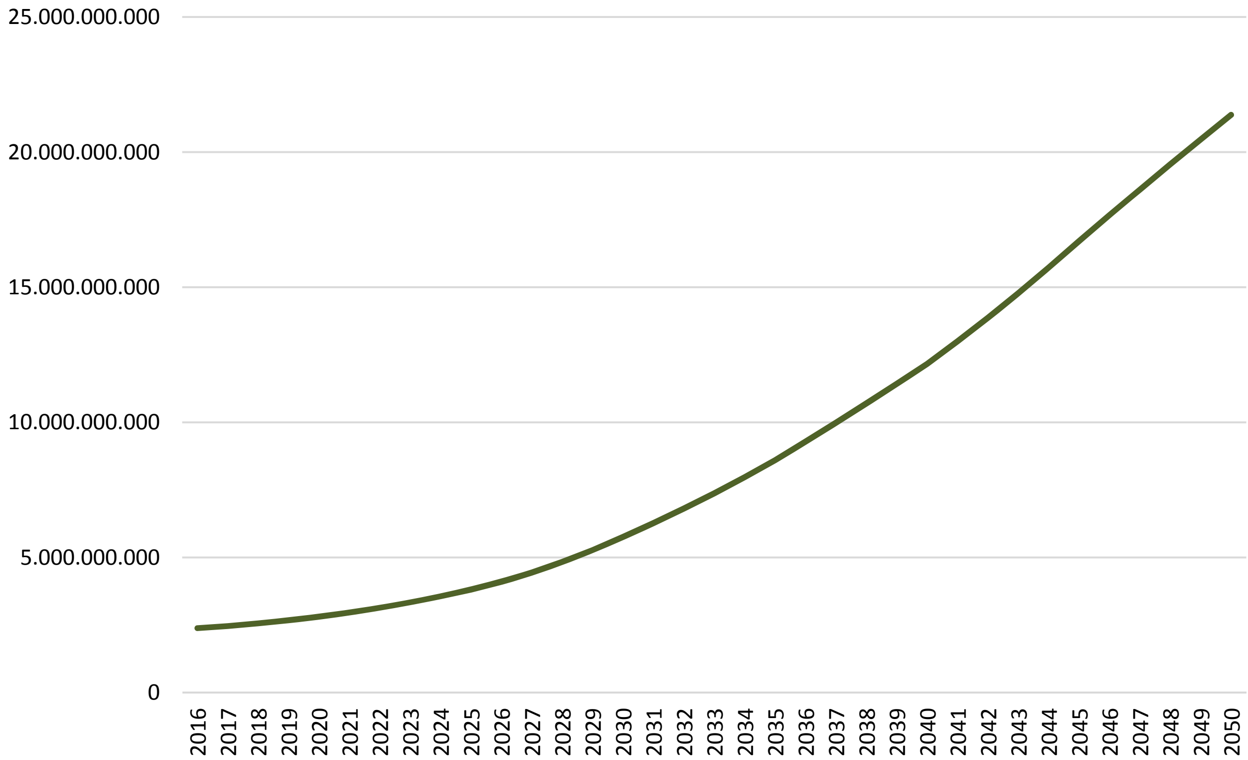

Figure 17. Ni stock in use evolution (GJ).

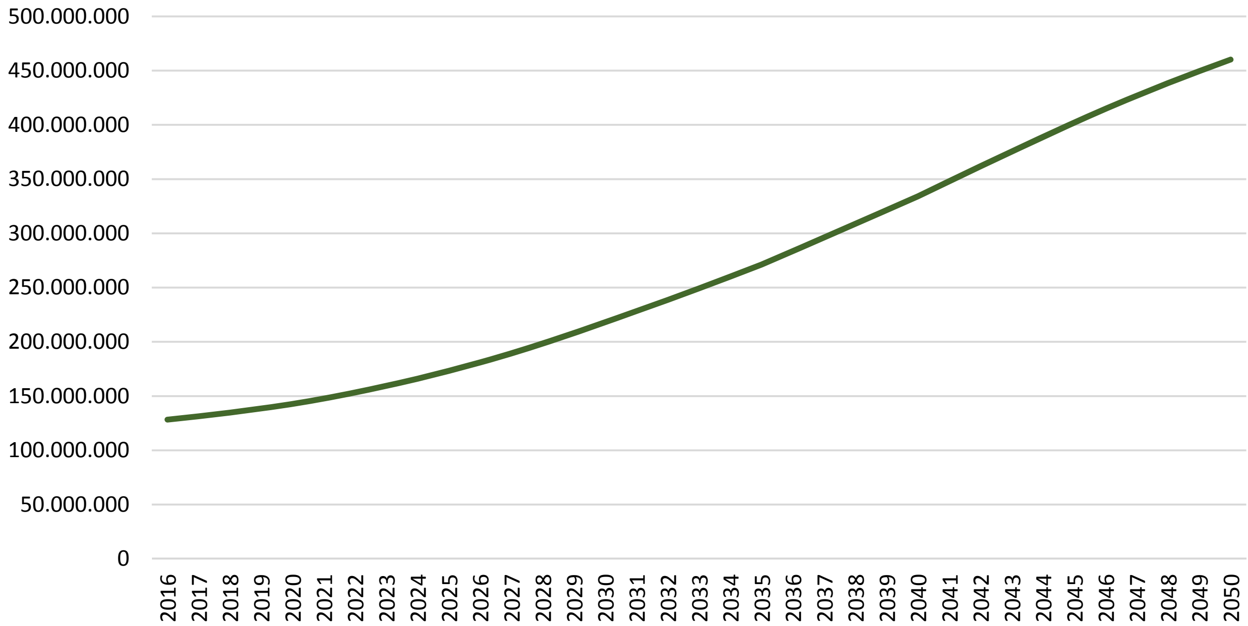

Figure 18. Ag stock in use evolution (GJ).

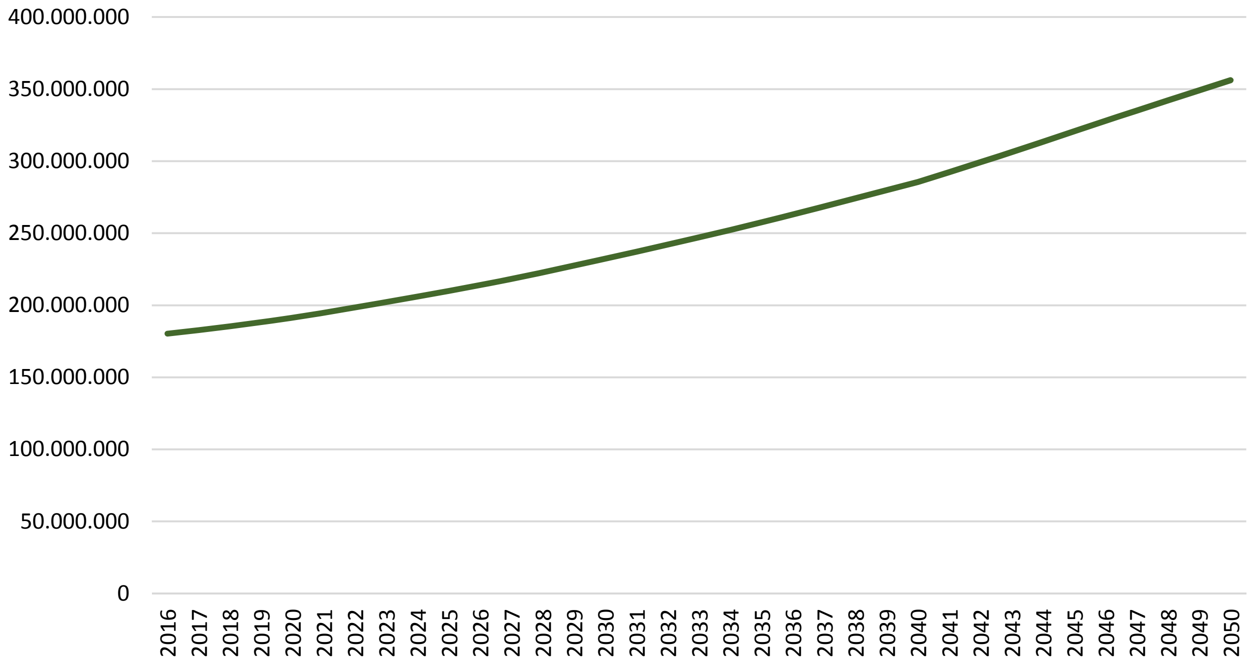

Figure 19. Mn stock in use evolution (GJ).

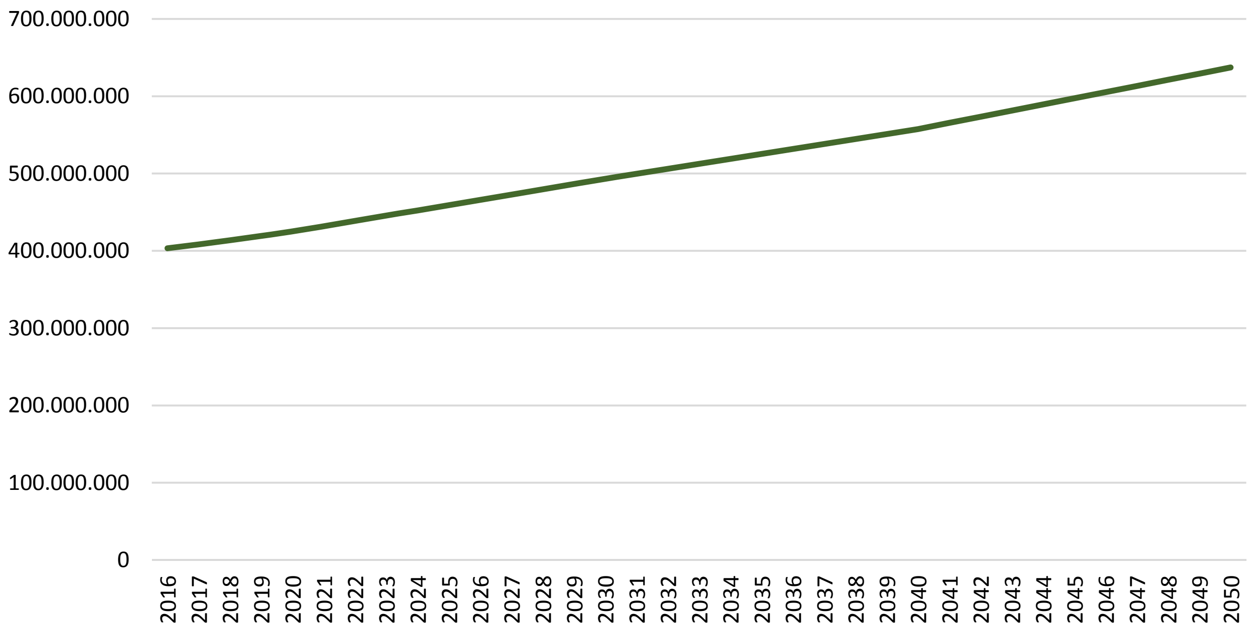

Figure 20. Nb stock in use evolution (GJ).

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In the case of Pt and Pd stock in use decreases from 2040 due to the reduction in sales of ICE vehicles which are equipped with catalytic converters. In turn, Li, Co, Mn, Ni, Ag and Nd stocks increase exponentially.

7.3. Material shortages due to passenger vehicles

Once different vehicles are studied from a material point of view, expected demand of materials from 2015 to 2050 are assessed. The aim is to identify possible material shortages due to passenger vehicles under a "Business as Usual" scenario. Recall that the BAU scenario for material production has been built assuming that it will follow a Hubbert-curve trend.

Figure 21 compares Li demand to manufacture passenger vehicles with world estimated production of Li. A possible physical constraint is envisaged at around 2042.

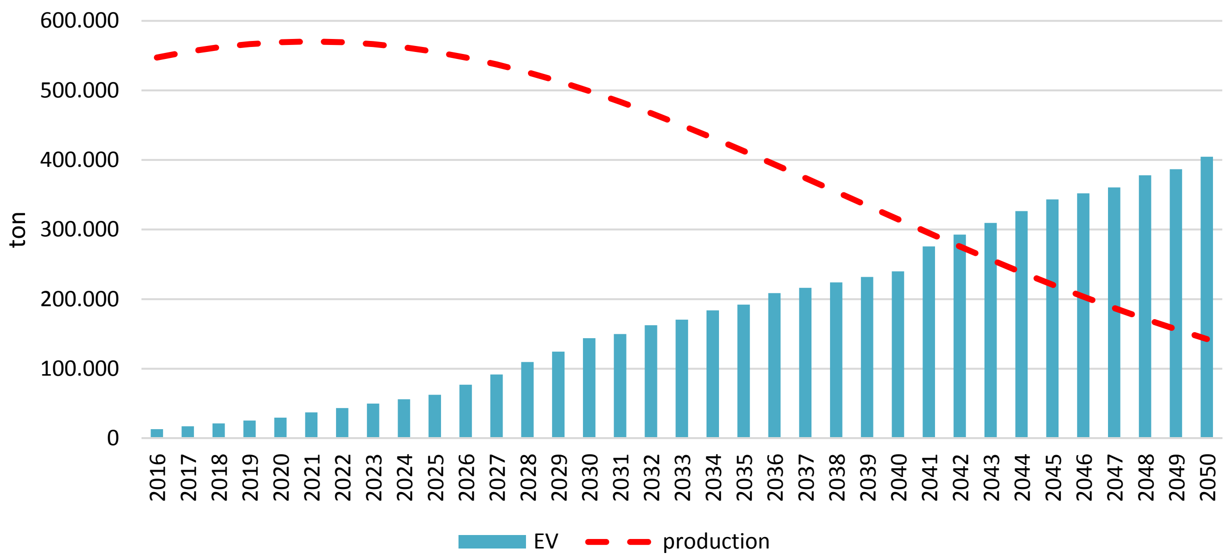

Figure 21. Li world production and transport demand projections from 2015 to 2050.

Figure 22 shows the values for Ni. In this case a possible physical constraint could eventually appear in 2021.

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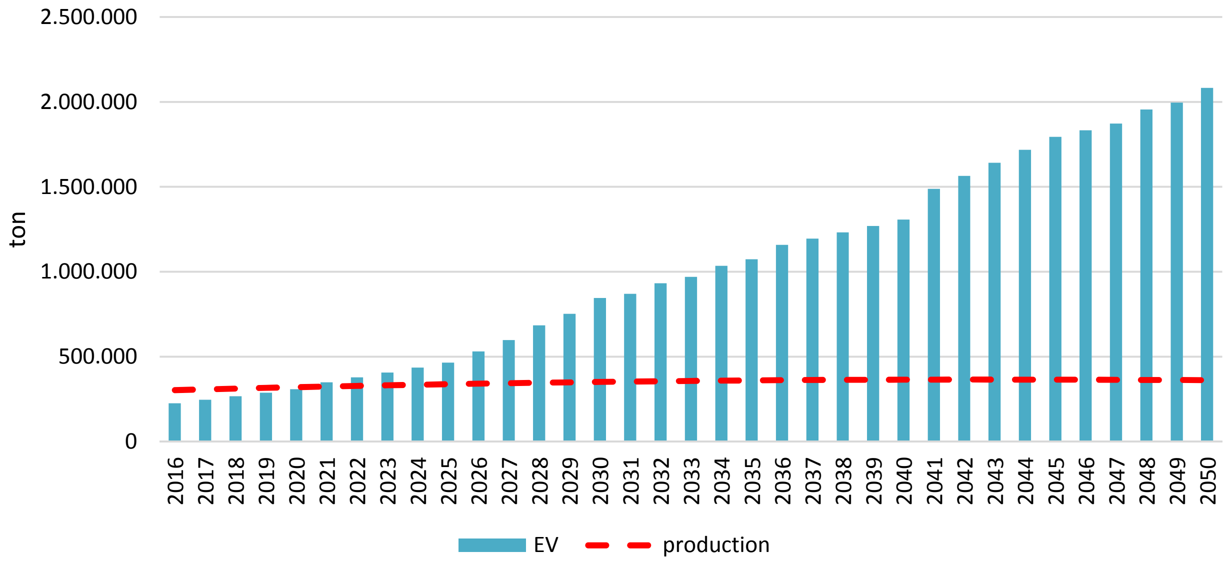

Figure 22. Ni world production and transport demand projections from 2015 to 2050.

Figure 23 shows the values for Co. In this case a possible physical constraint could eventually appear in 2030.

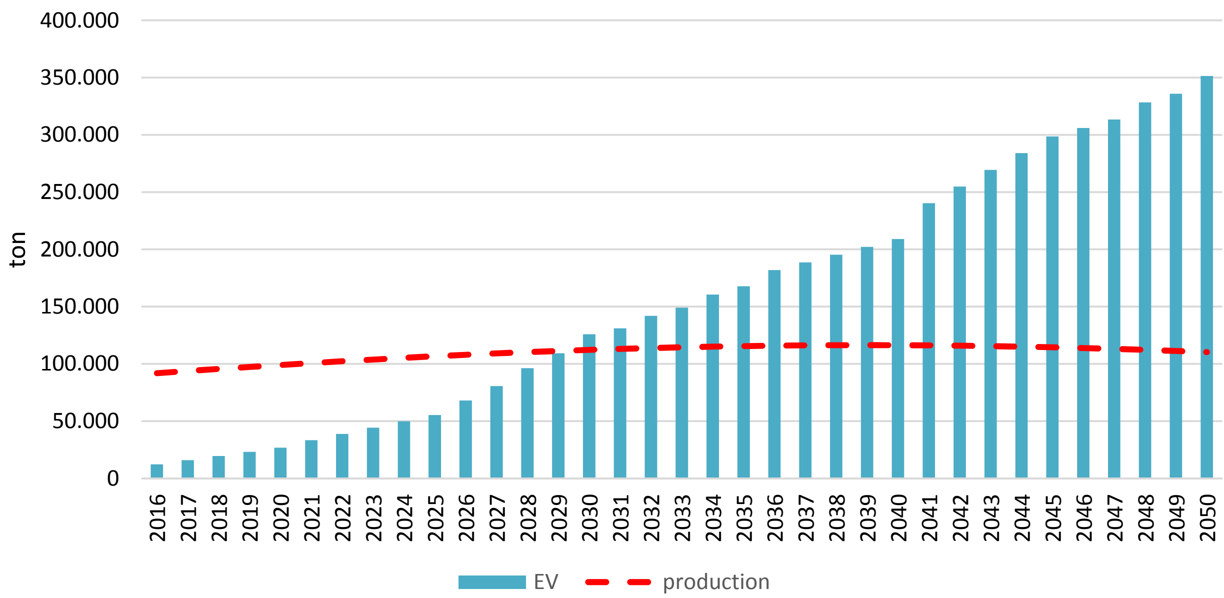

Figure 23. Co world production and transport demand projections from 2015 to 2050.

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Figure 24 shows the values for Ga. Due to the expected decrease of production from 2019, a physical constraint could eventually appear in 2035.

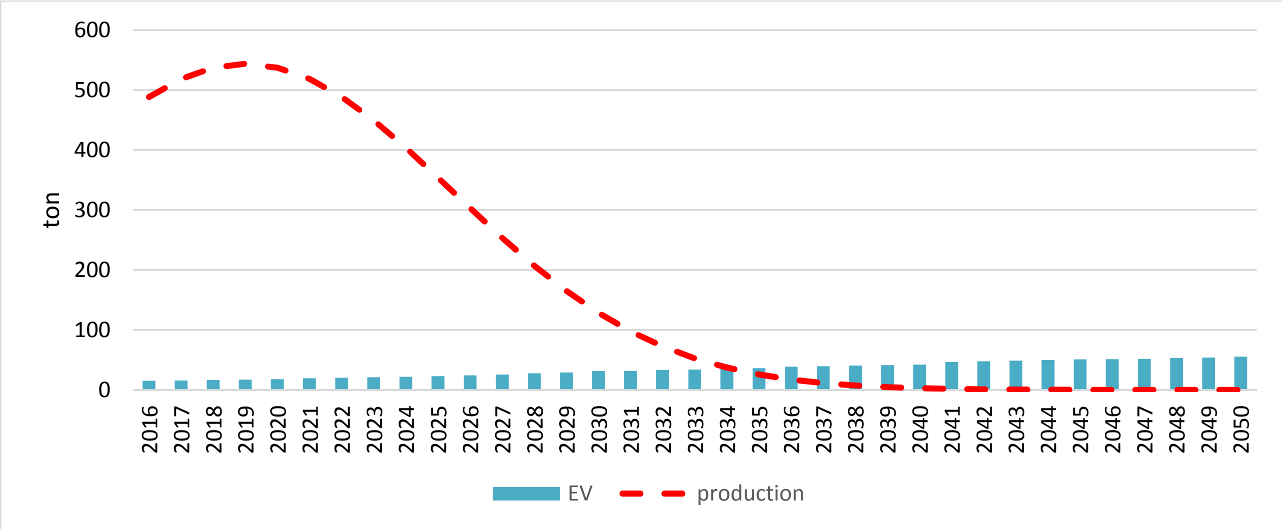

Figure 24. Ga world production and transport demand projections from 2015 to 2050.

Figure 25 shows the values for Mo. Due to the expected decrease of production from 2019, a physical constraint could eventually appear in 2049.

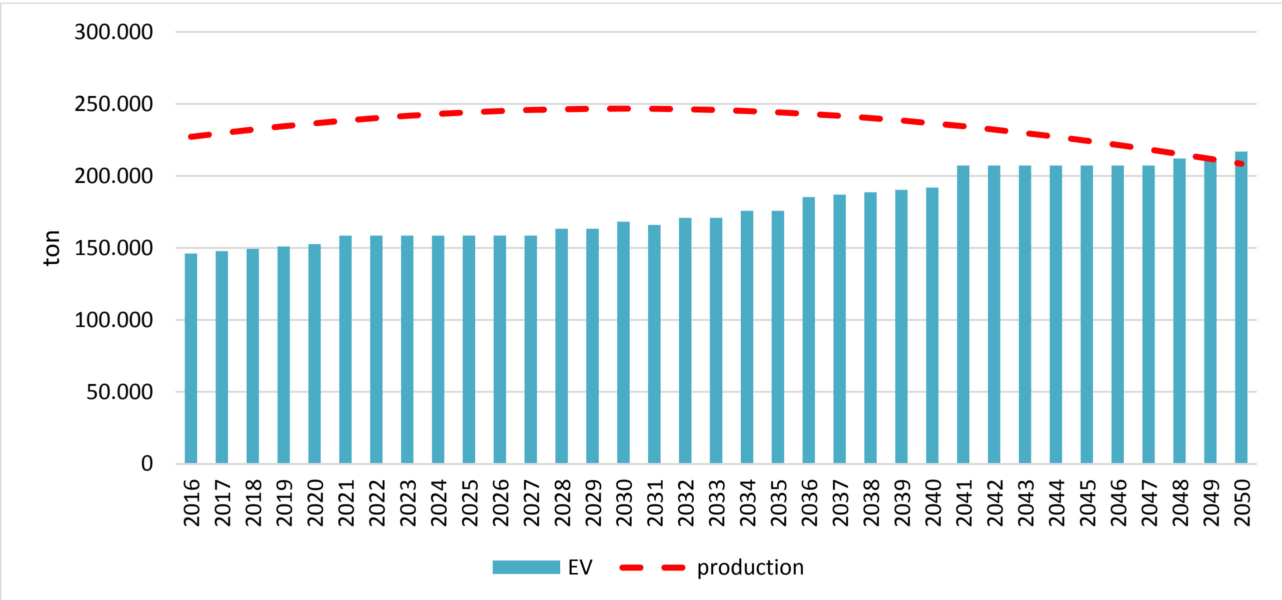

Figure 25: Mo world production and transport demand projections from 2015 to 2050.

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Figure 26 compares passenger vehicles material demand with current material production values. It can be seen for instance how passenger vehicles will demand more than world Co, Ga, Li, Mo and Ni in any year from 2016 to 2050 period of time.

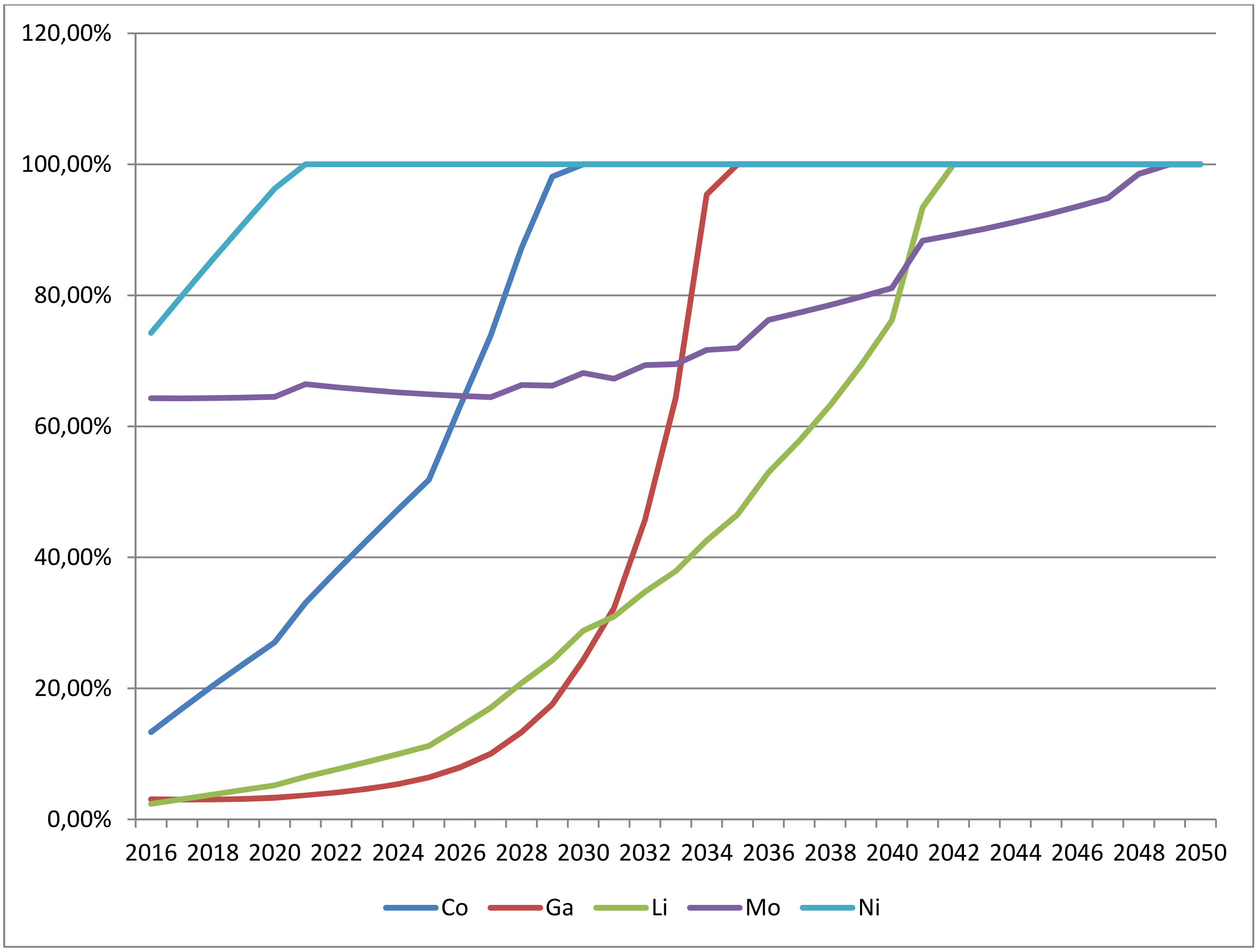

Figure 26. Co, Ga, Li, Mo and Ni transport demand with respect to world production from 2015 to 2050.

Yet there are other important metal demand such as and Ta, which will grow from 35 % in 2016 to 80 % in 2050.

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Considering current reserves values of studied materials with expected demand from 2015 to 2050 of these materials, the following figure shows the results.

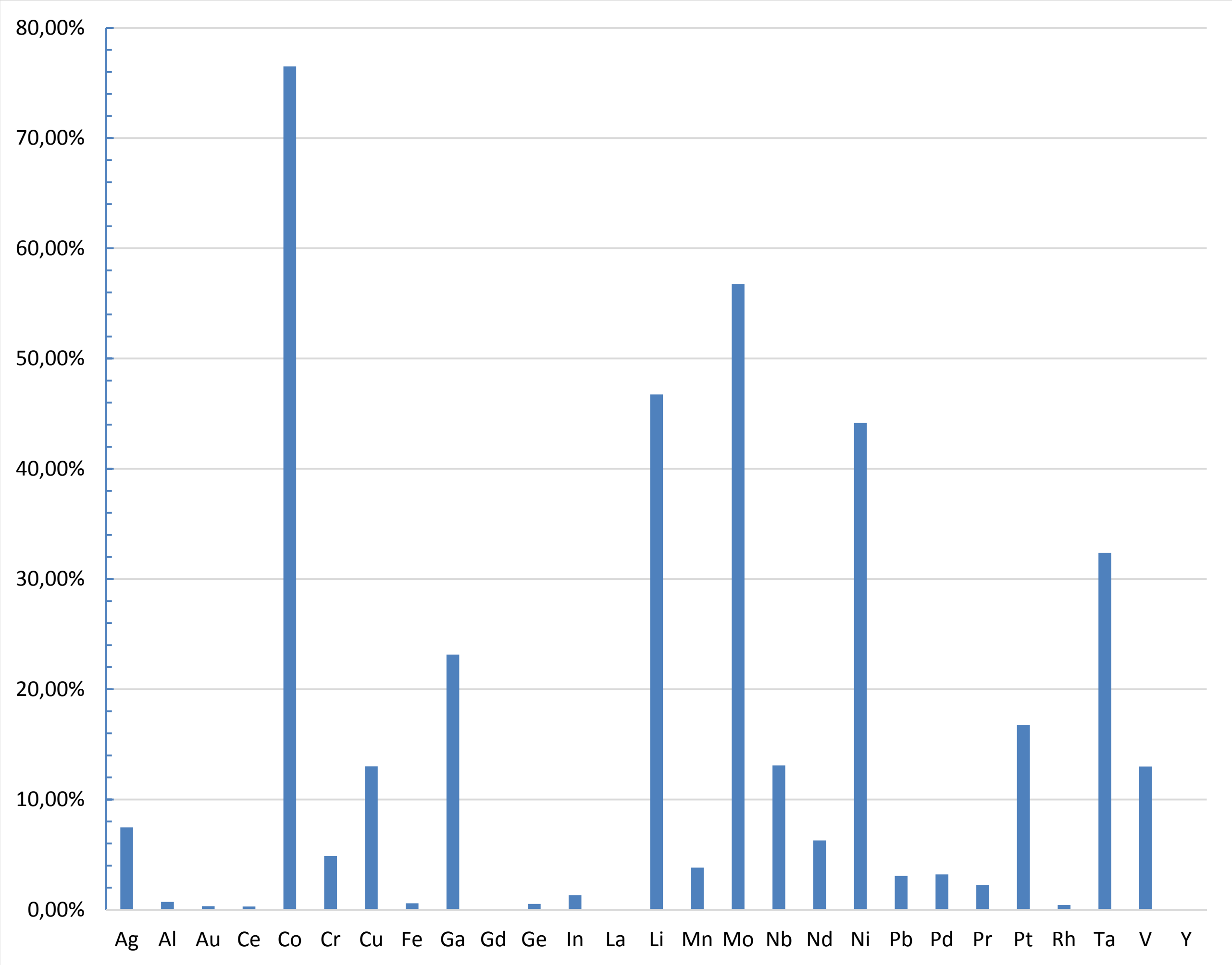

Figure 27. 2015-2050 world demand/reserves.

Ga, Pt, and Ga demand are between 15 % and 35 %. Li and Ni are between 35 % and 50 %. Mo and Co are 56 % and 76 % respectively. There are no cases in which 2016 – 2050 cumulative demand be higher than current reserves values.

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8. Conclusions

The most demanded metals from a Rarity point of view are: Al, Co, Cu, Fe, Li, Ni (for all types of vehicles) and Pd, Pt (only for ICE and PHEV).

From a rarity approach (considering the criticality of minerals through exergy), ICE is more sustainable than the other alternatives. ICE has a rarity content of 171 GJ while PHEV demands 219 GJ and BEV 379 GJ.

In passenger vehicle manufacturing and considering a BAU scenario for metal production using a Hubbert-like tendency, the following materials can be considered as critical (i.e. there might be supply shortages because demand in vehicles of a given metal is close or even surpasses global metal production):

- Ni, Co, Ga, Li and Mo → Annual demand will be higher than annual production with the following constraints data: Ni (2021), Co (2030), Ga (2035), Li (2042) and Mo (2049).
- Ta → 2050 annual demand will be between 75 % - 100 % of 2050 production.
- Cu, In, Nb, Nd, Pt and V → 2050 annual demand will be between 25 % - 75 % of 2050 production.

The most critical vehicle components are batteries and permanent magnets not only because the high demand of critical raw materials but also for the small recycling current figures. For this reason the evolution of storage sector will be so relevant from material point of view. NCA batteries demands similar Li quantity that NMC however Ni and Co demand is much higher.

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MEDEAS

MODELING THE RENEWABLE ENERGY TRANSITION IN EUROPE

D2.1: *Report with an analysis of the main limitations of variables and indicators selected to represent the pathways and scenarios.*

Annex 8: *RES for electricity generation and physical constraints. Wind Power.*

Grant agreement: 691287

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TABLE AND FIGURE INDEX

This work is part of the MEDEAS project, funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 691287

1. Scope and goal

This document is part of MEDEAS Deliverable 2.1. The main aim of this report is to explain in depth which physical constraints are expected in the electricity generation through wind power from 2015 to 2050 from the point of view of raw materials.

This activity is done through an assessment of the materials required to manufacture different types of wind turbines from 2015 to 2050.

The results of this Deliverable will be implemented in MEDEAS model through PAVs database values. For this reason, the following table shows the information covered in this document and its link to the PAV list specified in Deliverable 2.1.

Table 1. PAVs related to wind energy and covered in this Annex.

D2.1 Results	PAV	PAV description
Capacity factor of RES	34	productivity of each technology according not only technology evolution but also renewable resources potential (wind for electricity production)
Investment cost of RES*	35	Investment costs for each RES technology (wind for electricity production)
Electricity cost from RES*	36	Levelized Cost of Electricity for each RES technology (wind for electricity production)
RES production by technology	37	Yearly production of each RES technology (wind for electricity production)
RES power density from technology point of view	38	Power density of each RES technology (wind)
RES lifetime	40	Life time of each RES technology (wind for electricity production)
Cu, Al, Fe, Nd, and Ni wind power demand evolution from 2015 to 2050	109	Material intensity for RES

* Investment cost and electricity cost for RES have been indirectly taken into account by assessing the potential evolution of wind energy.

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2. Introduction

According to the International Energy Agency, without decisive action, energy related greenhouse gas emissions could more than double by 2050 and thus increased oil demand will heighten concerns over the security of supplies (IEA, Technology roadmap, 2013).

The EU is committed to reducing its greenhouse gas emissions by 20% by 2020. By 2050, it intends to slash its greenhouse gas emissions by 60% to 80%.

There is thus an increasing awareness of the need to change political statements and analytical work into concrete action. For this reason, the International Energy Agency has identified the most important technologies needed to achieve a global energy-related CO_2 reduction target to 2050 and Wind is the most advanced of current renewable technologies.

Nowadays, wind power generates 2.5 % of total world electricity demand. In some countries like Denmark, Portugal or Spain this figure is higher than 20 % (IEA, Technology roadmap, 2013) and an important growing for the following years is expected (GWEC, 2015).

Yet the deployment of renewable resources and in particular wind energy, will require an increasing demand of materials which might provoke serious bottlenecks. This is why it is crucial to analyze the expected production trend of wind power and its associated material needs in order to define future energy policies.

Indeed, a thorough analysis of the resources required for a certain economic sector needs to include not only the energy used throughout its life cycle, but also the materials required to manufacture the analyzed system. The supply of critical raw materials is an important issue that is currently regarded as a potential threat that may put at risk the so-called "Green Economy". Accordingly, a list of 20 raw materials considered as critical because risks of supply shortage and their impacts on the economy, was recently published by the European Commission (European Comission, 2014).

Some of these materials are Platinum Group Metals and Rare Earth Elements, however there are more materials which currently are not considered as critical in this list but need to be also monitored. The term “critical” as defined by the EC is not static and it changes with the socio-economic circumstances. This means that there is not a specific definition of the term, and hence there are more than 20 raw materials that must be considered when we talk about supply risk.

Going back to the wind power sector, the demand for materials used such us generators, electric grid, power converters, foundations is rapidly increasing. As an example, global installed wind power capacity multiplied threefold from 2007 (20,310 MW) to 2015 (63,013 MW) (EWEA, The European offshore wind industry-ket trends and statistics, 2015) and it is projected that this figure will increase to near 2,500 GW to 2050 (IEA, 2010). Moreover, the expected repowering of current wind turbines at the end of their lives, will imply a further increase of scarce raw material requirements. Both issues make it critical to urgently analyze deeply the use of raw materials in the wind power industry to guarantee that its evolution is not physically constrained.

3. Wind power technologies

Nowadays and likely in the coming future, wind turbine technologies are characterized by the following aspects:

- Towers with a height up to 140 m.
- Three blades rotor with an active yaw system to maintain the alignment with wind direction.
- High wind speed regulation with a pitch angle adjustment which allows that blades be turned along their axis.
- Variable rotor speed to increase the productivity at low wind speed and to balance the electricity production with the demand.

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- A drive train in which a gearbox adapts the slow angular speed of the rotor to the requirements of electricity generator. Although there are other types of generator, called multipolar, which can be used directly coupled to the rotor.

According to several authors (Lacal-Arantegui, 2012) and (Llorente, Lacal-Arantegui, & Aguado, 2011), turbines which use gearbox represent around 75 % of current market, however technologies without gearbox are already growing in market share and its contribution is expected to be higher in a short and medium term. For these reasons in the present study two types of turbines have been considered:

- **Model 1:** with gearbox to transfer power from rotor to generator.
- **Model 2:** power transmission from rotor to generator is made directly.

The main characteristics of these wind turbines are the following (Table 2):

Table 2. Characteristics of studied wind turbines **(Lacal-Arantegui, 2012)**.

	Model 1	**Model 2**
Gearbox	1-2 stages	none
Generator	Medium speed (60 – 600 rpm)	Low speed (8-20 rpm)
Power converter	full	full

4. Materials demand in wind turbines

To identify what materials are used in these types of wind turbines, a state of the art analysis obtained from the bibliography has been undertaken. In the following table a list of critical raw materials identified by different authors is shown (Table 3).

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Table 3. List of materials used in wind turbines through different authors[1].

Author	Cu (kg/MW)	Fe (kg/MW)	Al (kg/MW)	Nd (kg/MW)	Dy (kg/MW)	Ni (kg/MW)	Model
Habib & Wenzel (2016)				150	14		2
Guezuraga et al. (2012)	1,200	148,000					1
	5,500	98,900					2
Zimmermann (2013)			560				2
Habib & Wenzel (2016)	4,700			200	13.3		2
Lacal-Arantegui (2012)		120,000					2
Martinez et al. (2009)	1,750	89,840					1
IEA (2011)				30 %[2]	2%		2
Lacal (2015)				195	13		2
USDE (2011)				186	18		2
USGS (2011)	2,500			43.2	18		1
ELSAM (2004)	1,408		830				1
Elskaki & Graedel (2013)						111 (in steel)	1 and 2

[1] Type 1 (Doubled Fed Induction Generator) and Type 2 (Direct Drive Turbine)

[2] 30 % of permanent magnets mass

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In addition to the materials demanded to manufacture wind turbines, the demand for Cu used in transport infrastructure must be considered, as well as the steel demand for either on shore or off shore installations (as this figure varies greatly depending on both technologies) – see Table 4.

Table 4. Cu and Fe demand (kg/MW) in wind turbine, foundation and grid infrastructure.

Author	Material	On shore	Off shore
Garcia-Olivares et al., (2012)	Cu	2,700	11,500
Estate (2008)	Fe	---	120,000 more than on shore

Considering all previous bibliographic revision, the following table summarizes the materials used in the studied turbines and installation types.

Table 5. Material contained by type of turbine and installation (kg/MW).

	Model 1		Model 2	
	On shore	Off Shore	On shore	Off Shore
Al	840	840	560	560
Cu	2,700	11,500	7,000	15,800
Fe	172,100	292,100	112,670	232,670
Nd	60.92	60.92	182.75	182.75
Dy	4.86	4.86	14.58	14.58
Ni	111	111	111	111

These values have been used for the following reasons:

- Cu used values comes from (Lacal, 2015) since it was the only study that compares Model 1 and Model 2 wind turbines in a common study. The other studies that investigated the use of Cu were Martinez et al. (2009), ELSAM (2004), USGS (2011) and Habib & Wenzel (2016) but they didn´t compare Model

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1 and Model 2 together, so taking into consideration that values were similar, it was decided to use the same reference.

- As for Cu demand for grid infrastructure, there was only the reference from Garcia-Olivares et al. (2012) that studied Cu demand for on shore and off shore installations.
- Al values are obtained from Zimmermann (2013) and ELSAM (2004) for Model 1 and Model 2, respectively because there were the only studies that included Al contents.
- The case of Fe is similar to that of Cu. Different authors analyzed Fe contents in wind turbines but only Lacal (2015) made this analysis comparing Model 1 and Model 2 in the same study.
- As for Fe demand for foundation infrastructure in off shore installations, there was only the study from The Crown Estate (2008) that looked into this variable.
- The quantity of Nd has been calculated as an average value from (Habib & Wenzel (2014), Habib & Wenzel (2016), Lacal (2015) and USDE (2011) for Model 2. For Model 1 it was assumed that it contains 33 % of Nd content with respect to Model 2 according to USDE (2011).
- The amount of Dy has been calculated as the third part of Nd contain (USGS, 2011) and as the average value from (Habib & Wenzel, 2016), (Lacal-Arantegui, 2012), (USDE, 2011) and (USGS, 2011) for model 2.
- In the case of Ni there was only one study that analyzed this material, for this reason Elskaki & Graedel (2013) value was used.

5. Evolution of wind power

The expected power installed projections from 2015 to 2050 is required for assessing the impact of wind power material demand in reserves. To do so, sales projection values from IEA (2010), EWEA, The European offshore wind industry-ket trends and statistics, (2015), GWEC (2015), AEE (2016) and Lacal-Arantegui (2012) have been consulted.

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Considering these data, Figure 1 shows the evolution of installed power from 2016 to 2050 by type of installation: on shore and off shore. It can be seen how off shore installations are expected to grow in market share.

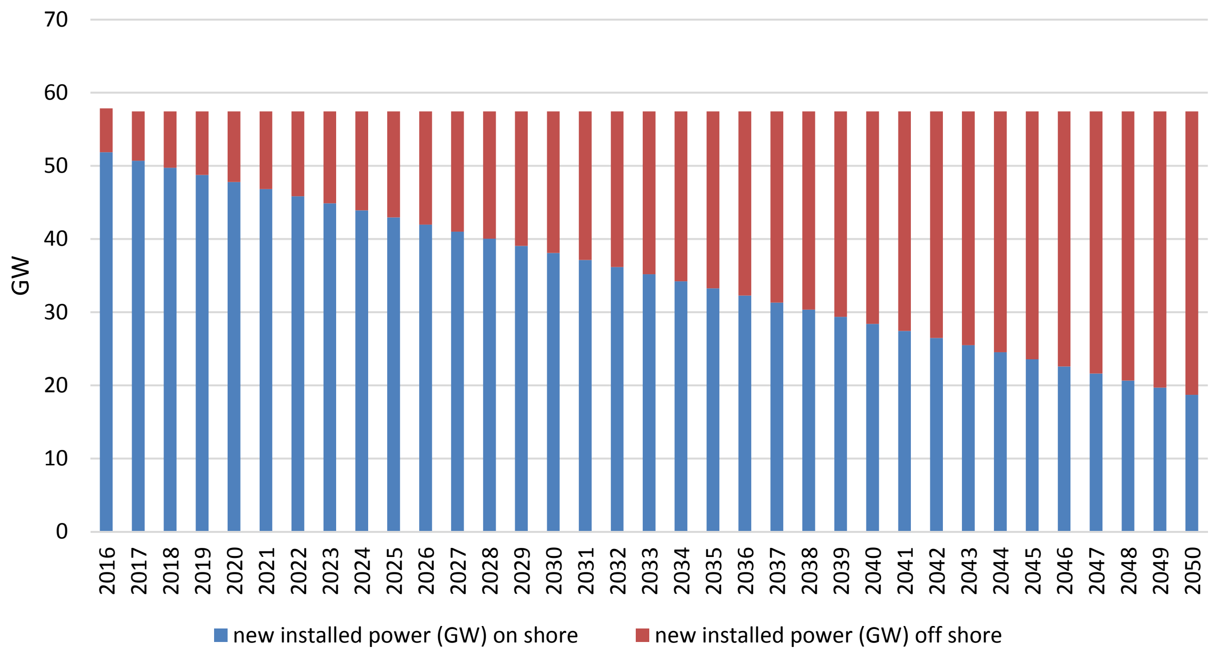

Figure 1. Projection of new installed (GW) wind power by type of installation.

One important factor to assess the future demand of materials is the repowering effect of wind power installations at the end-of-life. According to EWEA (2016) the lifetime in wind turbines is around 20 – 25 years. In the present study the most conservative figure with respect to raw material demand has been used.

To assess this impact, the age of current wind installations has been calculated. The following figure shows how more than 14 % of current installed power capacity has 1 year and around 40 % between 3 to 7 years.

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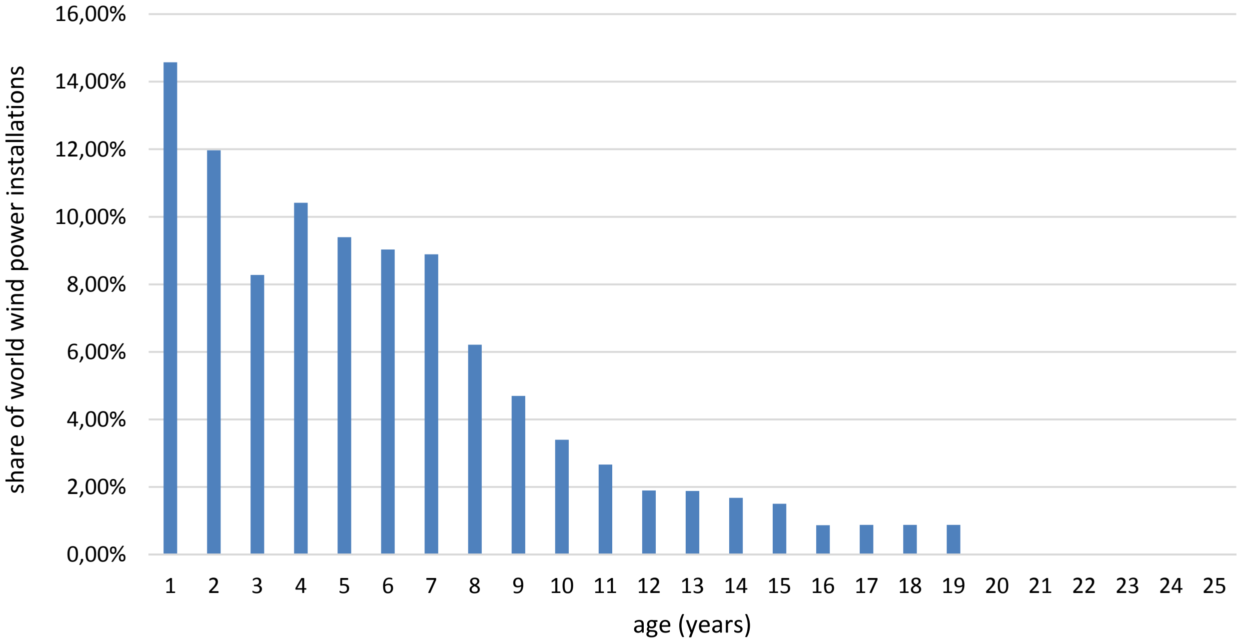

Figure 2. Age of world wind power installations (EWEA, The European offshore wind industry-ket trends and statistics, 2015).

The following figure shows the evolution of repowering to 2050. As it can be seen, repowering will be very significant especially from 2034 (Figure 3).

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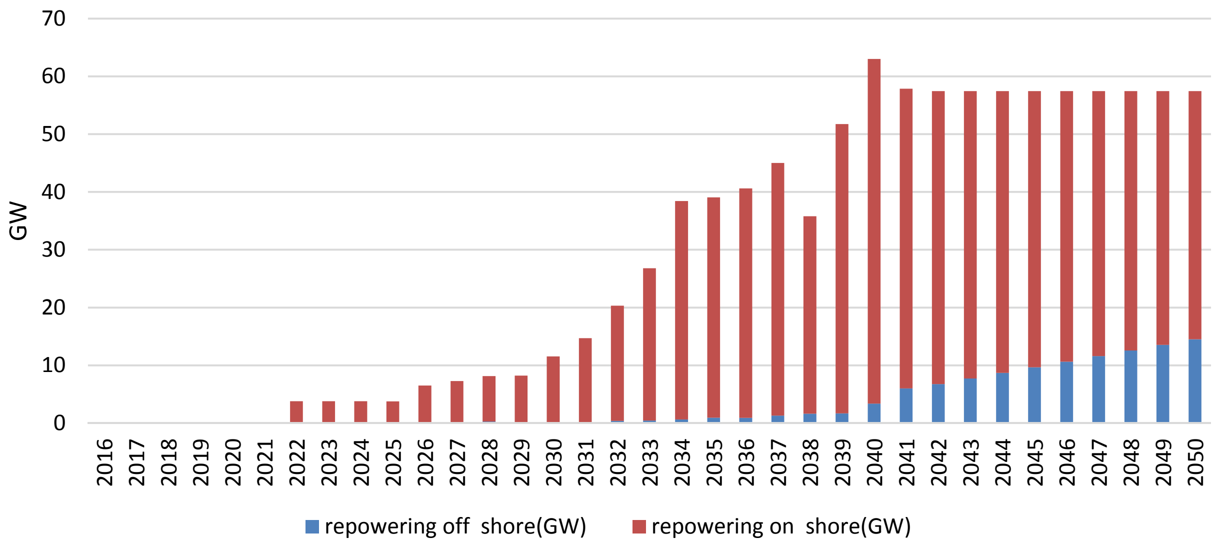

Figure 3. Projection of wind power repowering (GW) by type of installation.

Considering new installed power and repowering, Figure 4 shows the total installed power by year.

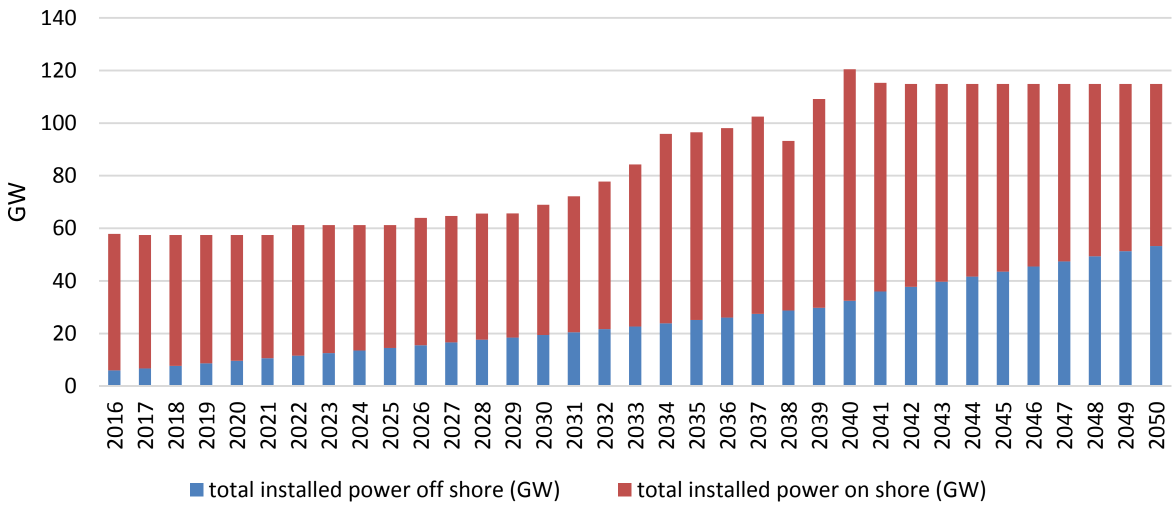

Figure 4. Projection of total new and repowered wind installation (GW) by type.

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To conclude the next figure represents the cumulative installed power capacity. It can be seen how in 2050 near 2,500 GW will be reached. The growing trend is linear with an increase of 54 GW/yr approximately.

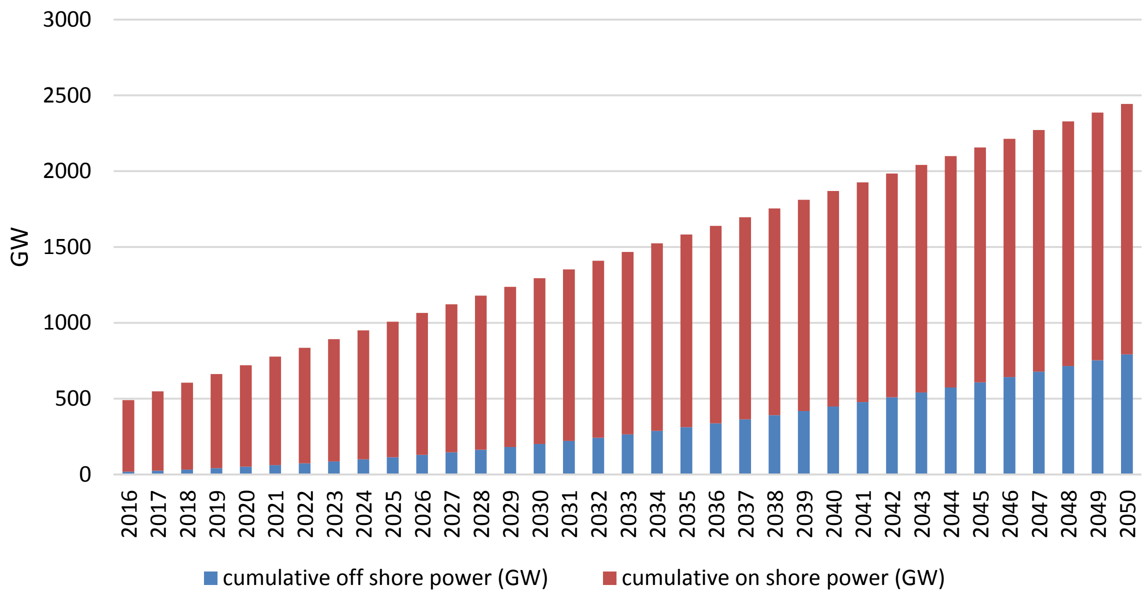

Figure 5. Projection of wind power cumulative installed power capacity (GW).

6. Methodology

To assess the impact of different used materials, the methodology developed by (Valero and Valero (2014) is used. This methodology covers the total life cycle, from cradle to gate including the grave to cradle approach.

- **Cradle to Gate approach:** assess the exergy cost to produce a refined metal from the mine to be used in industrial applications.
- **Grave to Cradle:** assess the exergy replacement cost to return raw materials from a dispersed state (i.e.: landfills) to the initial state in mines.

This methodology uses the concept of thermodynamic rarity (Valero and Valero, 2014). The thermodynamic rarity indicator is a rigorous exergy measure of a mineral´s quality considering physical aspects of the minerals such as natural concentration,

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chemical composition, comminution and energy requirements to beneficiate the given mineral.

This approach gives an additional dimension to the criticality of minerals taking into account physical aspects (scarcity in the crust and energy intensity to mine and beneficiate the mineral). Note that this new dimension is not yet included in current criticality assessments which are focused on supply risk and economic importance. Whereas the thermodynamic rarity concept is universal and absolute, the socio-economic criticality assessment is country-dependent and variable. For more information on the methodology, see Annex 5.

To identify physical constraints for the wind power sector, a combination of bottom-up and top-down approaches will be used:

- **Bottom-up**: assess the estimated evolution of material production according to current reserves and past production values. This method uses the Hubbert curve methodology traditionally used to assess peak oil. Reserves and production data comes from (Calvo, 2015) and are included in Annex 6.
- **Top-down**: assess the estimated demand of materials from different studied wind turbines according to material´s demand and expected projections of installed power by type of wind turbine and recycling current figures of different studied materials.

The values used to assess materials in exergy terms are included in the following table:

Table 6. Exergy values used (GJ/ton).

	(A) Grave-Cradle	(B) Cradle-Gate	(A)+(B) Rarity
Al	627.24	10.50	637.74
Cu	291.70	35.30	327.00
Fe	17.75	0.70	18.45
Dy	---	---	---
Nd	78.42	591.70	670.12
Ni	523.61	9.98	533.59

Considering these values and from a rarity point of view, it can be seen for instance that it is not the same to use 1kg of Fe (with a rarity of 18 MJ) than the same quantity of Nd (670 MJ).

The values of current recycling rates of the mineral commodities analyzed in this study are included in the following table:

Table 7. Recycling rates by element (UNEP, 2011).

Element	Recycling rate
Al	36 %
Cu	30 %
Fe	50 %
Dy	10 %
Nd	5 %
Ni	29 %

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7. Results

7.1. Exergy analysis per type of wind turbine

Figure 6 shows a mass comparison between the two studied wind turbines and the materials used. From a mass point of view, Fe constitutes the maximum weight of the turbine with figures around 94 to 98 % in turbines model 2 and 1, respectively. It is followed by Cu and Al. In the case of model 2, the Cu contribution is significantly larger than in model 1, (4.62 % and 0.68 %, respectively) as a consequence of the larger size of the multipolar generator.

Something similar happens to Nd, which share is 0.15 % in the case of model 2 and 0.03 % in model 1 due to the larger size of permanent magnets in model 2 turbines.

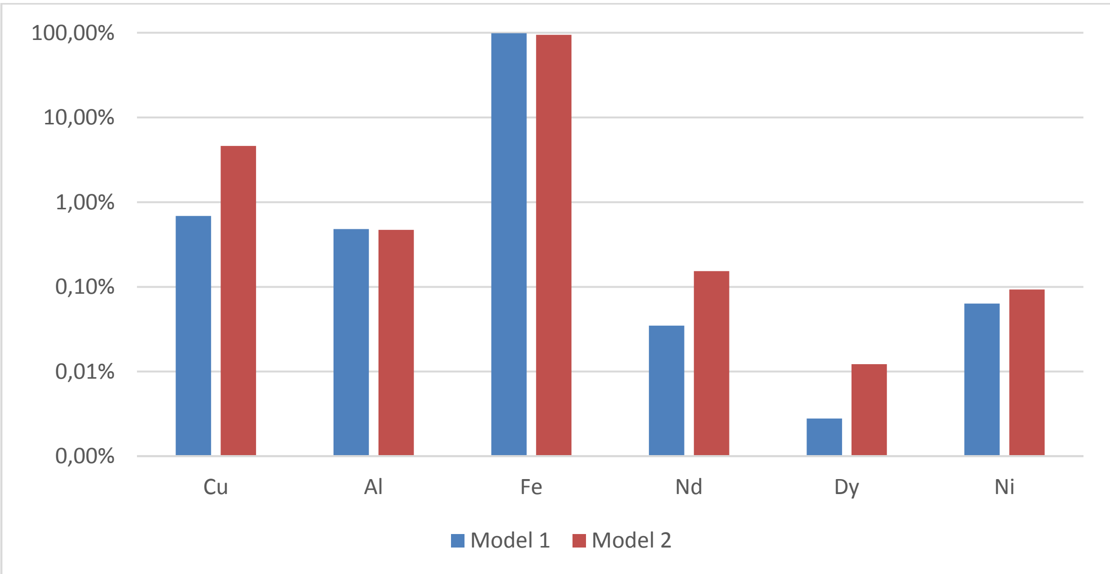

Figure 6. Mass comparison between two studied wind turbines.

Figure 7 shows the results with an exergy (rarity) point of view. In this case the contribution of Al and Cu is also as relevant as in the mass case, due to the high exergy content of Cu and Al with respect to Fe. In exergy terms, the Cu share is 40 % and 9 % in model 2 and 1, respectively while that of Nd is 2.77 % and 0.97 %, respectively.

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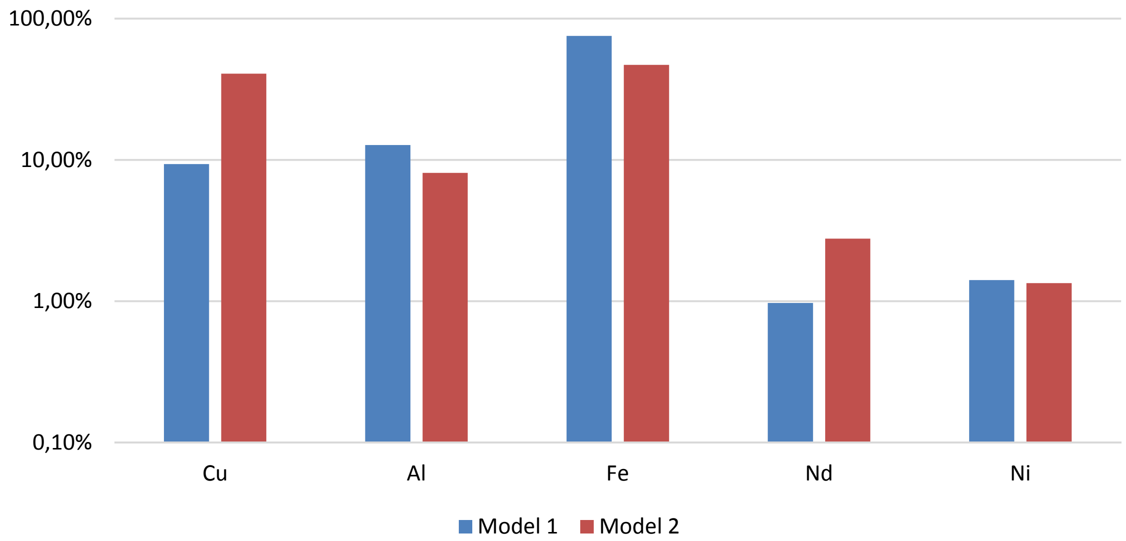

Figure 7. Exergy comparison between two studied wind turbines.

In the following table all exergy values for the different studied materials and turbines are shown. It can be seen how from an exergy point of view Model 1 requires less exergy (4,203 GJ/MW) than model 2 (4,416 GJ/MW).

Table 8. Exergy values for the different studied wind turbines.

Element	Model 1	Model 2
Cu (GJ/MW)	392	1,798
Al (GJ/MW)	536	357
Fe (GJ/MW)	3,175	2,079
Nd (GJ/MW)	40.8	122
Ni (GJ/MW)	59.2	59.2
Total (GJ/MW)	**4,203**	**4,416**

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7.2. Stock in use in wind power

In this stage stock in use materials from wind turbines is analyzed. The obtained figure could be relevant to analyze the quantity of raw materials available in the technosphere with respect to those in the ground.

The resulting information can be very valuable for instance to encourage more effective recycling polices. The following figures show stock in use evolution of the studied materials, assessed through exergy replacement costs.

Figure 8 shows the evolution of stock in use in the case of Cu and Fe. In 2050 Fe and Cu stock in use values will be likely multiplied by 5 and 9, respectively, with respect to current values.

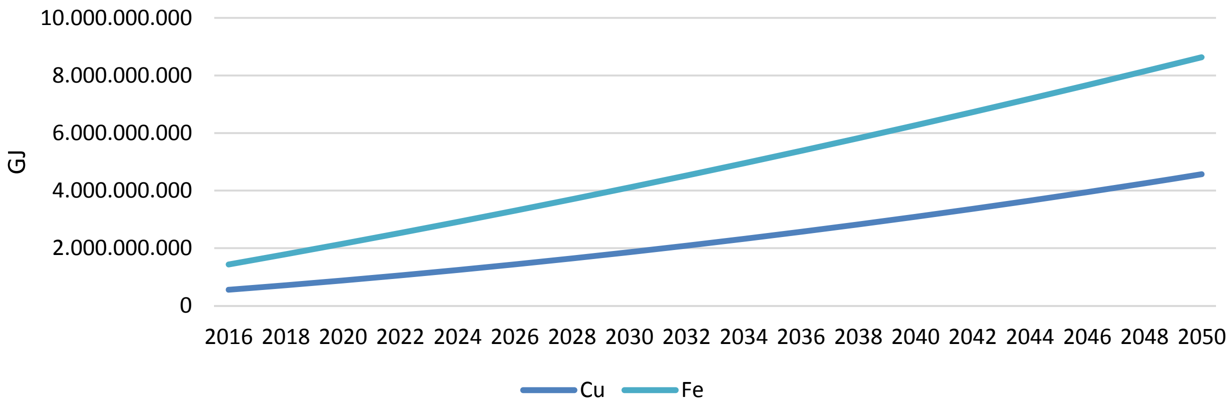

Figure 8. Fe and Cu stock in use evolution (GJ).

Figure 9 shows the evolution of stock in use in the case of Al, Nd and Ni. It should be stated that the final stock in use values for Nd will depend of the share of Model 1 and Model 2 turbines in the total wind turbines fleet, which has been assumed in this study to be constant throughout the analyzed period.

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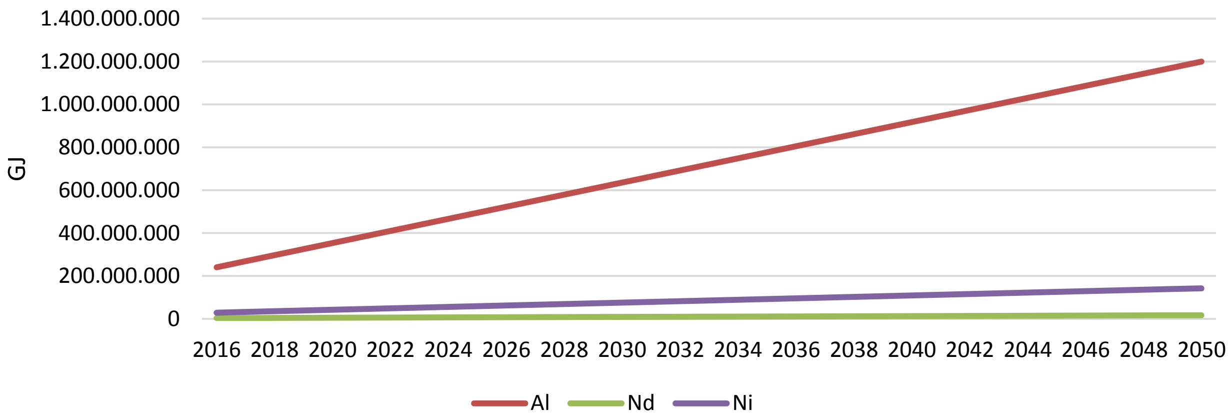

Figure 9. Al, Nd and Ni stock in use evolution (GJ).

7.3. Material bottlenecks in wind power installations

Once different wind turbines have been analyzed from a material point of view, expected demand of materials associated to wind power from 2015 to 2050 are assessed. The aim is to identify possible material shortages due to new installed repowered wind energy capacity under a "Business as Usual" scenario. Recall that the BAU scenario for material production has been built assuming that it will follow a Hubbert-curve trend assuming available reserves as registered in 2015 by the USGS. Note that the same results are obtained using tonnage or exergy values, hence curves are shown in mass terms.

Figure 10 compares Nd demand to manufacture wind turbines with world estimated production of Nd. Although demand and production do not cross in the studied period, it is relevant to highlight that only wind power applications are going to demand around 14 % of total Nd World production.

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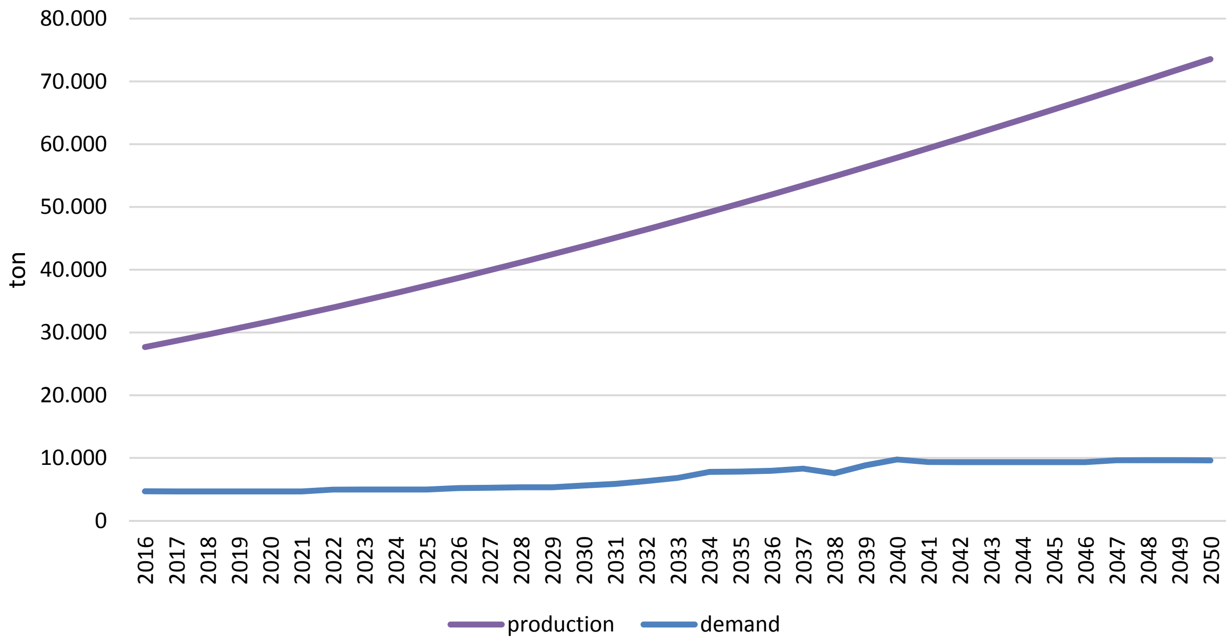

Figure 10. Nd world production and wind power demand projections from 2015 to 2050.

The following figure compares demand and production of Dy. It can be seen how in the study period practically all world Dy production will be used in Wind Power.

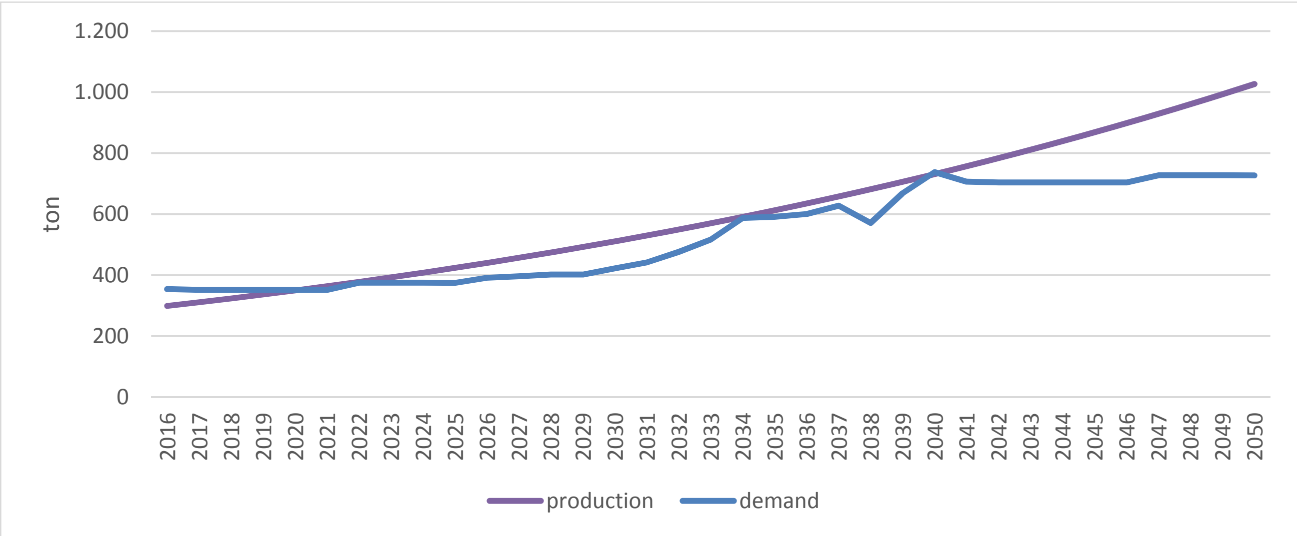

Figure 11: Dy world production and wind power demand projection from 2015 to 2050

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Figure 12 compares Cu demand to manufacture wind turbines with world estimated production of Cu. Although Cu production could reach the peak at around 2024 considering reserves data, demand for this metal in wind turbines does not seem to constitute a bottleneck by itself.

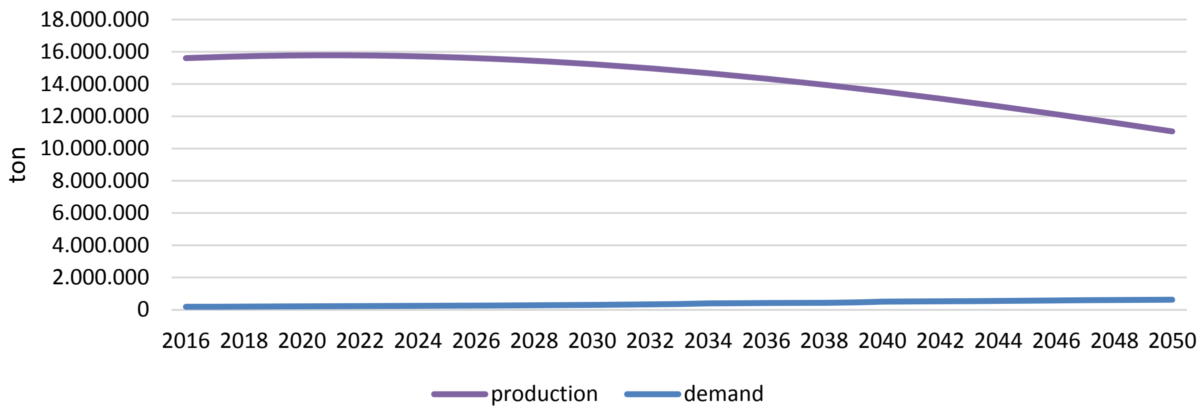

Figure 12. Cu world production and wind power demand projections from 2015 to 2050.

Figure 13 compares Fe demand to manufacture wind turbines with world estimated production of Fe. As with copper, iron will not constitute a bottleneck in the studied period.

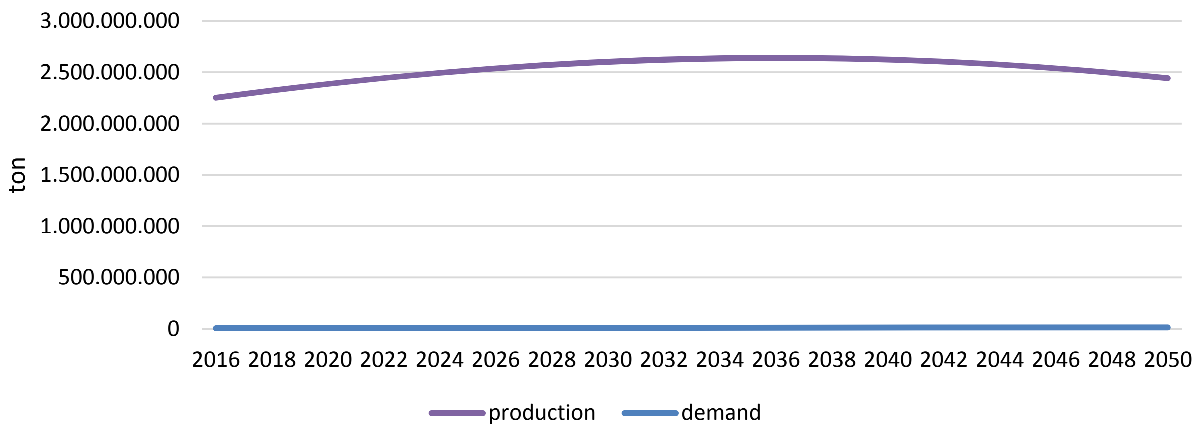

Figure 13. Fe world production and wind power demand projections from 2015 to 2050.

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Figure 14 compares Ni demand to manufacture wind turbines with world estimated production of Ni. No expected Ni constraint is foreseen in the studied period.

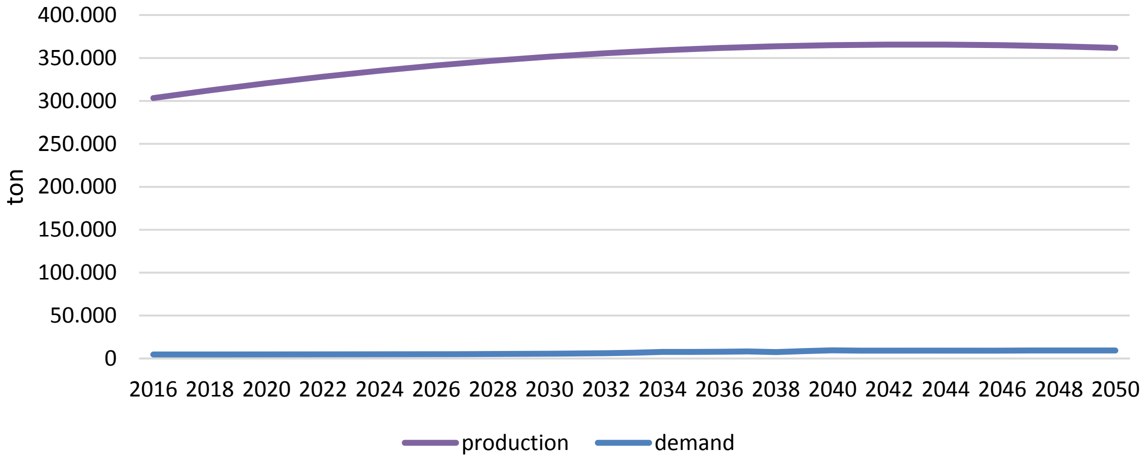

Figure 14. Ni world production and wind power demand projections from 2015 to 2050.

Figure 15 compares Al demand to manufacture wind turbines with world estimated production of Al. This metal doesn't either constitute a physical constraint in the studied period.

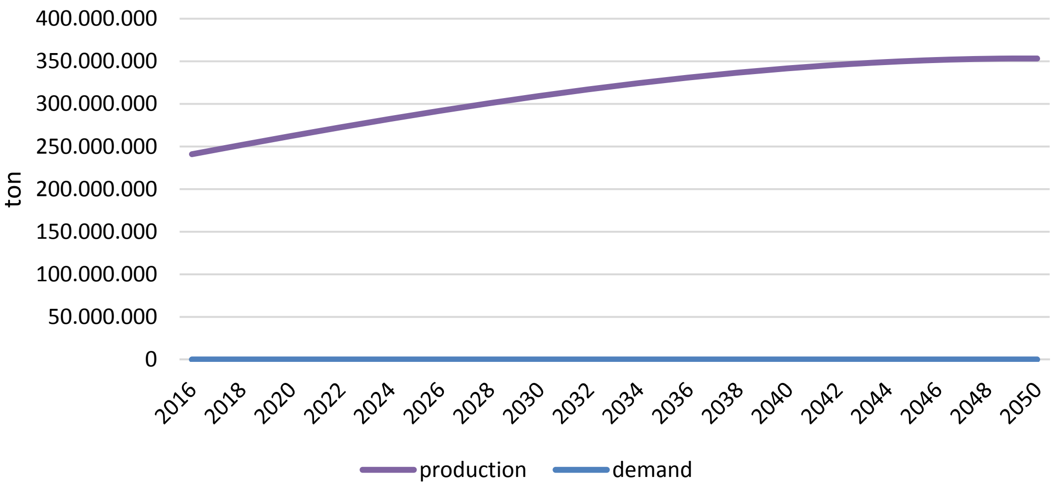

Figure 15. Al world production and wind power demand projections from 2015 to 2050.

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Figure 16 shows the ratios between demand and production for the major metals used in wind turbines (Al is not shown because of its small relative quantity with respect to the rest). Although there are no expected supply problems by the technology itself, it can be seen how the share of Fe, Cu and Ni demand caused by wind power will grow from 0.22 %; 1.2 % and 1.5 % to 0.52 %; 2.5 % and 5.7 % respectively.

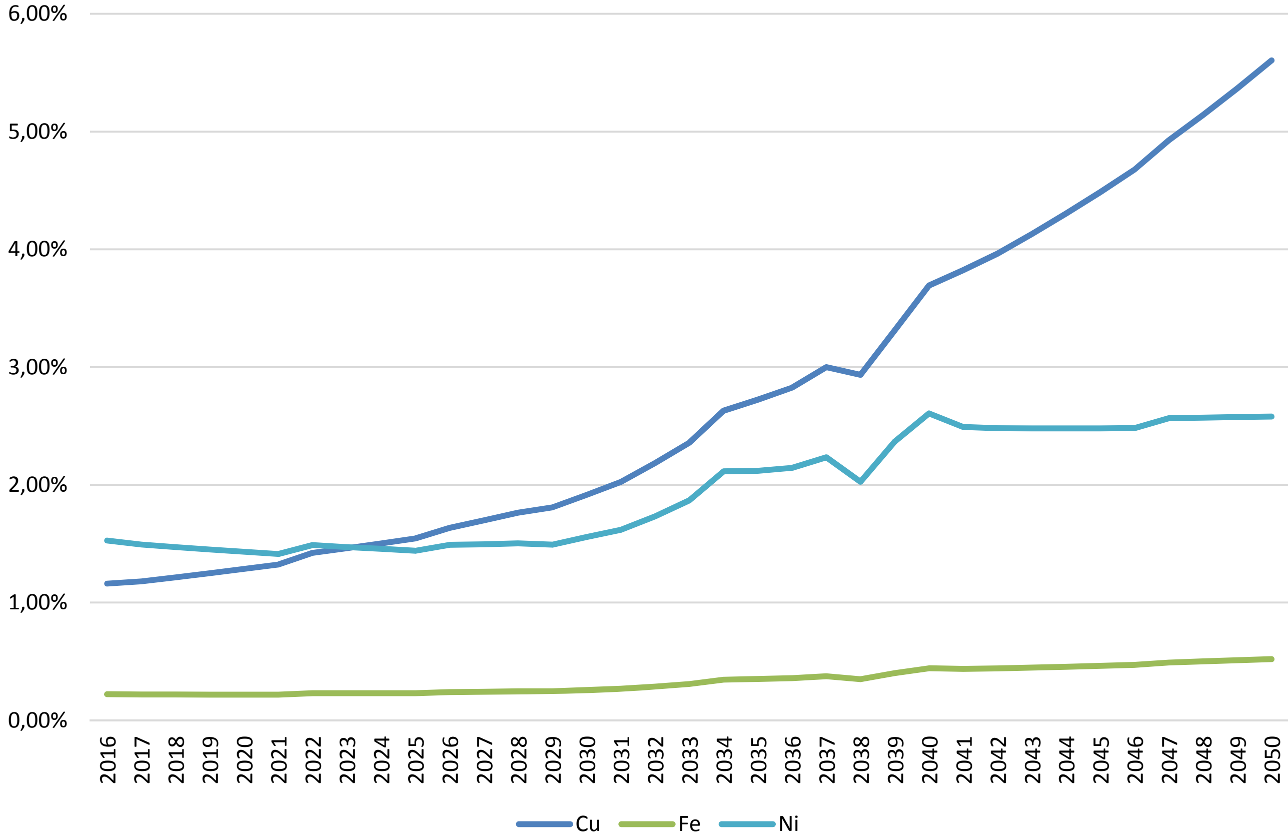

Figure 16. Cu, Fe and Ni world wind power demand with respect to world production from 2015 to 2050.

In the case of Nd, since production will likely increase until a foreseeable peak in 2100, Nd in wind turbines will pass from a share of 17% to 13% of world production in 2050.

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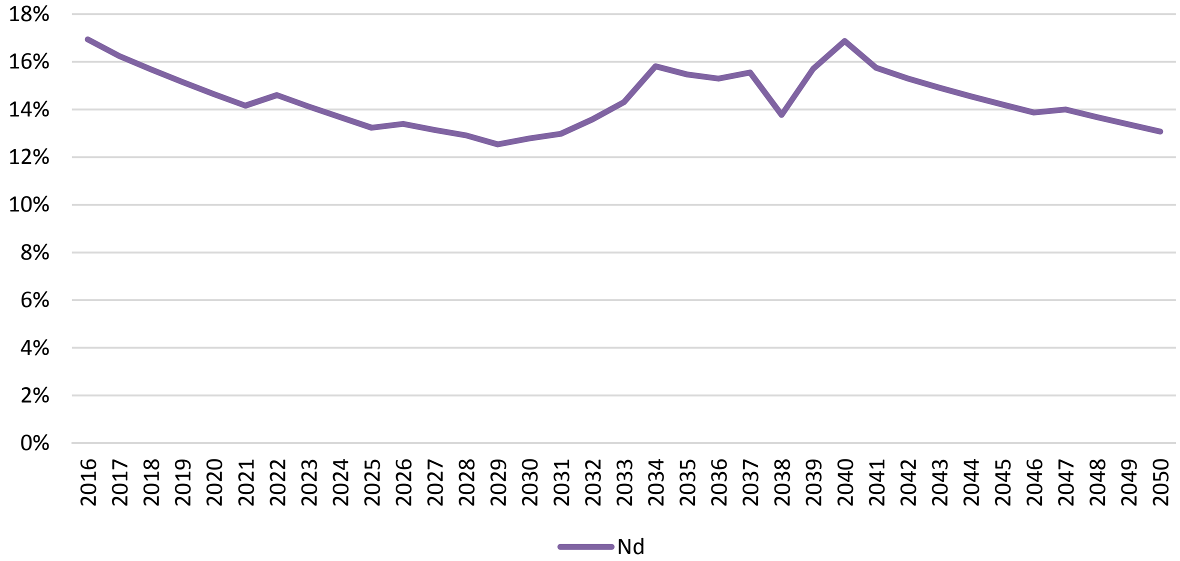

Figure 17. Nd world wind power demand with respect to world production from 2015 to 2050.

In the case of Dy, although production values will grow, the ratio between demand and production will be over the 80 %.

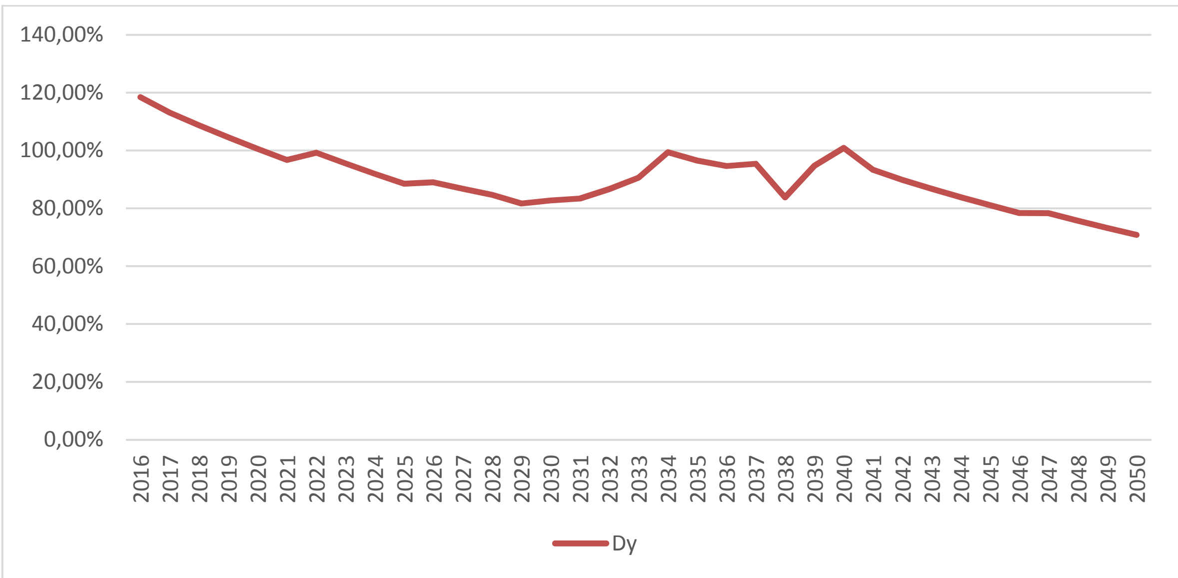

Figure 18: Dy world wind power demand with respect to world production from 2015 to 2050.

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Finally, considering the cumulative primary material demand from 2016 to 2050 (taking into account recycling figures of studied materials) and comparing these values with current reserves, it can be seen how wind power will not likely be constrained by material supply risk.

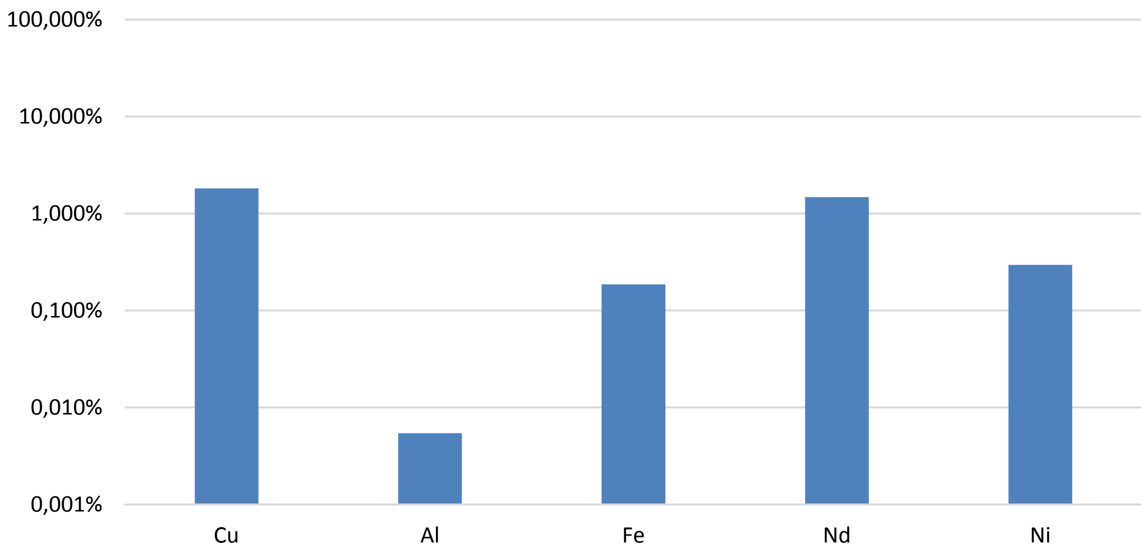

Figure 19. 2015-2050 world demand/reserves.

In the case of Dy there are not reserves data, considering resources value which is 2.980.000 ton, cumulative demand from 2016 – 2050 (18.581 ton) is so small to be compared.

8. Conclusions

The most demanded metals from an exergy-rarity (considering the physical criticality of minerals) point of view are: Al, Cu, Fe, Ni and Nd. Considering the type and again only considering their material content, Model 1 (with gearbox) wind turbine is more sustainable than Model 2 (direct-drive). Model 1 has a rarity content of around 4,200 GJ/MW while Model 2 about 4,400 GJ/MW.

On the other hand, off shore installations demand considerably more materials than their on shore counterparts. This is mainly because of the larger electricity transmission lines required. For instance, Cu demand in off shore installations is 10.30 ton/MW while in on shore installations it is only 1.50 ton/MW.

In wind turbines manufacturing and considering a BAU scenario for metal production using a Hubbert-like tendency assessed with reserves data, there is only possible to identify Dy as critical from a physical availability perspective because projections of demand and production from 2016 to 2050 will be over 80 %.

It is also important to highlight that wind power installations will likely demand near 15 % of world Nd production. This share will be maintained or will even decrease slightly by 2050. Yet the share is still significant and combined with the economic supply risk (most of it comes nowadays from China mines) it should be taken into account as a possible bottleneck.

Taking into consideration these facts, in can be stated that the most critical components in wind turbines are generator and power transmissions, due to their high Cu, Dy and Nd contents. This result is a guideline for future design and recycling policies in the wind sector.

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D2.1: *Report with an analysis of the main limitations of variables and indicators selected to represent the pathways and scenarios.*

Annex 9: *RES for electricity generation and physical constraints – Solar Photovoltaic*

Grant agreement: 691287

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TABLE AND FIGURE INDEX

1. Scope and goal

This document is part of the MEDEAS Deliverable 2.1. The main aim of this report is to explain in depth which physical constraints are expected in the RES sector for electricity generation from 2015 to 2050 in the raw materials approach.

This activity is done through an assessment of the materials required to manufacture different types of RES power production technologies from 2015 to 2050.

The results of this Deliverable will be implemented in the MEDEAS' model through PAVs database values. For this reason, the following table shows the information covered in this document and its link to the PAV list specified in Deliverable 2.1.

Table 1. PAVs related to wind energy and covered in this Annex.

D2.1 Results	PAV	PAV description
Capacity factor of RES	34	productivity of each technology according not only technology evolution but also renewable resources potential (solar pv)
Investment cost of RES*	35	Investment costs for each RES technology (solar pv)
Electricity cost from RES*	36	Levelage Cost of Electricity for each RES technology (solar pv)
RES production by technology	37	Yearly production of each RES technology (solar pv)
RES power density from technology point of view	38	Power density of each RES technology (solar pv)
RES lifetime	40	Life time of each RES technology (solar pv)
Si, Cu, Sn, Pb, Ag, Mg, Cd, Mo, Te, In, Zn, Se, Ni, Ga and Ge solar pv demand evolution from 2015 to 2050	109	Material intensity for RES

* Investment cost and electricity cost for RES have been indirectly taken into account by assessing the potential evolution of PV tecnologies.

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2. Introduction

Photovoltaic effect can be summarized as the capacity of some semiconductor materials able to generate direct current under solar irradiation when they are connected to an electrical resistance. In case these photovoltaic modules are connected to a direct current/alternate current inverter, an alternate current flux is obtained to fulfil electrical loads or to be injected into the electrical grid.

In both cases, one of the most remarkable characteristic to bear in mind is that the electric current will be proportional to the solar irradiation. Because of this, under a scenario where the PV modules are directly connected to electrical loads, the existence of backup systems (as diesel-generation or grid connections) to support the non-covered consumption will be required during night time or low-irradiation periods.

The PV modules technology, industrially exploited since the beginning of the 1990's, has reached a degree of maturity with a current PV power capacity in the world close to 220 GW and a projection of growth close to 4,500 GW at the end of 2050, able to cover almost the 16% of the global electricity consumption (Tyagi et al., 2013; IRENA and IEA-PVPS, 2016). This industrial maturity, joined to stable values of performances close to 15% for monocrystalline Silicon and ranged from 6 to 12% for thin film models, should be enough to considered PV as a reliable power generation system.

One of the historical limitation of this technology during the 1990's and the 2000's, able to avoid its advance as an extended method to generate electrical power was the high prices of the PV modules. Between the years 2005 and 2010, and increase in the number of manufacturers joined to legislative changes in most of the European countries orientated to reduce the subsidies associated to the technology, provoked a decrease in the cost of the technology up to 1.5 €/Wp. Nowadays, even the prices are affected by scale economy, it is possible to acquire PV modules with a price close to 0.6 €/Wp. To that effect, some studies indicate that in the short term – by the end of 2017 - an asymptotic value of 0.5 €/Wp with an expected lifetime of 25 years (according to the warranty offered by manufacturers) will be achieved (IEA, 2013), reaching grid parity with traditional thermal methods to produce power.

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Regarding this last point, the electricity cost will be totally dependent of the technology price. In the framework of the EC, Germany presents one of the highest prices of electricity (Solar Power Europe, 2015). In this country, at the end of this decade, an expected price of PV energy close to 17 c€/kWh is expected, being almost a half of current price of the electricity. This price could even be lower depending on the irradiation and the specific productivity of the technology.

In terms of productivity, also in the framework of the EC it is possible to identify a range from 1,550 kWh/m^2 (south of Spain) up to 800 kWh/m^2 (North of Finland) (JRC. Institute for Energy and Transport, 2016).

3. Solar PV technologies

The first step in order to evaluate the requirements of materials to manufacture the PV modules will be the identification of the currently available and future PV technologies. Table 2 shows the current share by technologies and a 2020 and 2030 projection.

Table 2. Market share of PV panels by technology groups **(IRENA and IEA-PVPS, 2016)**.

Technology		2014	2020	2030
Silicon-based (c-Si)	Monocrystalline	92%	73.3%	44.8%
	Multicrystalline			
	Ribbon			
	a-Si (amorph)			
Thin film	Copper Indium Gallium Selenide (CIGS)	2%	5.2%	6.4%
	Cadmium telluride (CdTe)	5%	5.2%	4.7%
Other	Concentrating solar PV (CPV)	1%	1.2%	0.6%
	Organic PV (OPV)		5.8%	8.7%
	Crystalline silicon (advanced c-Si)		8.7%	25.6%
	CIGS alternative heavy metals		0.6%	9.3%

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Historically, as table 2 shows, the majority of PV modules was based on Silicon technologies, mainly monocrystalline and multicrystalline. Nowadays the irruption of thin film modules (CIGS and mainly CdTe) in the market have spread the requirements of materials like Cu, In, Ga, Se, Cd and Te.

Even if there are differences in composition and in the manufacturing process, the working principle of all of these technologies is the same: semiconductors able to convert solar energy into electricity.

The main differences between the technologies are based on the efficiency (understanding efficiency as the power per m^2 under STC conditions, 1,000 W/m^2 and 25ºC). In table 3, a summary of the currently available technologies and their efficiencies are presented in a qualitative way (not based on any specific model).

Table 3. Performance of PV Technologies (gtmresearch, 2013).

	Cell efficiency (%)	Module efficiency (%)	Surface/kW (m^2/kW)	Lifetime
Mono-c-Si	16-22	13-19	7	25
Multi-c-Si	14-18	11-15	8	25
a-Si	4-8		15	25
CdTe	10-11		10	25
CIGS	7-12		10	25
Organic PV	2-4		15	N/A
CPV	20-25		N/A	N/A

Regarding the manufacturing process, crystalline modules include a serial of steps that can be summarized as follows: 1) Purification of metallurgical Silicon to solar grade polysilicon, 2) Manufacturing of ingots by a melting process, 3) Slicing of ingots into wafers, 4) Creation of PV cells by converting wafers into a p-n semiconductor and by adding contacts to cells, 5) assembling of PV cells into a PV module, 6) Connection of PV cells and encapsulation process (glass and thin polymers) and addition of Aluminium frames.

The main difference in the Silicon technology will be based on the structure of the ingot being, according to the name, a single or a multicrystalline structure.

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The other big block of technologies, Thin Film modules, are completely different regarding not only the metals used but in the manufacturing process. Thin film modules are based on a deposition of a thin film of metals on a polymeric, glass or metallic matrix. One of the advantages of using this method is that the required mass of "PV metals" are substantially lower than in the crystalline silicon panels. On the other hand, rare metals are used in the manufacturing process.

The typical manufacturing process of a Thin Film module can be summarized as following:

1) Coating of the matrix substrate with a transparent and conducting layer
2) Deposition of the active metals in the substrate
3) Creation of metallic contacts on the back of the module
4) Encapsulation on a glass or polymeric case.

In the case of amorphous Silicon modules, even it is based on Silicon the manufacturing process is similar to the other thin film technologies.

Once the market share and the main differences between technologies have been explained, the next important step is to determine the metal requirements by technology.

4. Materials demanded in PV modules

To identify what materials are used in these types of pv modules, a bibliographic revision of the state of the art was undertaken. In the following tables a list of critical raw materials identified by different authors are included for each main technology.

Table 4. c-Si material requirements [kg/MW].

	(Moss & al., 2013)	(Moss & al., 2013)	(Elshkaki & Graedel, 2013)	(Kaneko & al., 2006)	**Avg**
Ag	24	19.2	355.9		133.0
Cd		6.1			6.1
Cu	2,741	2,194.1	7,597.5		4,177.5
Ga		0.1			0.1
In		4.5			4.5

	(Moss & al., 2013)	(Moss & al., 2013)	(Elshkaki & Graedel, 2013)	(Kaneko & al., 2006)	**Avg**
Mg	53.5				53.5
Ni			1.1		1.1
Pb	336		21.2		178.6
Se		0.5			0.5
Si	3,653			9,000	6,326.5
Sn	577	463.1			520.0
Te		4.70			4.7

Table 5. CIGS material requirements [kg/MW].

	(Moss & al., 2013)	(Elshkaki & Graedel, 2013)	(Fthenakis, 2009)	(USGS, 2010)	(Sandén & Jacobsson, 2000)	(ICEPT, 2011)	**Avg**
Cd						1.8	1.8
Cu	21.0					16.9	19.0
Ga	2.3	5.0		7.5	5.0	5.0	4.9
In	18.9	27.4	15.5	22.5	27.4	27.4	23.2
Mo						94.3	94.3
Se	9.6	45.3		45.0	45.3	45.3	38.1
Zn						85.8	85.8

Table 6. CdTe material requirements [kg/MW].

	(Moss & al., 2013)	(Elshkaki & Graedel, 2013)	(Fthenakis , 2009)	(Berger & al., 2010)	(USGS, 2010)	(Sandén & Jacobsson, 2000)	(ICEPT, 2011)	**Avg**
Cd		63.3			85.0	63.3	49.2	65.2
Cu				42.8				42.8
In	15.9							15.9
Mo							100.5	100.5
Sn							6.6	6.6
Te		61.9	55.0		97.5		47.2	65.4

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Table 7: a-Si material requirements [kg/MW].

	(Elshkaki & Graedel, 2013)	(Fthenakis, 2009)	(Sandén & Jacobsson, 2000)	(ICEPT, 2011)	**Avg**
Ge	6.9	42.0	6.9	3.4	14.8

As a summary of the previous tables, in the figure 1, the kg of metal required by MW of modules are shown. One of the differences between PV and Wind power systems is that in the case of PV, all the facilities are built in a similar manner independently of being off-grid, grid connected or self-consumption. On the contrary, off-shore and on-shore wind turbine systems are demanding different metals.

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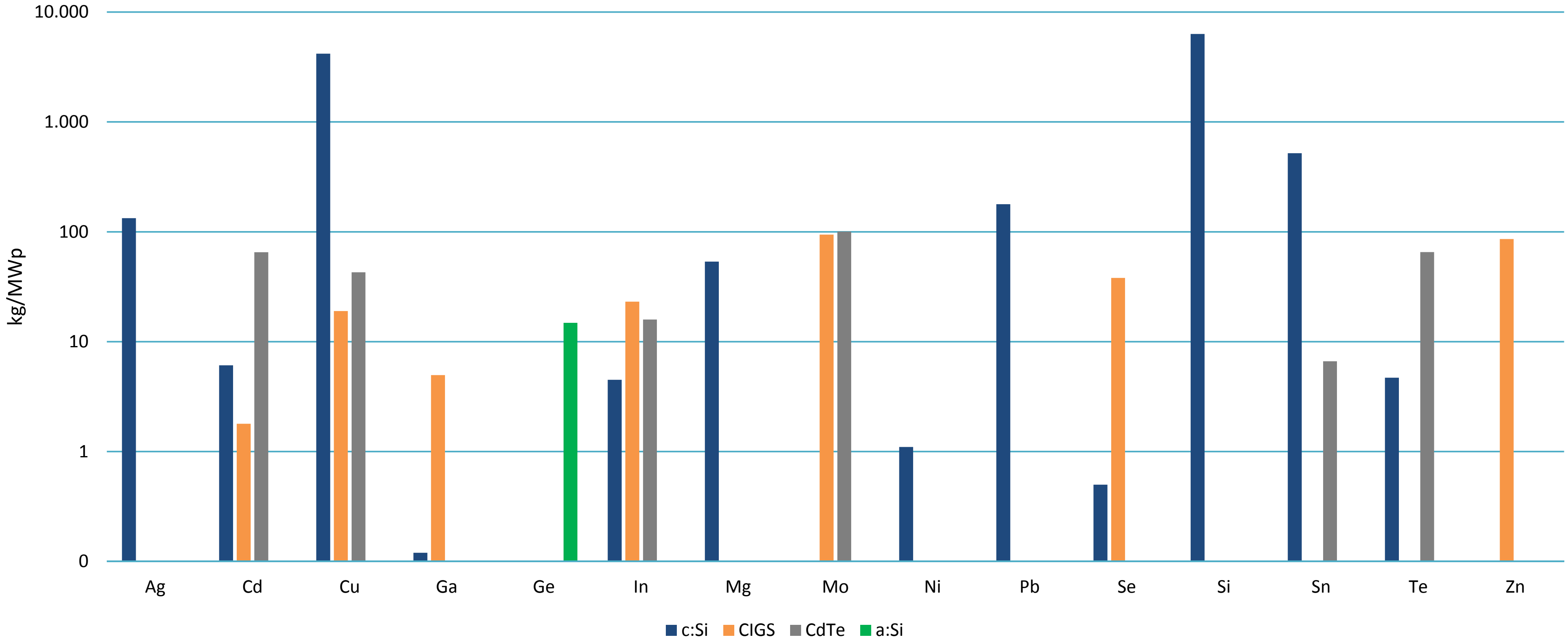

Figure 1. Metals mass requirement by technology.

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5. Evolution of PV power

In order to evaluate the potential physical constrains and to assess about the impact of PV technology per MW capacity, it is necessary to determine a base technology share. Based on the information and the analysis done by Elshkaki & Graedel (2013), a base share of 85% for c-Si, 5% for CIGS, 5% for CdTe and 5% for a-Si was assumed. This technology distribution that is close to the current state of the technology, can suffer (as the prediction shown in table 2) modifications that could affect to the estimated requirements. The contribution of each metal to a base MW of PV module can be summarized in the Table 8.

Table 8. Contribution in mass (kg per MW) of and average PV module.

	c-Si	CIGS	CdTe	a-Si	Average
Ag	133.0	0	0	0	113.0
Cd	6.1	1.8	65.2	0	8.5
Cu	4,177.5	19.0	42.8	0	3,554.0
Ga	0.11	4.9	0	0	0.3
Ge	0	0	0	14.8	0.7
In	4.5	23.2	15.9	0.0	5.8
Mg	53.5	0	0	0	45.5
Mo	0	94.3	100.5	0	9.7
Ni	1.1	0	0	0	0.9
Pb	178.6	0	0	0	151.8
Se	0.5	38.1	0	0	2.3
Si	6,326.5	0	0	0	5,377.5
Sn	520.0	0	6.6	0	442.4
Te	4.7	0	65.4	0	7.3
Zn	0	85.8	0	0	4.3

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Once the mass requirement per MW of PV modules is obtained, the next step is to determine the expected evolution of the installed capacity in order to obtain the PV demand up to year 2050.

In the case of PV modules, two complementing alternatives were taken into consideration: self-consumption facilities and power plants. Because of the easy to connect capacity of PV modules, the relatively reduced space of roofs that is required to fulfil the electricity demands of a house and the possibility to be coupled with storage systems, PV is a technology that will be present in a scenario where the consumers will be also producers of their own electricity. On the other hand similar to traditional power plants but built with PV modules to produce electricity must be also considered.

Based on different studies and projections (Parrado & al., 2016; Greenpeace, 2010; UNEF, 2015; Fraunhofer ISE, 2016) and by using the consideration analysed in Luthander et al. (2015 and Widén & Munkhammar (2013) that foresees in 2050 a 30% of self-consumption penetration with an annual growth rate of 15%, it is possible to obtain the expected installed capacity until 2050.

It is important to bear in mind that because PV technology is already implemented, at this moment there exist PV plants that should be replaced (repowered) at their end-of-life. To be able to evaluate the reposition rate, an age module fleet analysis (using as temporal reference the end of 2015). Figure 2 shows the age fleet of current existing PV facilities.

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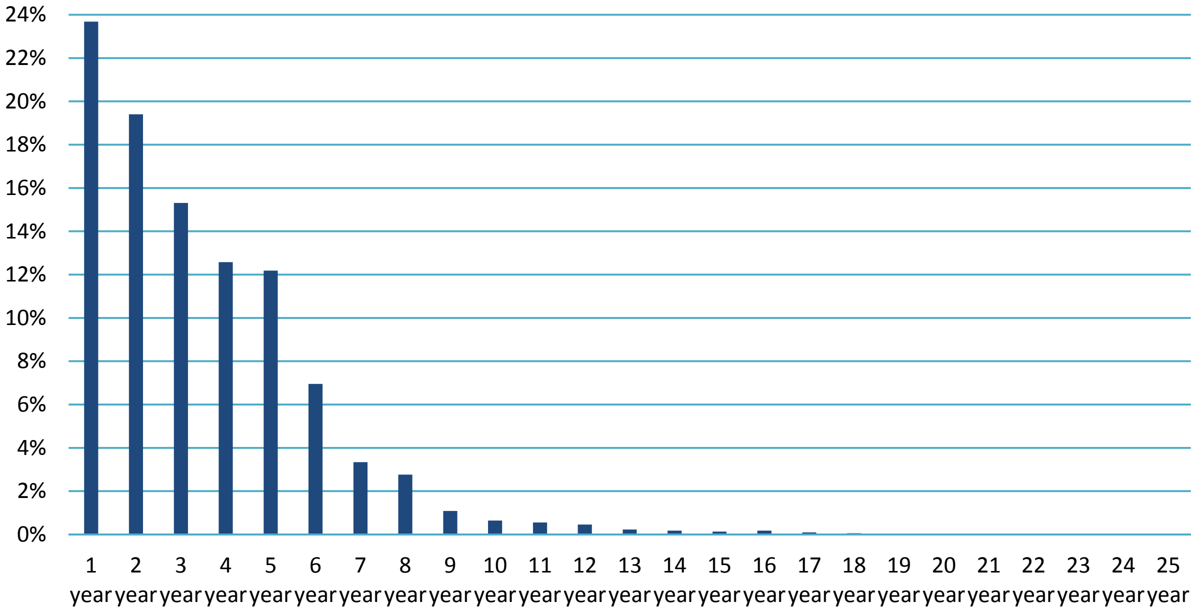

Figure 2. Existing solar power plants age analysis.

According to a replacement rate of 25 years and based on the previsions emitted by the authors of the previous stated bibliographic analysis, it is possible to graphic the accumulated capacity from 1992 to 2050 and the annual installed power from 2016 to 2050. This information is included in the figures 3 and 4.

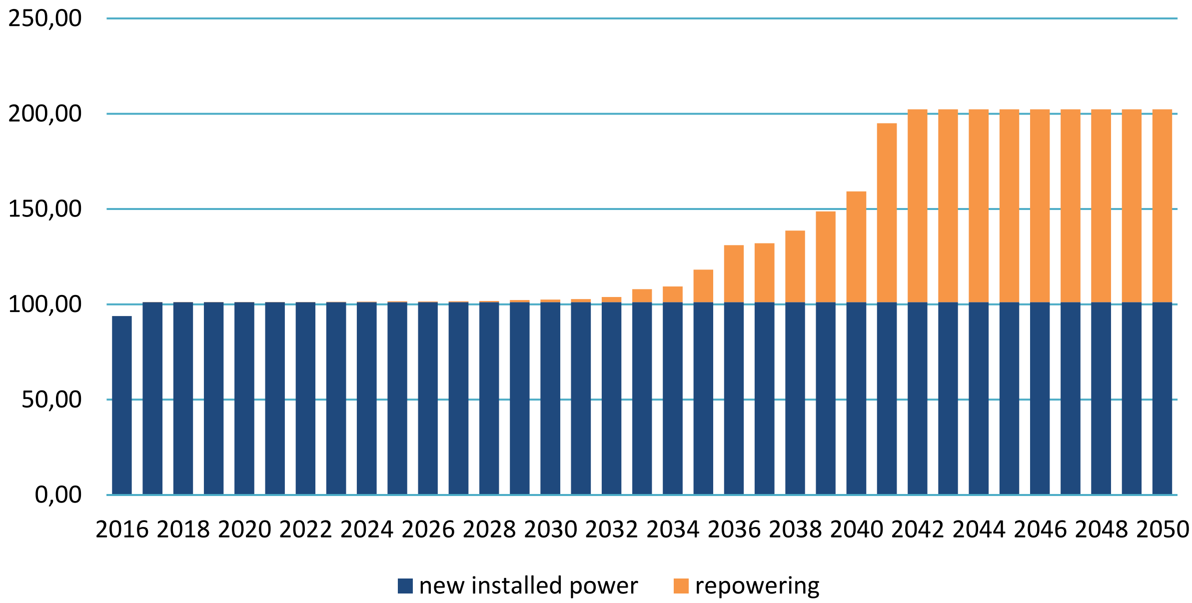

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Figure 3. Annual PV installations including repowering (GW).

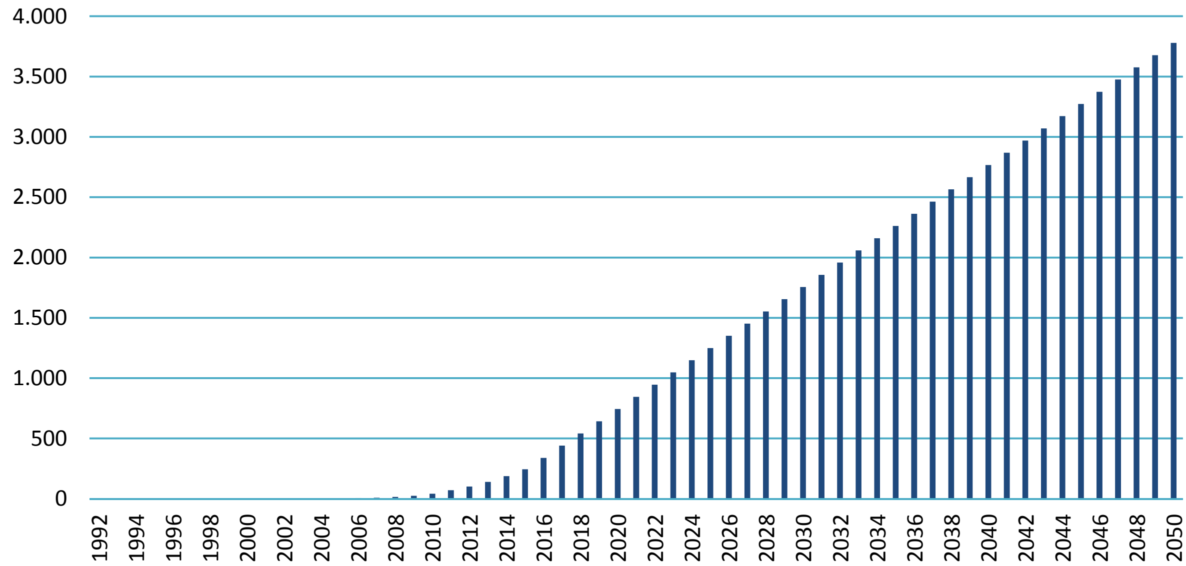

Figure 4. Accumulated PV capacity projection with 25 years repowering (GW).

According to figure 3, once the accumulated PV capacity is obtained and by means of the information contained in table 8, it is possible to calculate the metals associated to PV energy. To this end, one also needs to take into account the recycling rate of each of the metals as material constraints are only associated to primary material consumption. Table 9 includes the recycling rate considered by UNEP (2011) for each of the used metals in PV manufacturing.

Table 9. Recycling rate of PV metals.

Material	Recycling rate	Material	Recycling rate
Ag	30%	Mo	33%
Al	36%	Ni	29%
Cd	25%	Pb	51%
Cu	30%	Se	5%
Fe	50%	Si	0%
Ga	25%	Sn	22%
Ge	35%	Te	1%

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In	37.5%	Zn	22.5%
Mg	33%		

6. Methodology

To assess the impact of different used materials, the methodology developed by Valero and Valero (2014) is used. This methodology covers the total life cycle, from cradle to gate including the grave to cradle approach.

- **Cradle to Gate approach:** assess the exergy cost to produce a refined metal from the mine to be used in industrial applications.
- **Grave to Cradle:** assess the exergy replacement cost to return raw materials from a dispersed state (i.e.: landfills) to the initial state in mines.

This methodology uses the concept of thermodynamic rarity (Valero and Valero, 2014). The thermodynamic rarity indicator is a rigorous exergy measure of a mineral´s quality considering physical aspects of the minerals such as natural concentration, chemical composition, comminution and energy requirements to beneficiate the given mineral.

This approach gives an additional dimension to the criticality of minerals taking into account physical aspects (scarcity in the crust and energy intensity to mine and beneficiate the mineral). Note that this new dimension is not yet included in current criticality assessments which are focused on supply risk and economic importance. Whereas the thermodynamic rarity concept is universal and absolute, the socio-economic criticality assessment is country-dependent and variable.

To identify physical constraints for the PV sector a combination of bottom-up and top-down approaches will be used:

- **Bottom-up**: assess the estimated evolution of material production according to current reserves and past production values. This method uses the Hubbert curve methodology traditionally used to assess peak oil. Reserves and production data comes from (Calvo, 2015).

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- **Top-down**: assess the estimated demand of materials from different studied PV modules according to material´s demand by type of module and recycling current figures of different studied materials.

The values used to assess material rarity are included in the following table:

Table 10: Exergy values used (GJ/ton)

		(A) Grave-Cradle	(B) Cradle-Gate	(A)+(B) Rarity	(A)+(B) Rarity	Mass fraction	Rarity fraction
	kg/MW	GJ/Ton	GJ/Ton	GJ/Ton	GJ/MW	%	%
Ag	113,08	1,281.4	7,371.0	8.652.4	978.4	1.16%	3.86%
Cd	8,54	263.9	5,898.0	6,161.9	52.6	0.09%	0.21%
Cu	3.554,00	35.3	291.7	327.0	1,162.1	36.55%	4.58%
Ga	0,35	610,000.0	144,828.0	754,828.0	264.4	0.00%	1.04%
Ge	0,74	498.0	23,749.0	24,247.0	17.9	0.01%	0.07%
In	5,78	3,319.7	360,598.0	363,917.7	2,102.7	0.06%	8.30%
Mg	45,48	---	25.5	25.5	25.5	0.47%	0.10%
Mo	9,74	136.0	907.9	1,043.9	10.1	0.10%	0.04%
Ni	0,94	9.9	523,6	533.5	0.5	0.01%	0.00%
Pb	151,82	0.9	36.6	37.5	5.7	1.56%	0.02%
Se	2,33	-----	----	----	----	0.02%	0.00%
Si	5.377,53	0.7	0.7	1.4	7.6	55.30%	0.03%
Sn	442,37	15.2	426.3	441.5	195.3	4.55%	0.77%
Te	7,27	589,366.1	2,235,699.0	2,825,065.1	20,525.5	0.07%	80.97%
Zn	4,29	1.5	155.0	156.5	0.6	0.04%	0.00%

Considering these values and from a rarity point of view, it can be seen for instance that it is not the same to use 1kg of Si (with a rarity of 0.7 MJ, that puts into scene the easiness to be obtained) than the same quantity of Te (2825 MJ).

Based on the Table 10 information, one of the most interesting conclusions of the previous analysis is the great difference between mass and rarity impact per MW of PV

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technology that brings into light the importance of using alternative indicators to evaluate the impact of using certain materials. This difference is analysed in the next section for each technology.

7. Results

7.1. Rarity analysis per type of PV module

Figure 5 shows a comparison between a mass and exergy (rarity) analysis for a crystalline Silicon module. From a mass point of view, Cu and Si constitute around 90 % of the module. However in rarity terms, Fe and Al only account for 7.5 %. This is because more valuable metals (led by Te and In) have a greater exergy content.

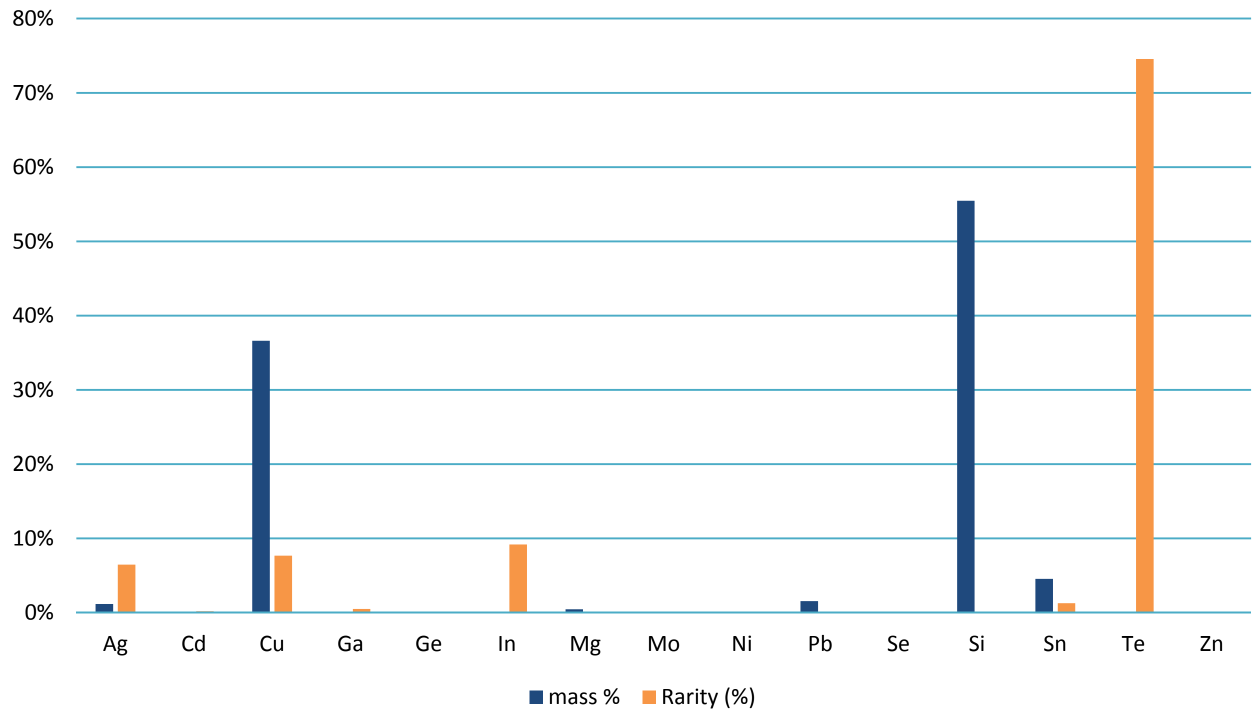

Figure 5. Mass and Exergy-rarity comparison for c-Si modules.

A similar analysis was carried out for the Thin Film modules. The results are contained in figures 6 to 7 represented in an alternative diagram form (Pareto).

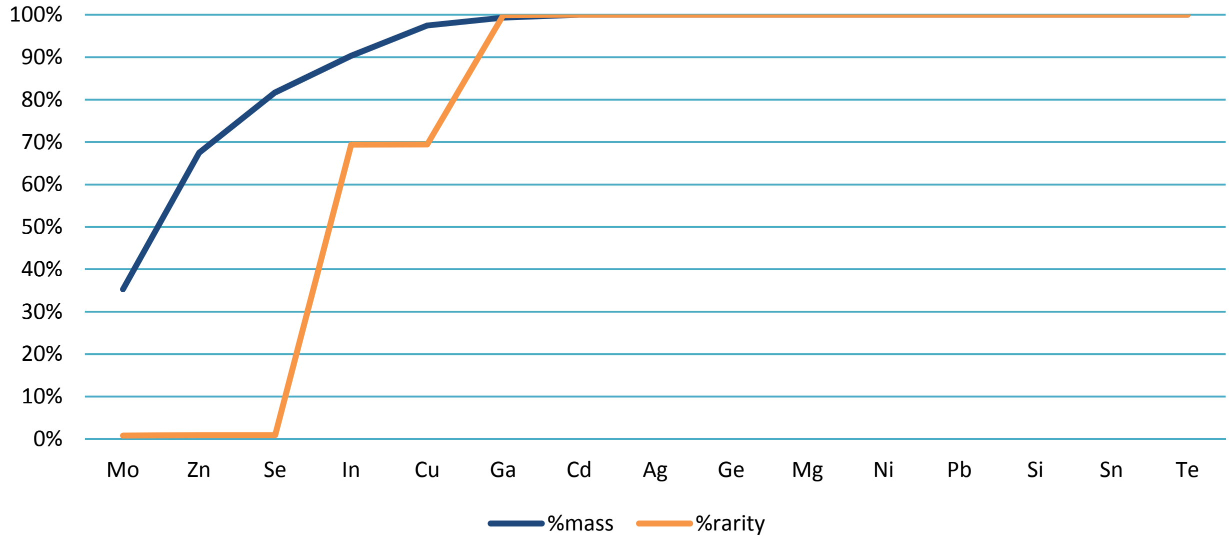

Figure 6. Mass and Exergy-rarity comparison for CGIS modules.

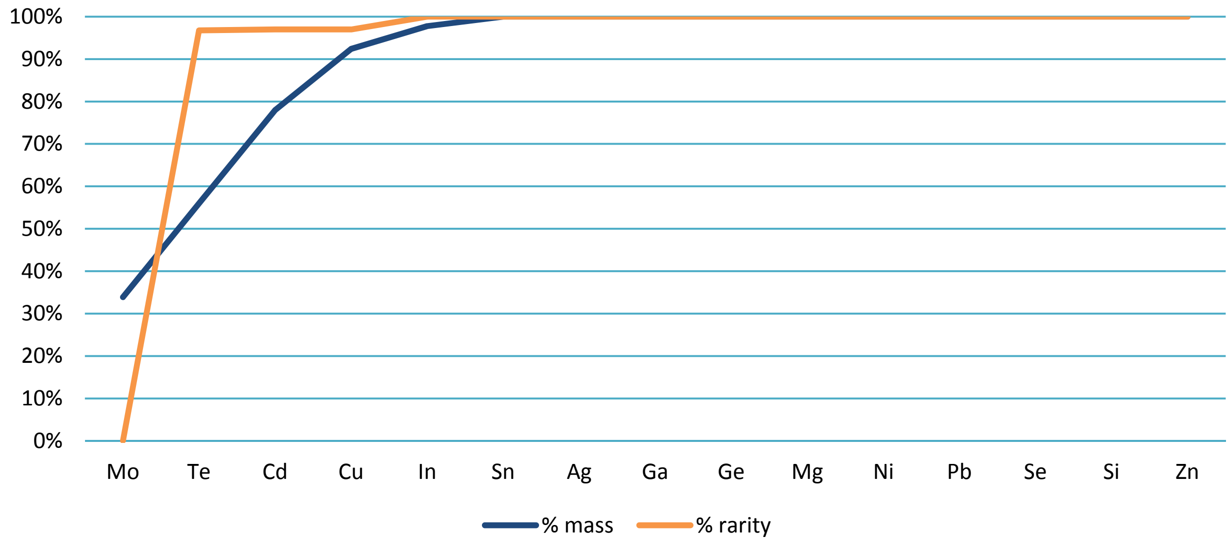

Figure 7. Mass and Exergy-rarity comparison for CdTe modules.

7.2. Stock in use for an average PV module

In this stage stock in use materials from wind turbines is analysed. The obtained figure could be relevant to analyse the quantity of raw materials available in the

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technosphere with respect to those in the ground. The resulting information can be very valuable for instance to encourage more effective recycling polices. The following figures show stock in use evolution of the studied materials grouped by similar magnitudes of values and assessed through exergy replacement costs.

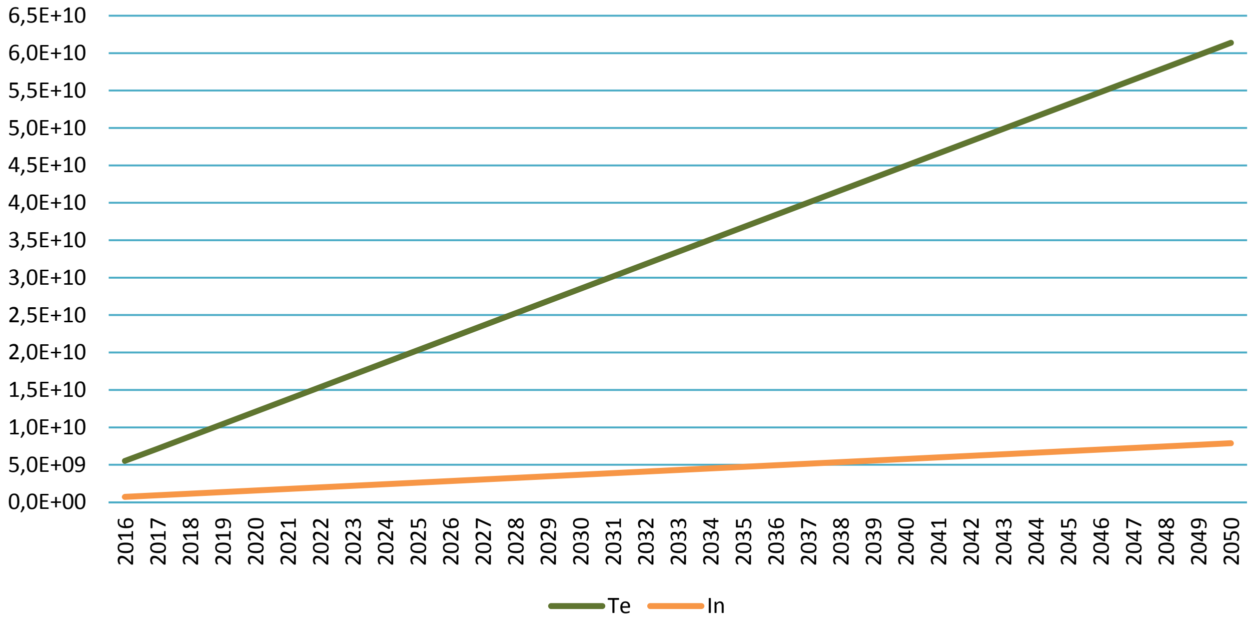

Figure 8. Te and In stock in use evolution (GJ).

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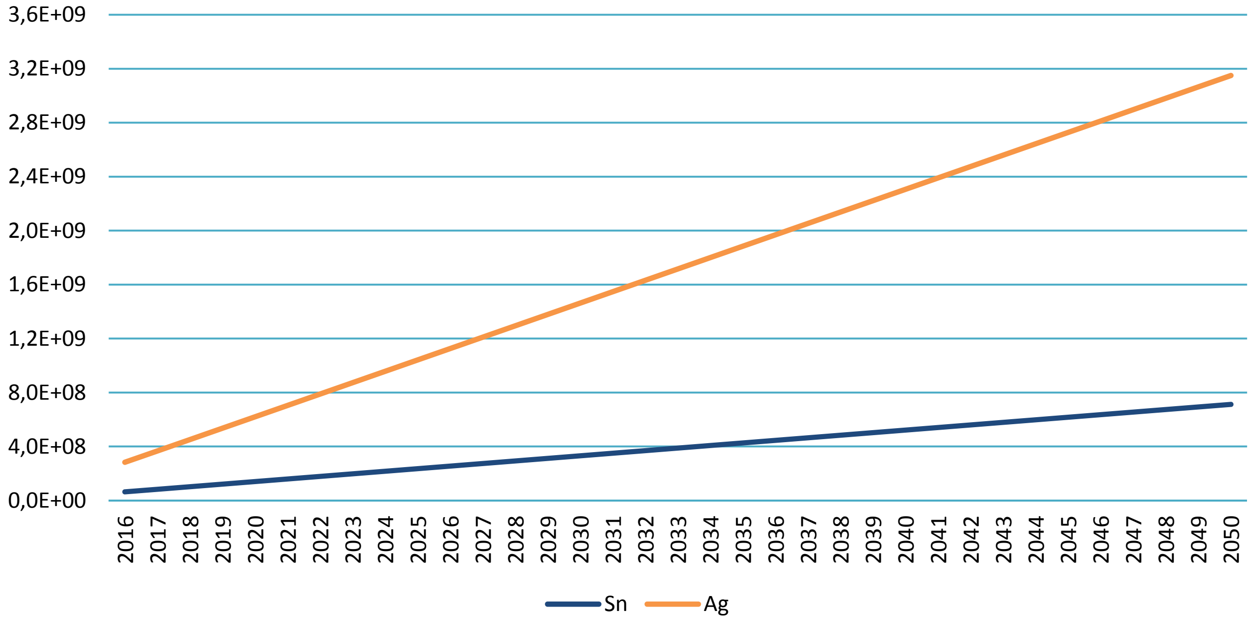

Figure 9. Sn and Ag stock in use evolution (GJ).

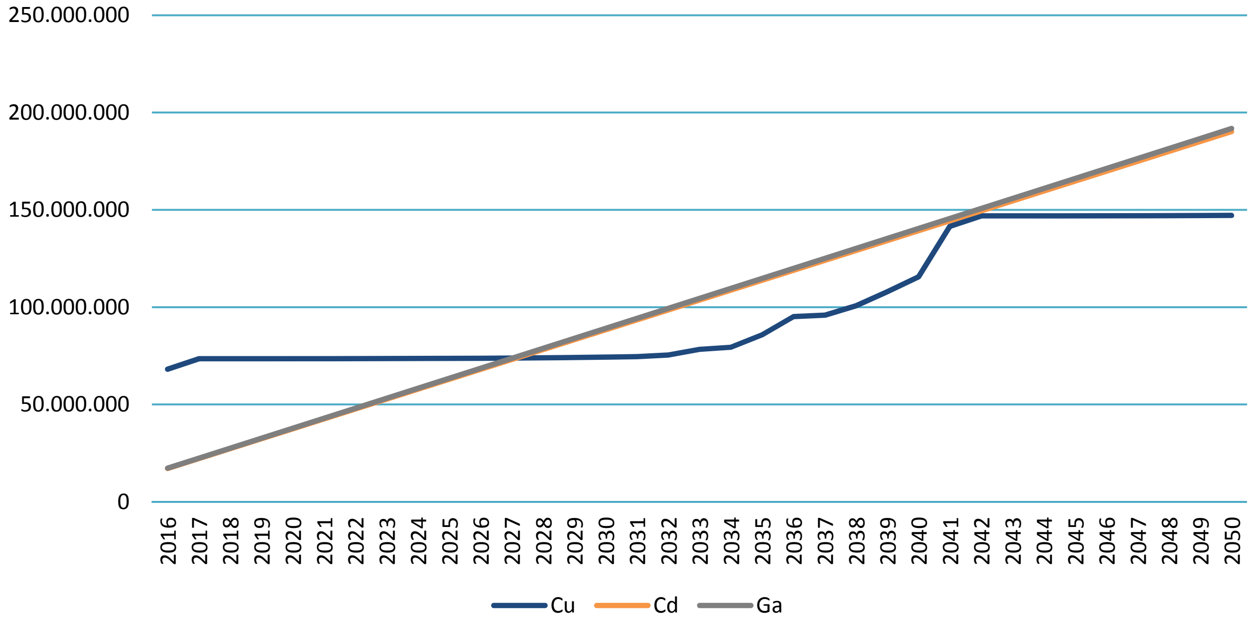

Figure 10. Cu, Cd and Ga stock in use evolution (GJ).

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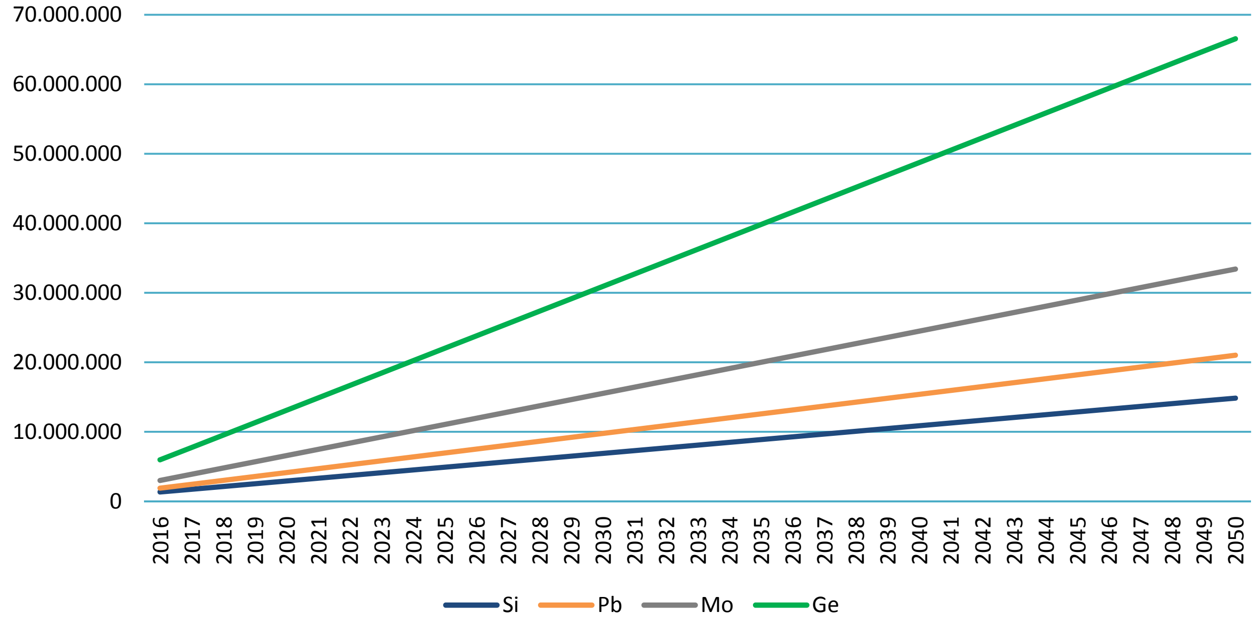

Figure 11. Si, Pb, Mo and Ge stock in use evolution (GJ).

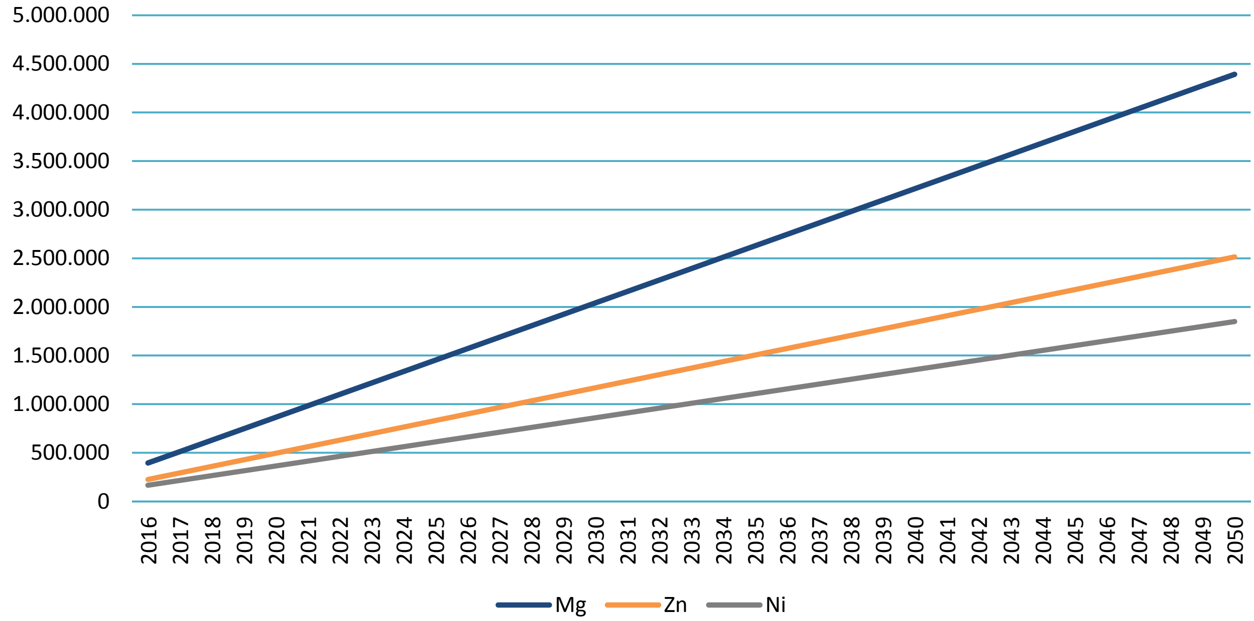

Figure 12. Mg, Zn and Ni stock in use evolution (GJ).

As expected, stock in use for each material in PV modules increases throughout time.

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7.3. Material shortages due to PV facilities

Once different PV modules are studied from a material point of view, one of the expected worries would be the possible lack of the demanded materials due to a possible shortage in the available reserves or because demand cannot be fully satisfied with the expected production from 2015 to 2050. Recall that the BAU scenario for material production has been built assuming that it will follow a Hubbert-curve trend based on reserves.

Figure 13 shows the ratio for 2050 demanded metals over estimated production in order to check for possible physical constraints. In the figure the Silicon and Selenium metals have not been included because of lack of production information. On the other hand, as Silicon is one of the most abundant elements in the Earth's crust, it will never constitute a bottleneck and thus it won't be considered in this analysis. Selenium is also not included in the analysis due to its low demand for this specific technology.

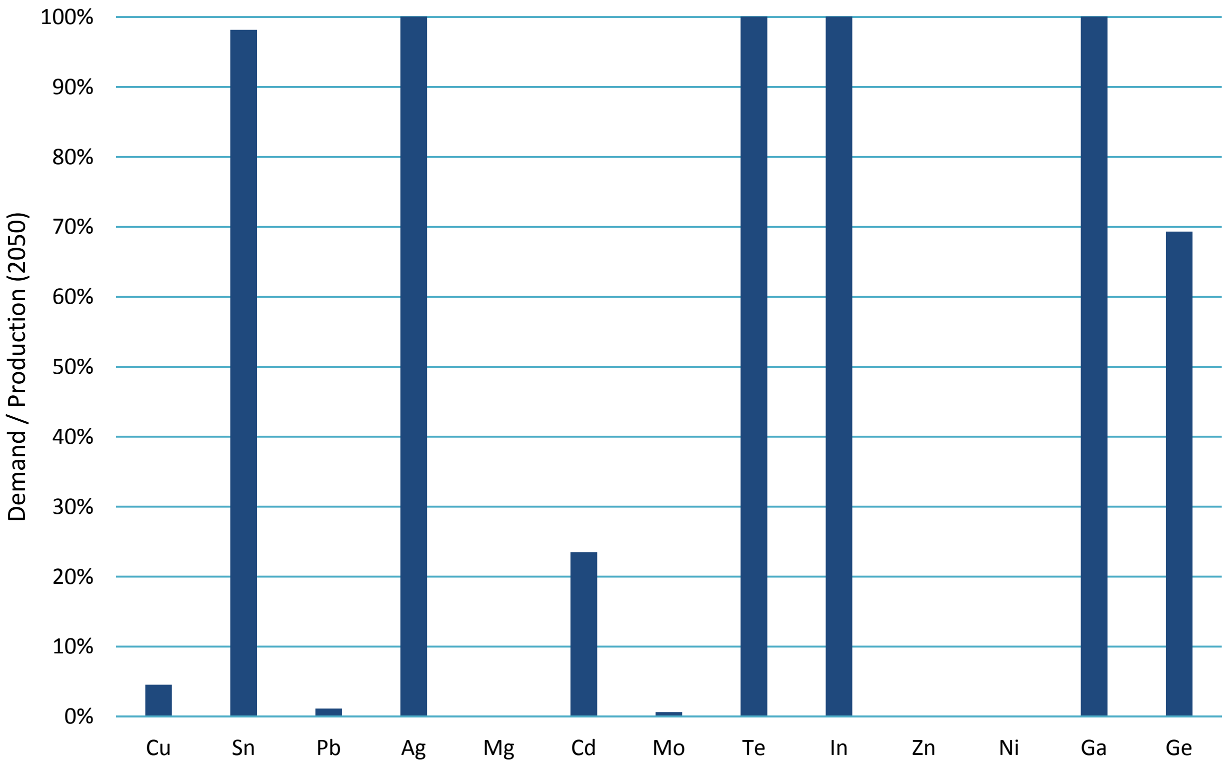

Figure 13: Demand vs Production (year 2050)

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As figure 13 indicates, there are 5 metals whose demand is expected to be close or higher than the estimated production in 2050.

Figures 14 to 18 show the annual evolution of the demand for these metals compared to the estimated production. If both curves cross, it is an indication of a possible temporal estimation for the possible material constraint.

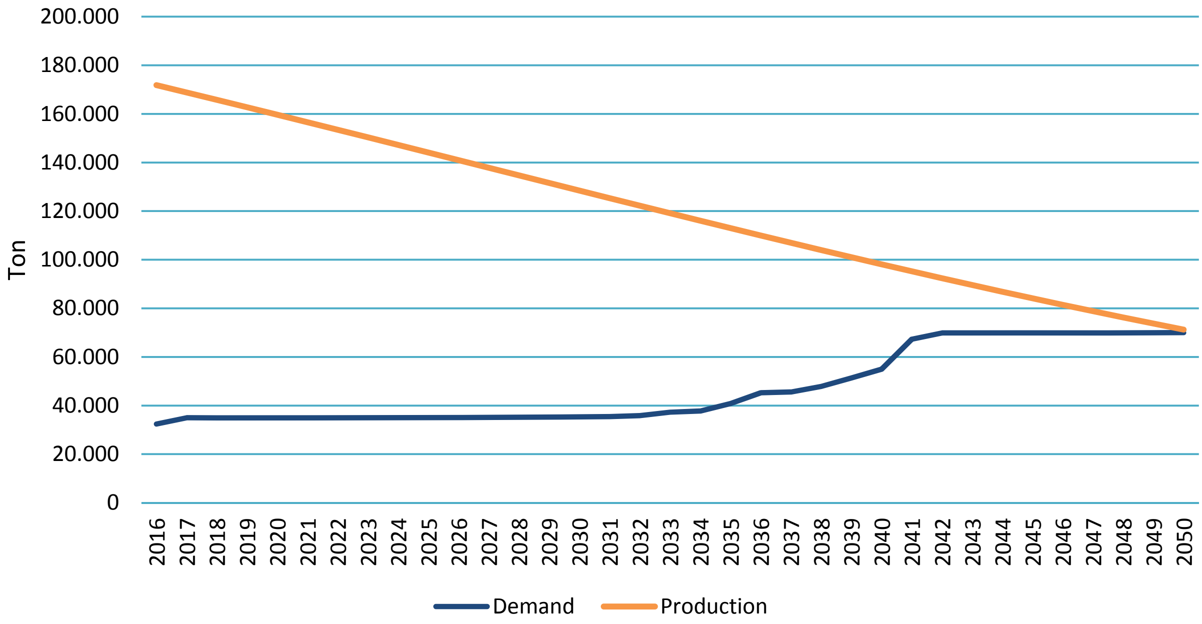

Figure 14. Sn world production and PV demand projections from 2016 to 2050.

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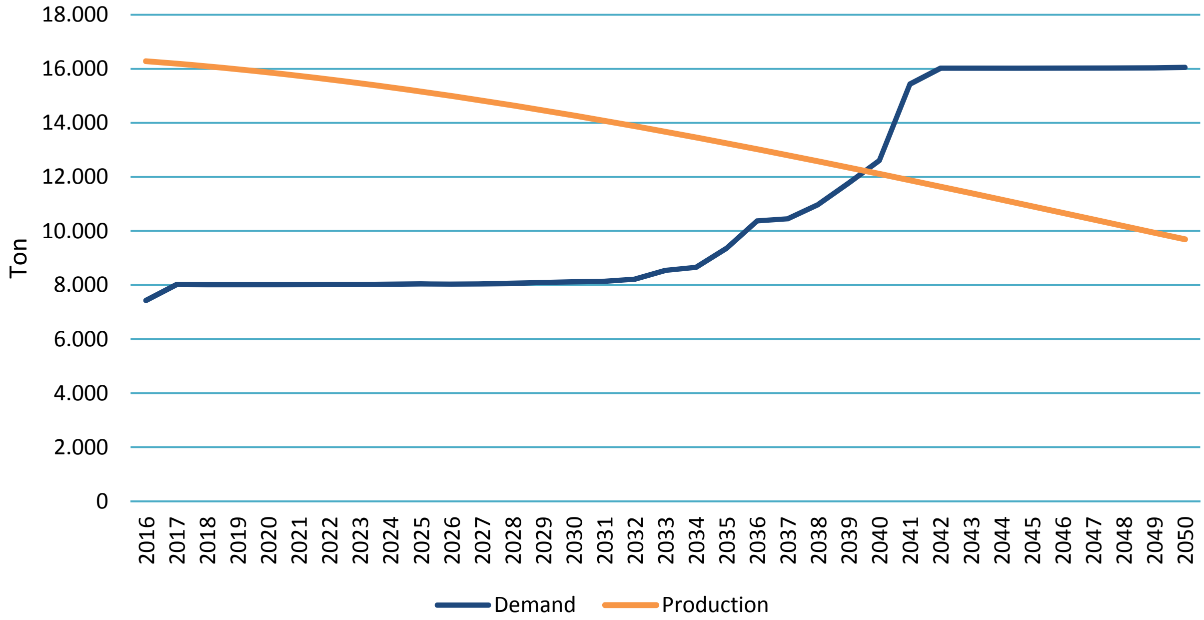

Figure 15. Ag world production and PV demand projections from 2016 to 2050.

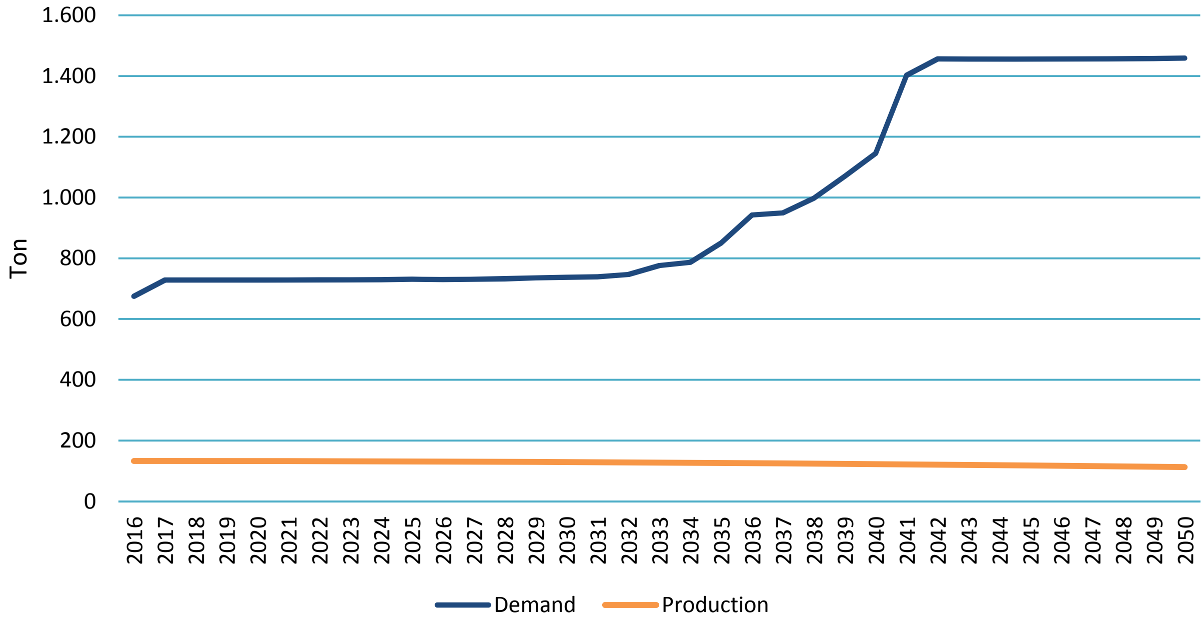

Figure 16. Te world production and PV demand projections from 2016 to 2050.

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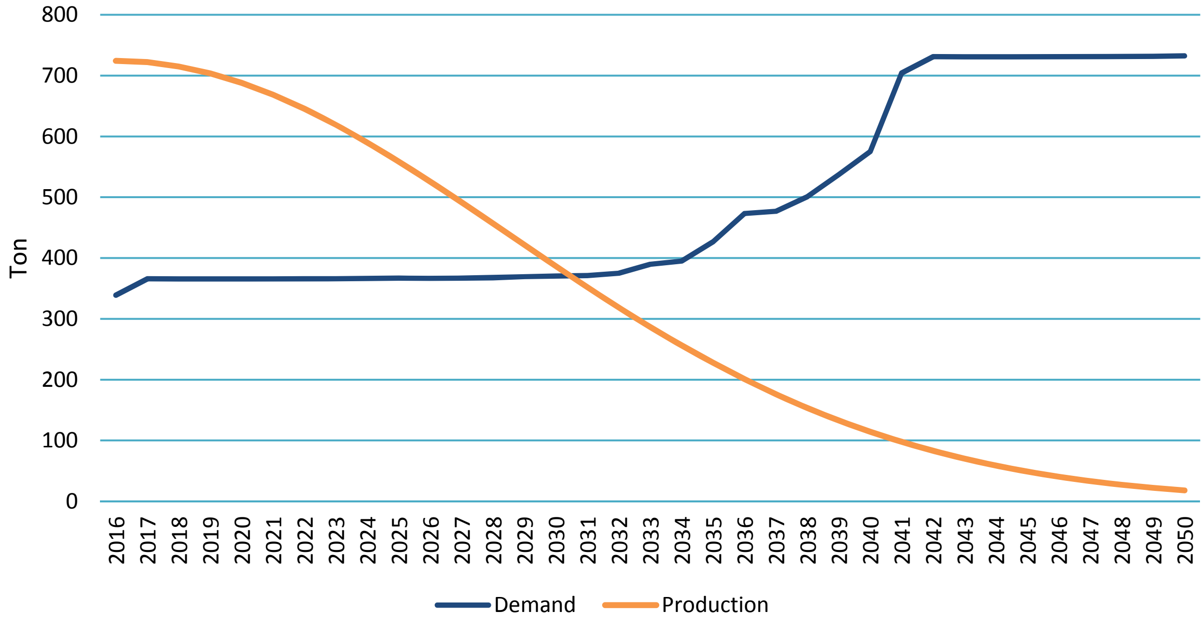

Figure 17. In world production and PV demand projections from 2016 to 2050.

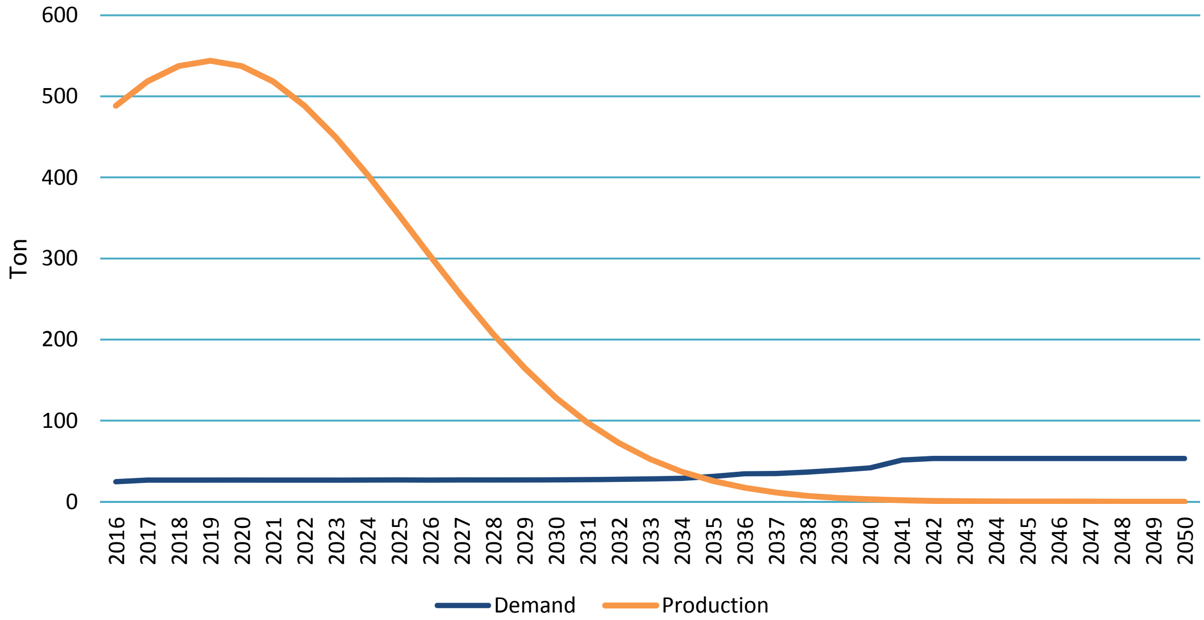

Figure 18. In world production and PV demand projections from 2016 to 2050.

According to the previous figures, some physical constrains could take place to cover the metals requirement for manufacturing PV modules for In (~2030), Ga (~2035), Ag

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(~2040) and Sn (~2050). In the case of Te, the source of information used indicates that at this moment it would not be possible to manufacture PV modules because of the lack of Te production. Yet at this moment it is indeed possible to find available PV modules that make use of this material. This is a clear indication of the deficiencies in the information sources. Regarding Sn, even if there seems to appear a possible bottleneck by 2050, this is because production has been estimated assuming that only reserves will be available for extraction. The reserves figure for Sn is nowadays low compared to the available resources (which are 16 times greater). Accordingly, the fact that reserves are so low is not due to geological scarcity, but rather to economic factors. It is thus foreseeable that when demand for Sn increases, associated reserves will also increase.

The last step is to account for the expected demand from 2016 to 2050 of PV metals compared to world reserves.

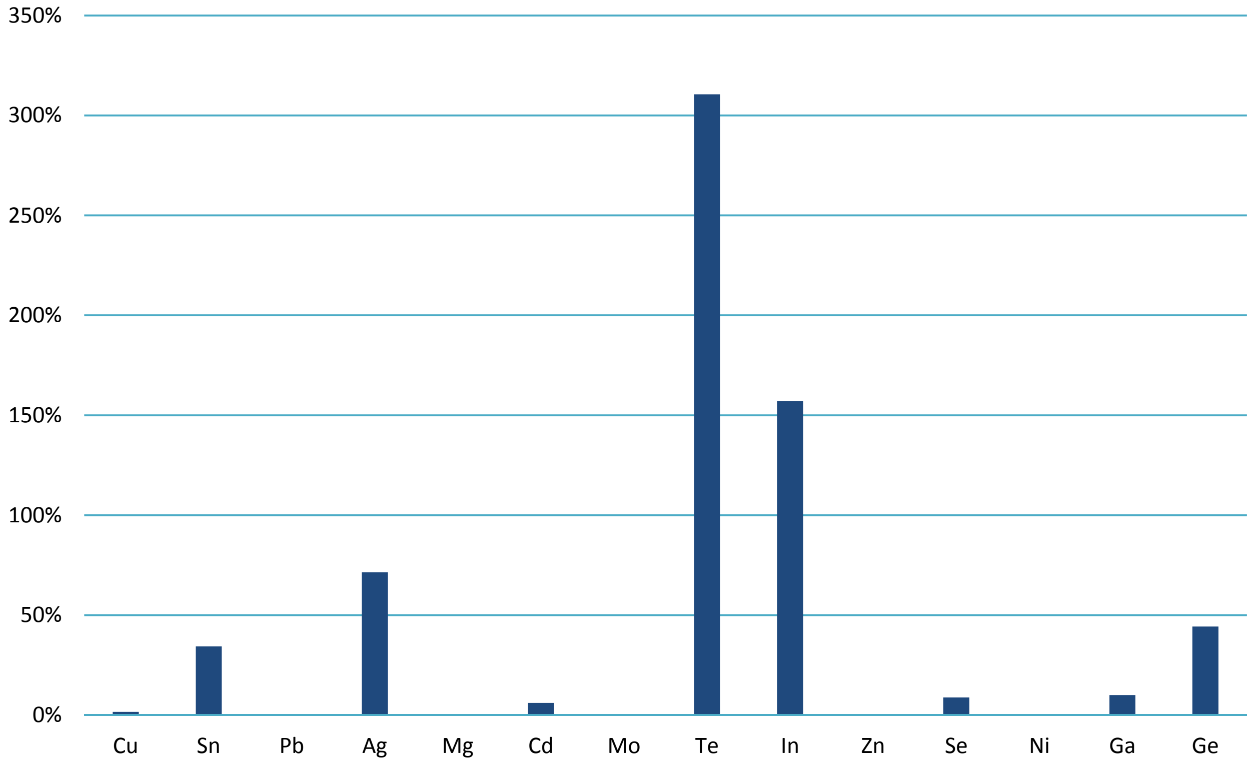

Figure 19. 2015-2050 world demand/reserves.

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Sn included in PV will require by 2050 around 35% of the world's reserves as registered in 2015 by the USGS, Ge 45% and Ag 70%. Regarding the In and Te it seems that the demanded materials are even higher than current reserves.

8. Conclusions

The most demanded metals from an exergy-rarity (considering the physical criticality of minerals) point of view are: Te, In, Cu and Ag.

One of the most relevant information obtained from the previous analysis is that supply for certain metals (assuming a Hubbert peak BAU scenario based on 2015 reserves) might not be able to satisfy demand for the PV industry at some point until year 2050 (Ag, Te, In and Ga). Additionally, for the case of In and Te, the expected demand is even higher than the available reserves of those metals. Moreover, PV modules will not be the only demanding good of these types of materials. Accordingly, in order to ensure availability for the materials, higher recycling rates will be required.

Solar photovoltaic industry must develop technologies with use less critical material and for this reason technologies based on In, Te, Ag and Ga shouldn´t be considered as a solution to led solar photovoltaic growing.

It should be nonetheless stated that this analysis is a preliminary one, as there is still a very important information gap regarding available reserves and estimated production. This becomes especially clear for the case of Te, which points out that according to the available information, at this moment it would not be possible to manufacture modules. This is obviously not the case, as it is possible to find CdTe modules in the PV market.

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D2.1: *Report with an analysis of the main limitations of variables and indicators selected to represent the pathways and scenarios.*

Annex 10: *RES for electricity generation and physical constraints - Solar Thermal Power.*

Grant agreement: 691287

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Document info sheet

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Authors:

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TABLE AND FIGURE INDEX

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1. Scope and goal

This document is part of MEDEAS Deliverable 2.1. The main aim of this report is to explain in depth which physical constraints are expected in the electricity generation through solar thermal power from 2015 to 2050 from the point of view of raw materials.

This activity is done through an assessment of the materials required to manufacture different types of solar thermal power installations from 2015 to 2050.

The results of this Deliverable will be implemented in the MEDEAS model through PAVs database values. For this reason, the following table shows the information covered in this document and its link to the PAV list specified in Deliverable 2.1.

Table 1. PAVs related to Solar Thermal Power and covered in this Annex.

D2.1 Results	PAV	PAV description
Capacity factor of RES	34	productivity of each technology according not only technology evolution but also renewable resources potential (solar thermal power for electricity production)
Investment cost of RES*	35	Investment costs for each RES technology (solar thermal power for electricity production)
electricity cost from RES*	36	Levelized Cost of Electricity for each RES technology (solar thermal power for electricity production)
RES production by technology	37	Yearly production of each RES technology (solar thermal power for electricity production)
RES power density from technology point of view	38	Power density of each RES technology (solar thermal power)
RES lifetime	40	Life time of each RES technology (solar thermal power for electricity production)
Ag, Al, Cr, Co, Fe, Mn, Mo, Ni, V, Ti and Zn in solar thermal power demand evolution from 2015 to 2050	109	Material intensity for RES

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* Investment cost and electricity cost for RES have been indirectly taken into account by assessing the potential evolution of Solar Thermal Power.

2. Introduction

According to the International Energy Agency, without decisive action, energy related greenhouse gas emissions could more than double by 2050 and thus increased oil demand will heighten concerns over the security of supplies (IEA, 2013).

The EU is committed to reducing its greenhouse gas emissions by 20% by 2020. By 2050, it intends to slash its greenhouse gas emissions by 60% to 80%.

There is an awareness of the need to change political statements and analytical work into concrete action. For this reason, the International Energy Agency has identified the most important technologies needed to achieve a global energy-related CO_2 reduction target to 2050 and Solar Thermal Power (STP) is one of the technologies that is able to lead the change.

Nowadays, solar thermal power is already a commercial reality in 19 countries, being Spain and United States where the highest part is concentrated. Nevertheless throughout the last years, the sector has needed to face challenges due to political instability and strong competition with other renewables technologies, mainly with photovoltaic due to its past and future expected cost reductions (Mayer et al., 2015).

That said, hopeful future expectations are foreseen by some actors, because according to (Greenpeace, 2016) Solar Thermal Power could deliver up to 12 % of the world´s electricity consumption.

Yet the deployment of renewable resources and in particular solar thermal power, will require an increasing demand of materials which might provoke serious bottlenecks. This is why it is crucial to analyze the expected production trend of solar thermal power and its associated material needs in order to define future energy policies.

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Indeed, a thorough analysis of the resources required for a certain economic sector needs to include not only the energy used throughout its life cycle, but also the materials required to manufacture the analyzed system. The supply of critical raw materials is an important issue that is currently regarded as a potential threat that may put at risk the so-called "Green Economy". Accordingly, a list of 20 raw materials considered as critical because risks of supply shortage and their impacts on the economy, was recently published by the European Commission (European Comission, 2014).

Some of these materials are Platinum Group Metals and Rare Earth Elements, however there are more materials which currently are not considered as critical in this list but need to be also monitored. The term "critical" as defined by the EC is not static and it changes with the socio-economic circumstances. This means that there is not a specific definition of the term, and hence there are more than 20 raw materials that must be considered when we talk about supply risk.

Going back to the solar thermal power sector, the demand for materials used such us generators, the electric grid, heat storage and mirrors is rapidly increasing. As an example, solar thermoelectric installed power multiplied six-fold from 2009 (600 MW) to 2013 (3,600 MW) and it is projected that this figure will increase to near of 1,000 GW to 2050 (International Energy Agency, 2014). Moreover, the expected repowering of current solar thermal power installations at the end of their lives, will imply a further increase of scarce raw material requirements. Both issues make it critical to urgently analyze deeply the use of raw materials in the solar thermal power industry to guarantee that its evolution is not physically constrained.

3. Solar thermal power technologies

Solar thermal power plants concentrate solar irradiation to heat a fluid, which directly or indirectly runs a turbine that operates in a Rankine Thermodynamic cycle. This solar irradiation concentration allows that the fluid reaches enough working

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temperature to ensure fair efficiency in turning the heat into electricity, while limiting heat losses in the receiver.

The three current world predominant technologies are Parabolic Troughs (PT), Linear Fresnel Reflectors (LFR) and Central Receiver Systems (CRS). Although there is an additional type called Parabolic Dishes (PD) which use a Stirling engine to transform heat power into electricity. That said, there are no large scale projects of the latter and hence PD technology cannot be considered a competitor for the others (Greenpeace, 2016).

According to the International Energy Agency (International Energy Agency, 2014), PT is the most mature technology but CRS are making progresses. In fact, CRS present higher efficiencies than PT technologies (Solar-Thermal, 2016). Moreover, CRS are less sensitive to seasonal variations than PT, what makes it reasonable to think that the first will presumably increase their market share with respect to the latter. Note that currently the share of PT over CRS is 85 to 10, respectively.

Taking into consideration these facts, the following types of technologies have been considered in the present study:

Table 2. Characteristics of studied Solar Thermal Power installations

	PT	**CRS**	**Author**
Operating temperature	400 ºC	1.000 ºC	(International Energy Agency, 2014)
Capacity	10 – 300 MW	10 – 200 MW	(khan & Arsalan, 2016)
Efficiency	11 – 16 %	7 – 20 %	(khan & Arsalan, 2016)
Equivalent hours/year[1]	4,000	6,450	(Martin, Hoz, & Velasco, 2015)
Share of solar thermal power	85 %	10 %	(Greenpeace, 2016)

[1] Considering thermal storage system

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4. Materials demanded in solar thermal power installations

To identify what materials are used in these types of solar thermal power plants, a state of the art analysis obtained from the bibliography has been undertaken. In the following table the list with used raw materials is shown.

Table 3. List of materials used in Solar Thermal Power installations **(Pihl, Kushnir, & Sanden, 2012)**.

Material	PT (ton/GW)	CRS (ton/GW)
Ag	13	16
Al	740	23,000
Cr	2,200	3,700
Cu	3,200	1,400
Fe	650,000	393,000
Mn	2,000	5,700
Mo	200	56
Ni	940	1,800
Ti	25	0
V	2	2
Zn	650	1,400

It should be stated that material demand for storage systems (KNO_3 and $NaNO_3$) are not considered in this study. Current demand of these substance are between 150,000 and 220,000 ton/GW in CRS and PT, respectively. Although this figure seems to be large, when compared to the available reserves and resources, it becomes insignificant. For instance, the production peak for K is estimated to be beyond 2300 (Valero and Valero, 2014), and for Na there are "unlimited" reserves according to the USGS.

5. Evolution of solar thermal power

The expected installed capacity projections from 2015 to 2050 is required for assessing the impact that solar thermal power material demand has on reserves. To do so, sales projection values from (International Energy Agency, 2014; Greenpeace, 2009, 2016) have been consulted.

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Considering these data, Figure 1 shows the evolution of installed power from 2016 to 2050 by type of installation: PT and CRS. It can be seen how CRS installations will likely grow in market share.

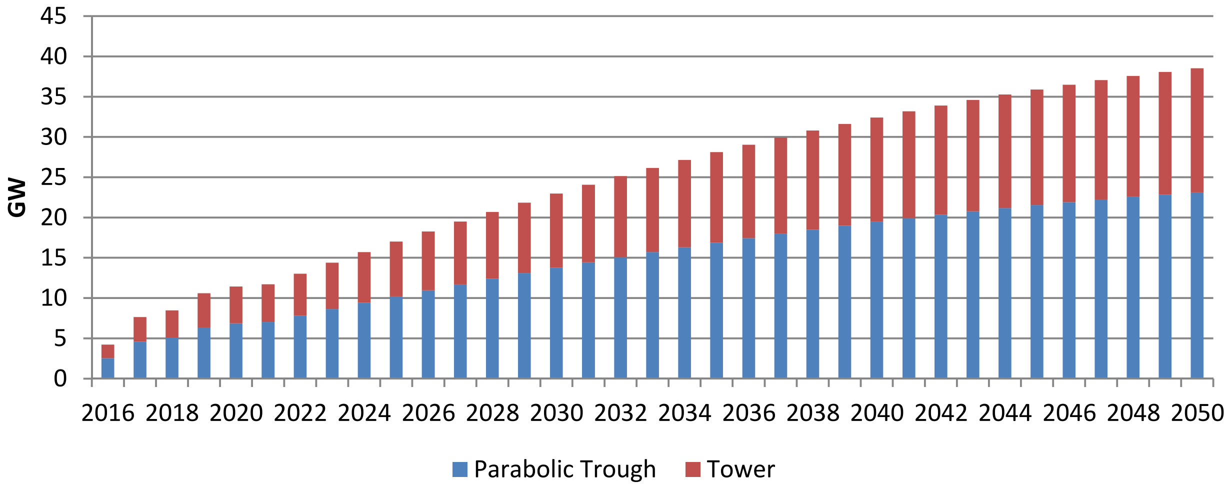

Figure 1. Projection of new installed (GW) solar thermal power by type of installation.

One important factor to assess the future demand of materials is the repowering effect of solar thermal power installations at the end-of-life. According to (Raccurt et al., 2015) the lifetime of this kinds of installations is 25 years due to absorber degradation.

To assess this impact the age of current solar thermal power installations has been calculated. The following figure shows how more than 87 % of current installed power has less than 7 years (Figure 2). As opposed to wind energy, solar thermal power has experienced a non-homogenous growth, mostly linked to national feeding tariff regulation. For instance, much of the power was installed in 2012 and 2004 (with 21% and 9.8%, respectively). This heterogeneous growing will obviously affect future STP installed power when the repowering effect is considered.

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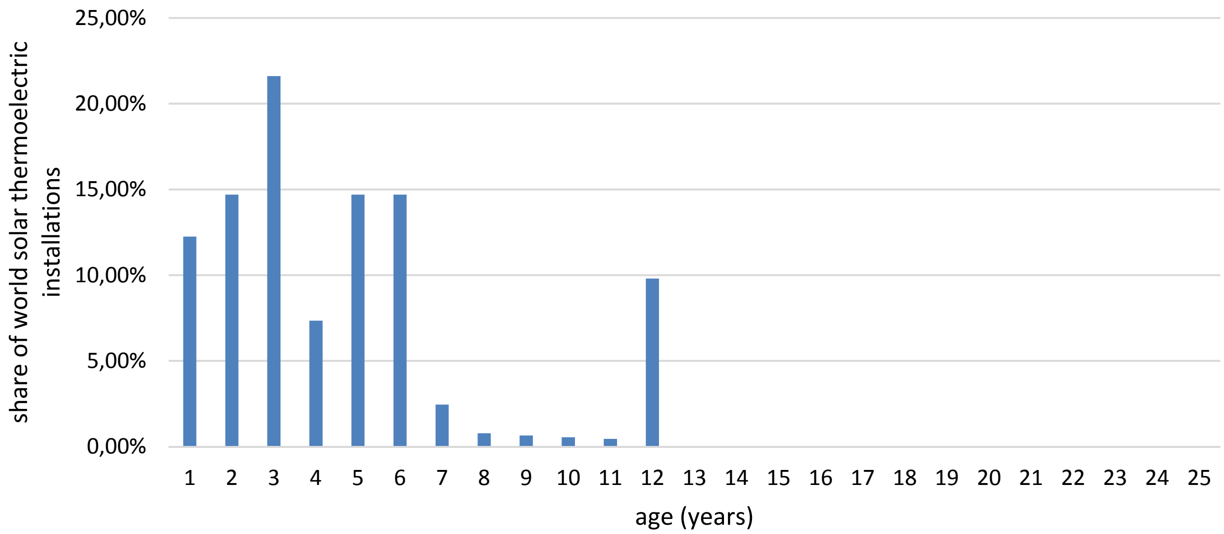

Figure 2. Age of world solar thermal power installations.

The following figure shows the evolution of repowering to 2050. As it can be seen, repowering will be very significant especially from 2042 (Figure 3).

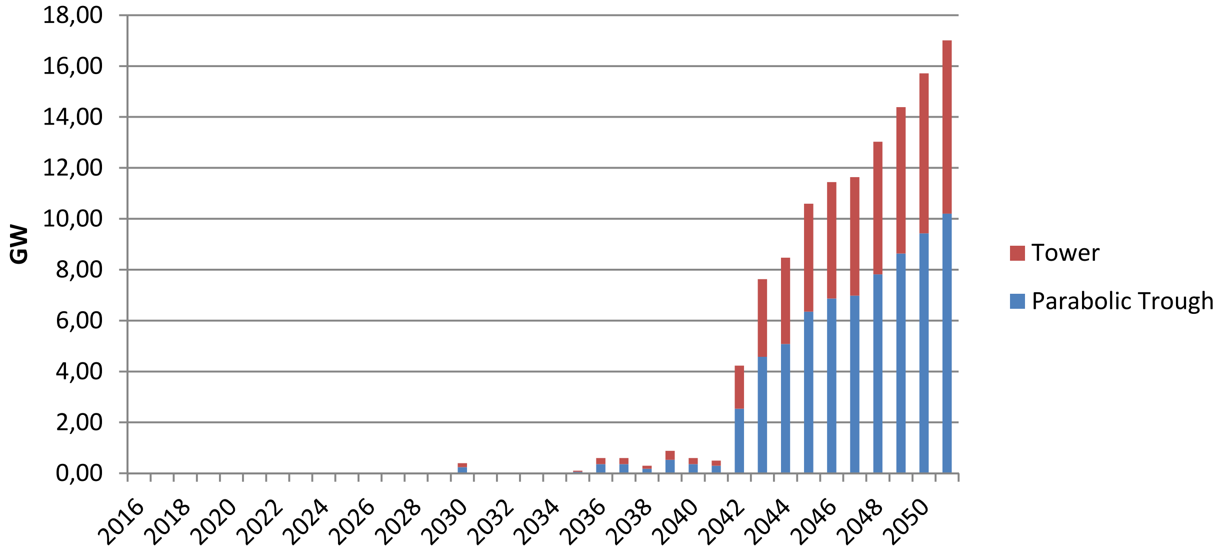

Figure 3. Projection of solar thermal power repowering (GW) by type of installation.

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Considering new installed power and repowering, Figure 4 shows the total installed power by year.

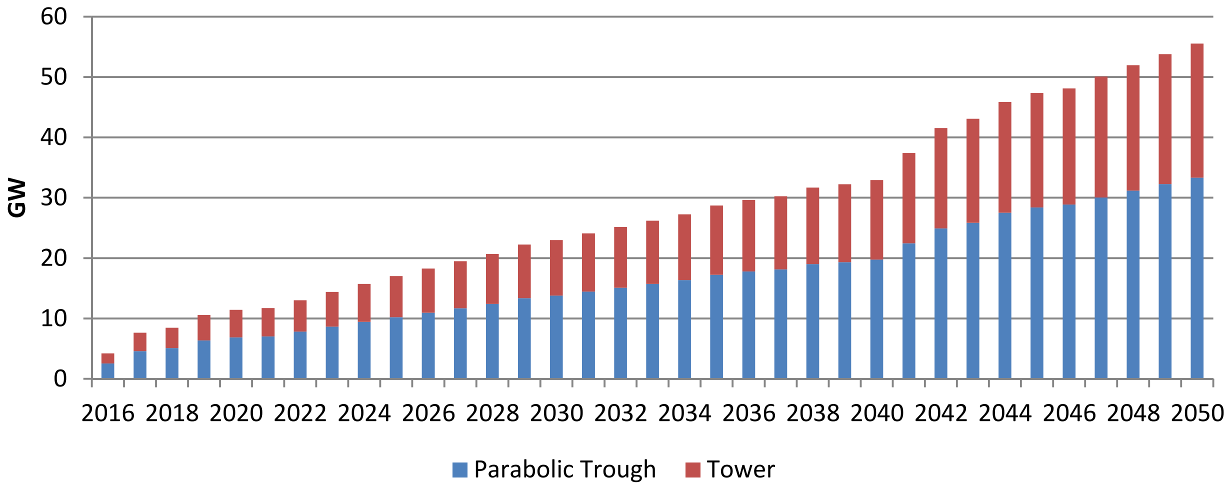

Figure 4. Projection of solar thermal power total installation (GW) by type of installation.

To conclude the next figure represents the cumulative installed power. It can be seen how in 2050 near 900 GW will be reached (Figure 5).

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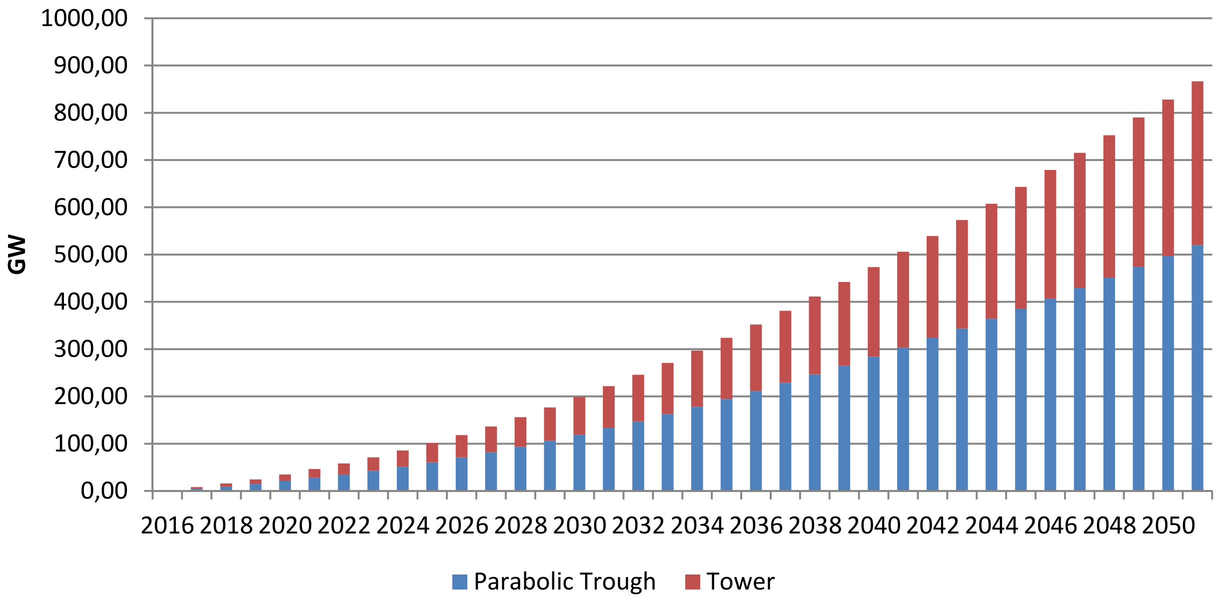

Figure 5. Projection of solar thermal power cumulative installed power (GW).

6. Methodology

To assess the impact of different used materials, the methodology developed by (Valero and Valero, 2014) is used. This methodology covers the total life cycle, from cradle to gate including the grave to cradle approach.

- **Cradle to Gate approach:** assess the exergy cost to produce a refined metal from the mine to be used in industrial applications.
- **Grave to Cradle:** assess the exergy replacement cost to return raw materials from a dispersed state (i.e.: landfills) to the initial state in mines.

This methodology uses the concept of thermodynamic rarity (Valero and Valero, 2014). The thermodynamic rarity indicator is a rigorous exergy measure of a mineral´s quality considering physical aspects of the minerals such as natural concentration, chemical composition, comminution and energy requirements to beneficiate the given mineral.

This approach gives an additional dimension to the criticality of minerals taking into account physical aspects (scarcity in the crust and energy intensity to mine and

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beneficiate the mineral). Note that this new dimension is not yet included in current criticality assessments which are focused on supply risk and economic importance. Whereas the thermodynamic rarity concept is universal and absolute, the socio-economic criticality assessment is country-dependent and variable.

To identify physical constraints for the STP sector a combination of bottom-up and top-down approaches will be used:

- **Bottom-up**: assess the estimated evolution of material production according to current reserves and past production values. This method uses the Hubbert curve methodology traditionally used to assess peak oil. Reserves and production data comes from (Calvo, 2015).
- **Top-down**: assess the estimated demand of materials from different studied STP technologies according to material´s demand and expected projections of installed power by type of technology and recycling current figures of different studied materials.

The values used to assess material rarity are included in the following table:

Table 4: Exergy values used (GJ/ton)

	(A) Grave-Cradle	(B) Cradle-Gate	(A)+(B) Rarity
Ag	7,371	1,281.40	8,652.40
Al	627.24	10.50	637.74
Cr	4.54	0.10	4.64
Cu	291.70	35.30	327.00
Fe	17.75	0.70	18.45
Mn	15.64	0.20	15.84
Mo	907.91	136	1,043.91
Ni	523.61	9.98	533.59
Ti	6.20	9.18	15.38
V	1,055	136	1,191
Zn	155.03	1.5	156.53

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Considering these values and from a rarity point of view, it can be seen for instance that it is not the same to use 1kg of Fe (with a rarity of 18 MJ) than the same quantity of Ni (534 MJ).

The values of current recycling rates of the mineral commodities analyzed in this study are included in the following table:

Table 5: Recycling rates by element (UNEP, 2011)

Element	Recycling rate	Element	Recycling rate
Ag	30 %	**Mo**	33 %
Al	36 %	**Ni**	29 %
Cr	20 %	**V**	0 %
Cu	30 %	**Tn**	52 %
Fe	50 %	**Zn**	22.5 %
Mn	37 %		

7. Results

7.1. Rarity analysis per type of solar thermal power installations

Figure 6 shows a mass comparison between the two studied installations and the materials used. From a mass point of view, Fe constitutes the maximum weight of the STP with figures around 91 to 98 % in CRS and PT respectively. It is followed by Al and Mn, which demands depend on the type of installation. In the case of CRS, the Al contribution is significantly higher than for PT, (5.34 % and 0.11 % respectively). A similar case is that of Mn, which share is 1.32 % in the case of CRS and 0.30 % in PT.

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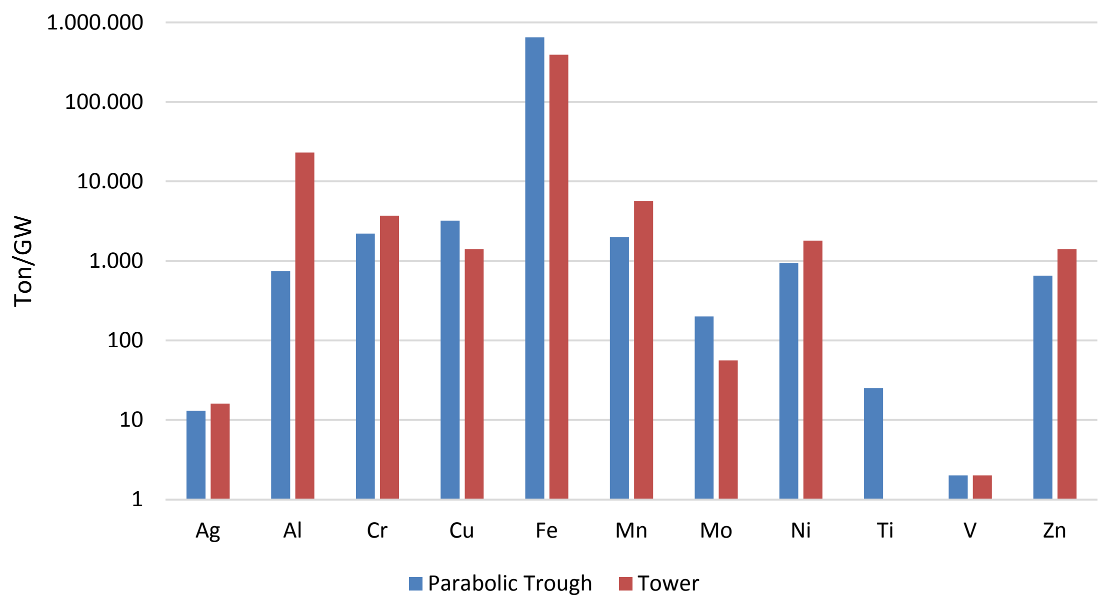

Figure 6. Mass comparison between PT and CRS installations.

Figure *7* shows the results with an exergy (rarity) point of view. In this case the contribution of Al, Cu and Ni is also as relevant as in the mass case, due to the high exergy content of Al, Cu and Ni with respect to Fe. In exergy terms, the Al share is 61% and 3% in CRS and PT, respectively whereas Cu share is 1.91 % and 7.22 %, respectively while that of Ni is 4.02 % and 3.46 %, respectively.

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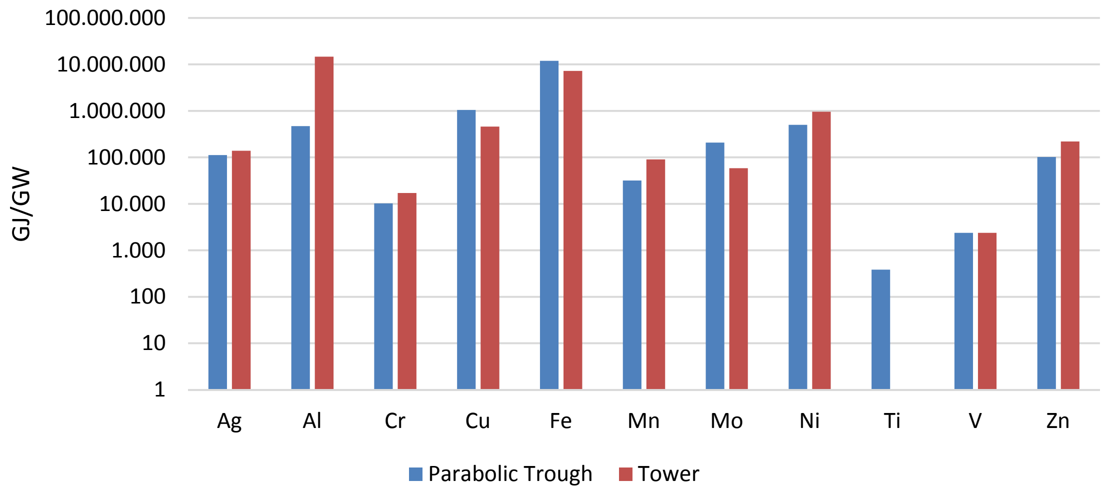

Figure 7. Exergy comparison between PT and CRS installations.

In the following table all exergy values for the different studied materials and installations are shown (Table 6). It can be seen how from an exergy point of view view PT requires less exergy (14,480 GJ/MW) than CRS (23,867 GJ/MW).

Table 6. Exergy values for the different studied installations.

Element	**PT**	**CRS**
Ag (GJ/GW)	112,481	138,438
Al (GJ/GW)	472,046	14,671,700
Cr (GJ/GW)	10,208	17,168
Cu (GJ/GW)	1,046,400	457,800
Fe (GJ/GW)	11,992,500	7,250,850
Mn (GJ/GW)	31,680	90,288
Mo (GJ/GW)	208,782	58,459
Ni (GJ/GW)	501,575	960,462
Ti (GJ/GW)	385	0
V (GJ/GW)	2,382	2,382
Zn (GJ/GW)	101,745	249,142

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Total (GJ/MW)	**14,480,183**	**23,866,689**

7.2. Stock in use in Solar Thermoelectric Power

In this stage the importance of assessing stock in use materials is analyzed with the aim to encourage recycling polices. The following figures show stock in use evolution of the studied, measured in Exergy.

Figure 8 shows the evolution of stock in use in the case of Al, Fe and Ni.

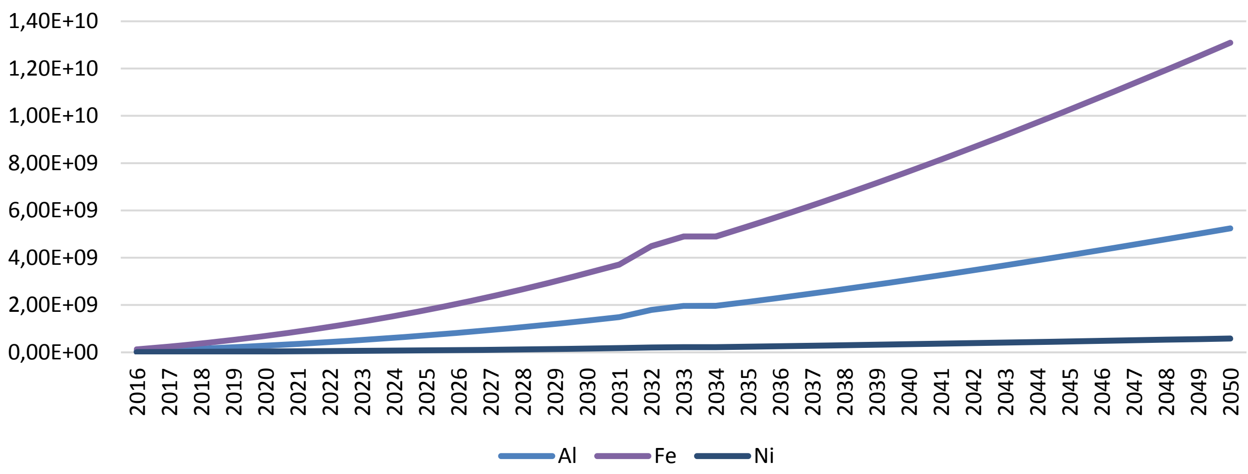

Figure 8. Al, Fe and Ni stock in use evolution (GJ).

Figure 9 shows the evolution of stock in use in the case of Cr, Cu, Mn, Mo, Ag and Zn.

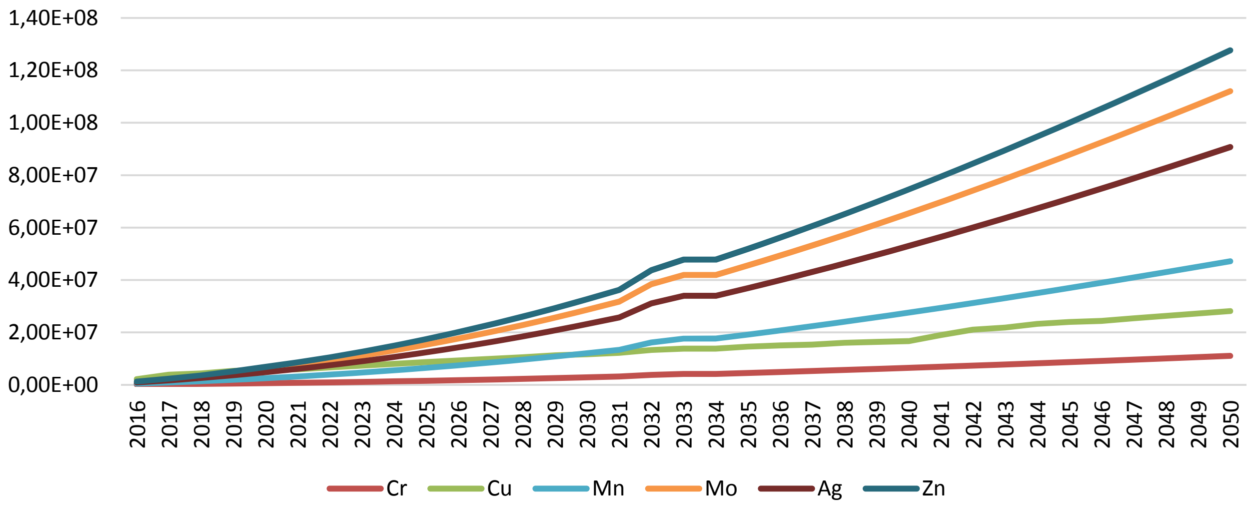

Figure 9. Cr, Cu, Mn, Mo, Ag and Zn stock in use evolution (GJ).

Figure 10 shows the evolution of stock in use in the case of V and Ti.

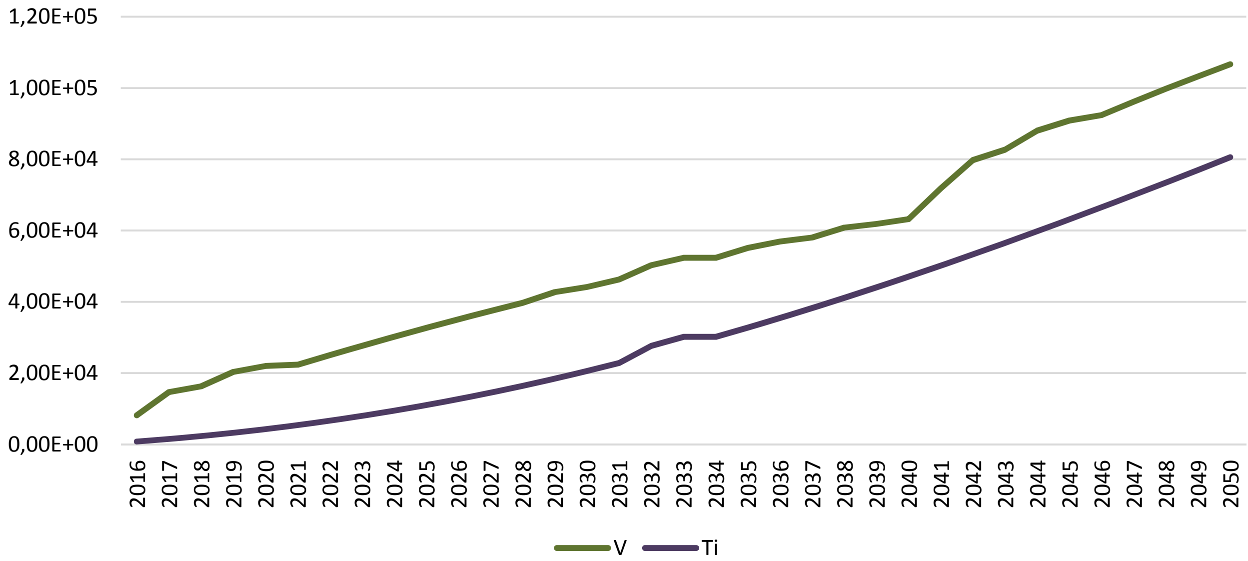

Figure 10. V and Ti stock in use evolution (GJ).

7.3. Material bottlenecks in solar thermoelectric installations

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Once different solar thermal power installations have been analyzed from a material point of view, expected demand of materials associated to STP from 2015 to 2050 are assessed. The aim is to identify possible material shortages due to new installed repowered STP energy capacity under a "Business as Usual" scenario. Recall that the BAU scenario for material production has been built assuming that it will follow a Hubbert-curve trend assuming available reserves as registered in 2015 by the USGS. Note that the same results are obtained using tonnage or exergy values, hence curves are shown in mass terms.

Figure 11 to Figure 21 compare Cu, Fe, Mn, Al, Ag, Cr, Mo, Ni, V, Zn and Ti demand to manufacture solar thermal power installations with their world estimated production trends in the period from 2015 to 2050. Apparently none of the materials considered in STP installations will constitute a bottleneck in the studied period.

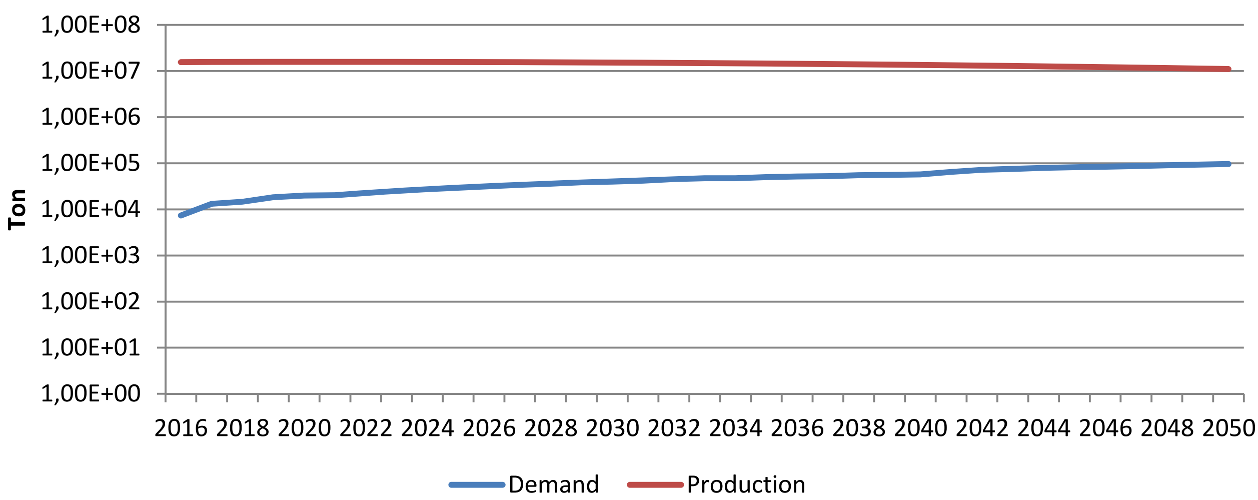

Figure 11. Cu world production and solar thermal power demand projections from 2015 to 2050.

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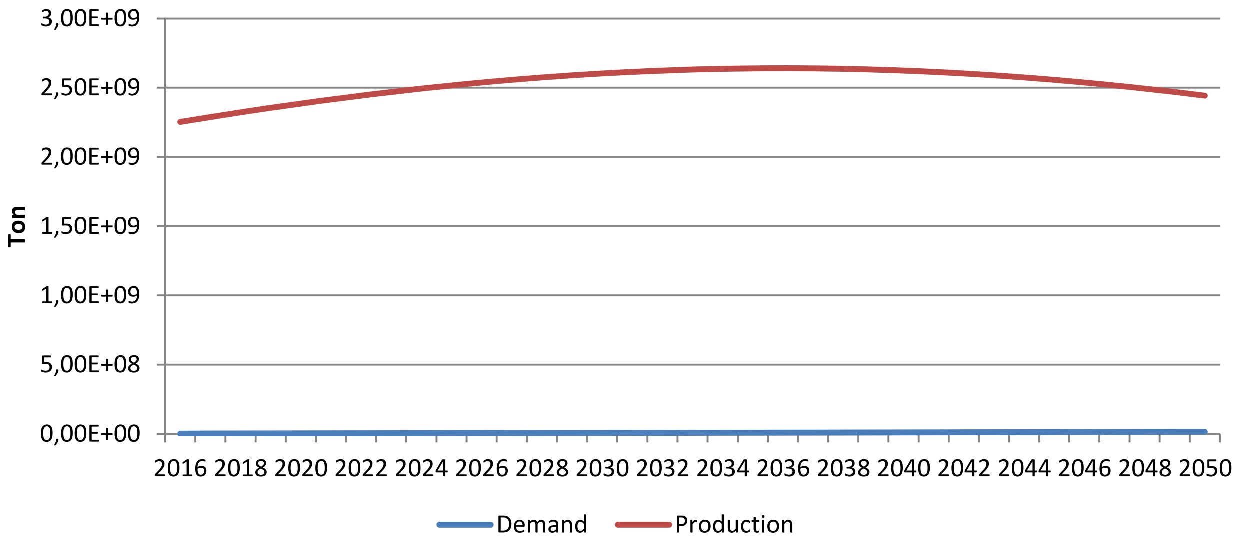

Figure 12. Fe world production and solar thermal power demand projections from 2015 to 2050.

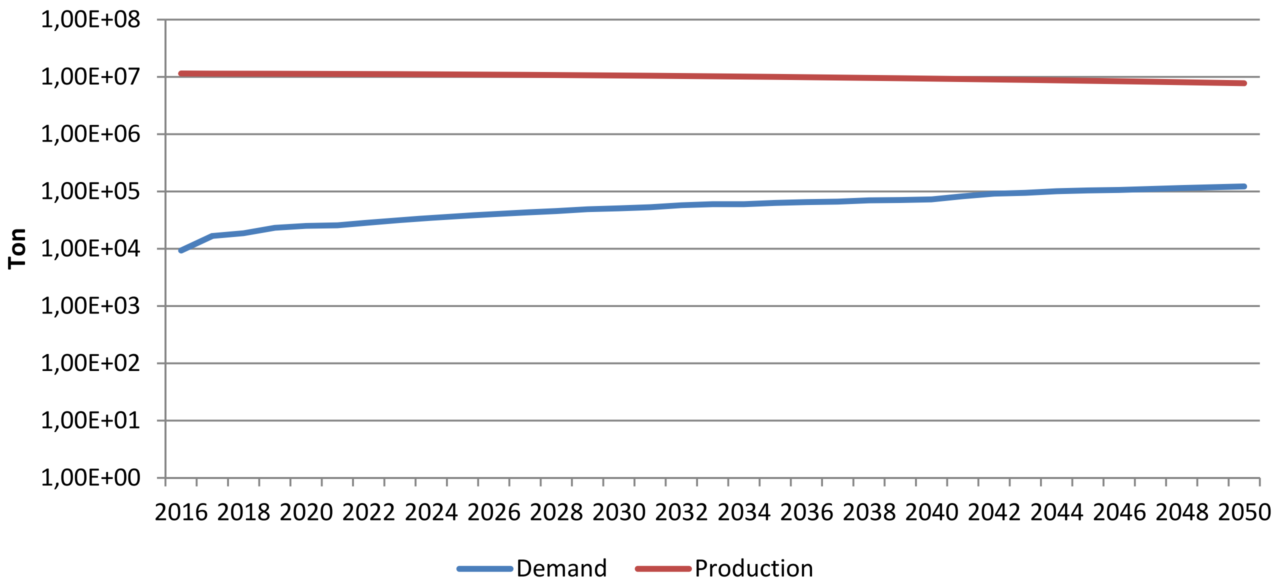

Figure 13. Mn world production and solar thermal power demand projections from 2015 to 2050.

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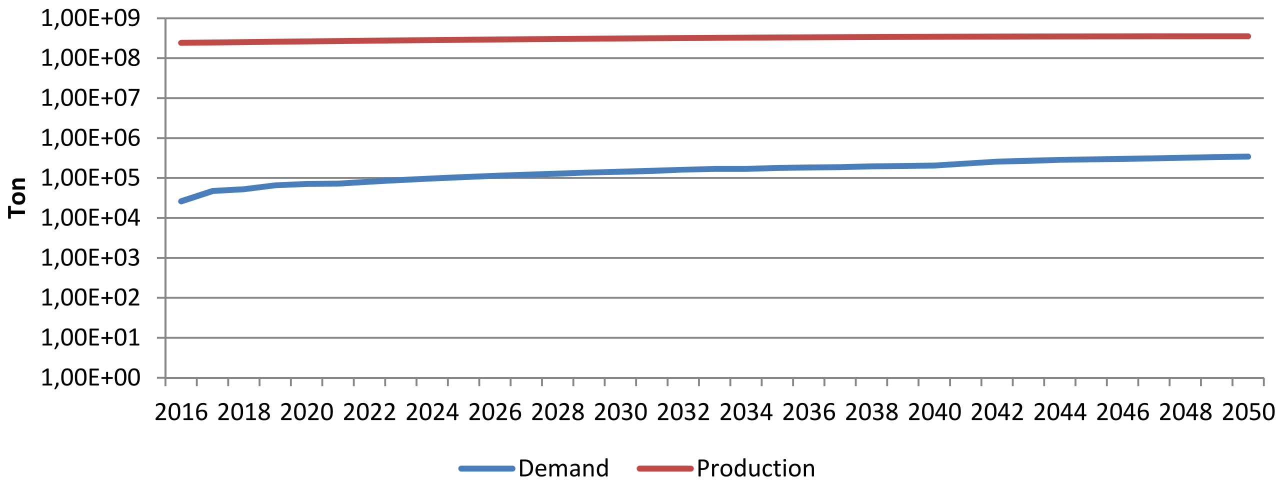

Figure 14. Al world production and solar thermal power demand projections from 2015 to 2050.

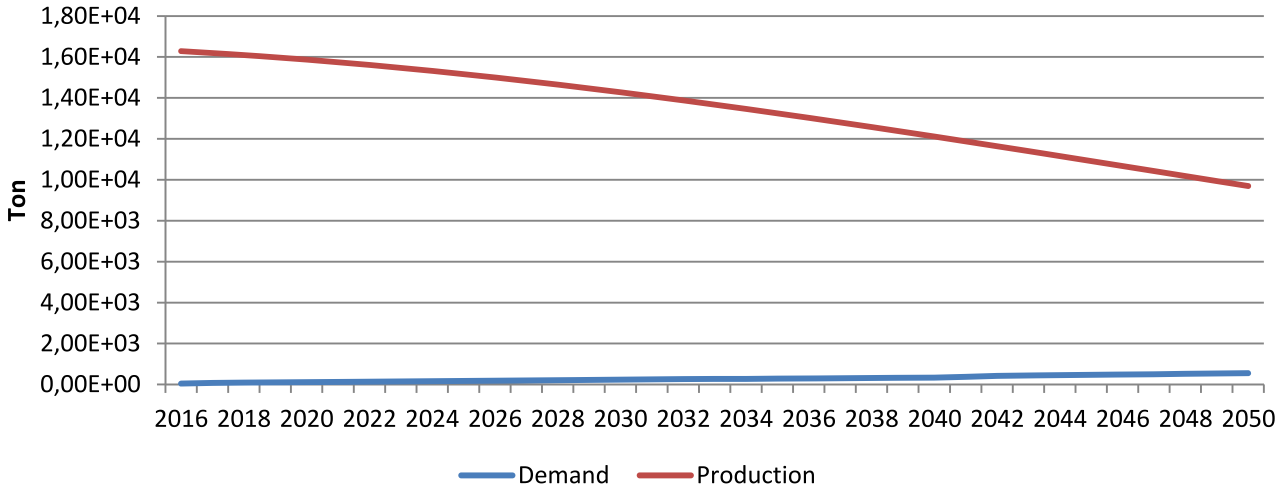

Figure 15. Ag world production and solar thermal power demand projections from 2015 to 2050.

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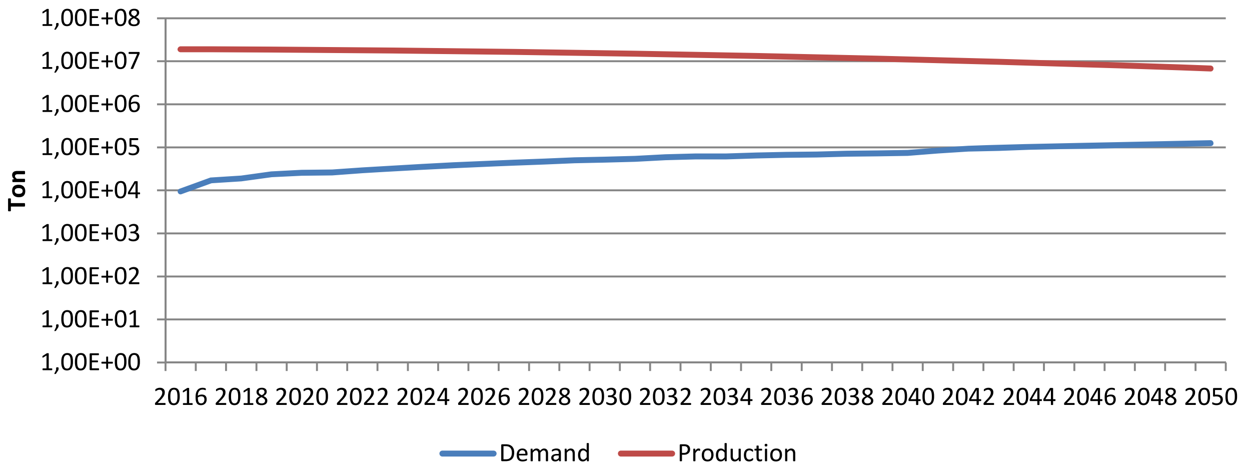

Figure 16. Cr world production and solar thermal power demand projections from 2015 to 2050.

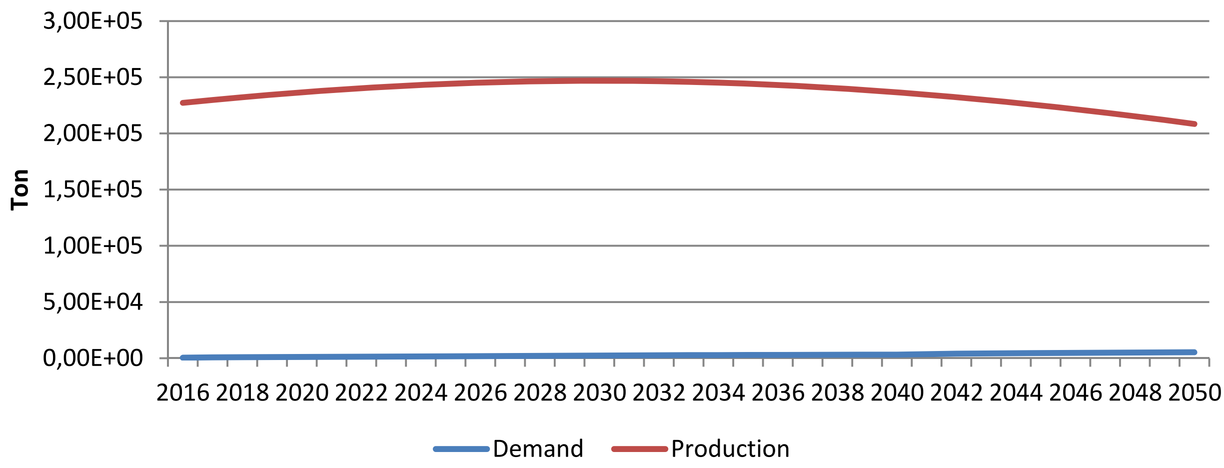

Figure 17. Mo world production and solar thermal power demand projections from 2015 to 2050.

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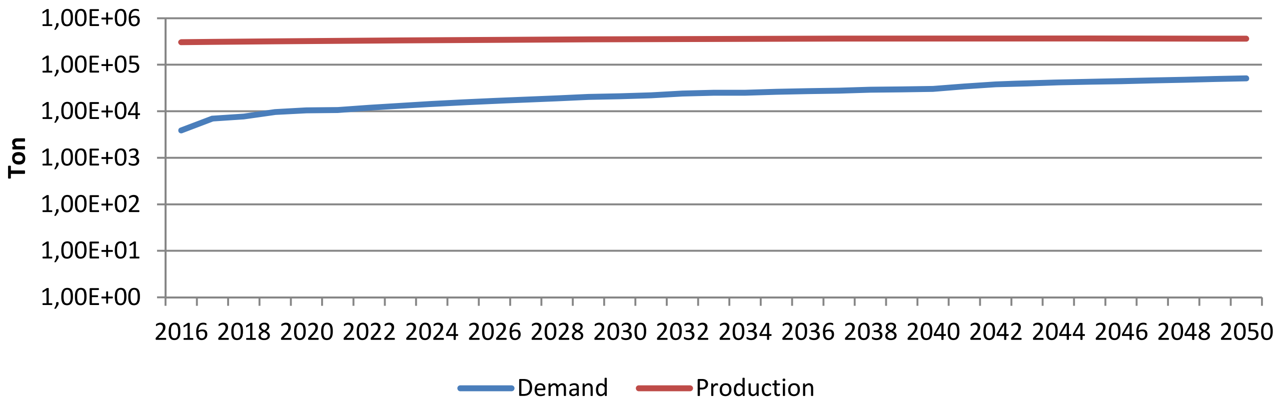

Figure 18. Ni world production and solar thermal power demand projections from 2015 to 2050.

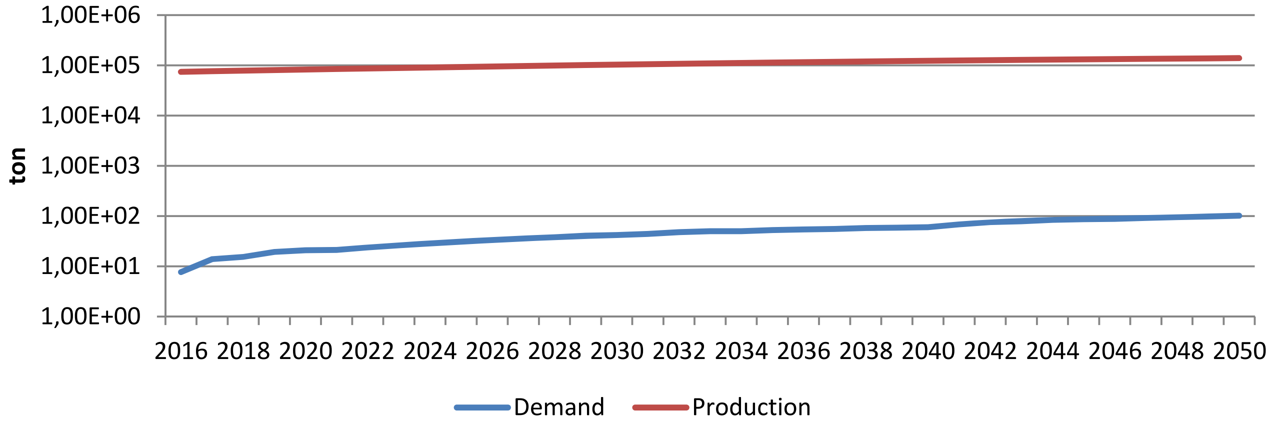

Figure 19. V world production and solar thermal power demand projections from 2015 to 2050.

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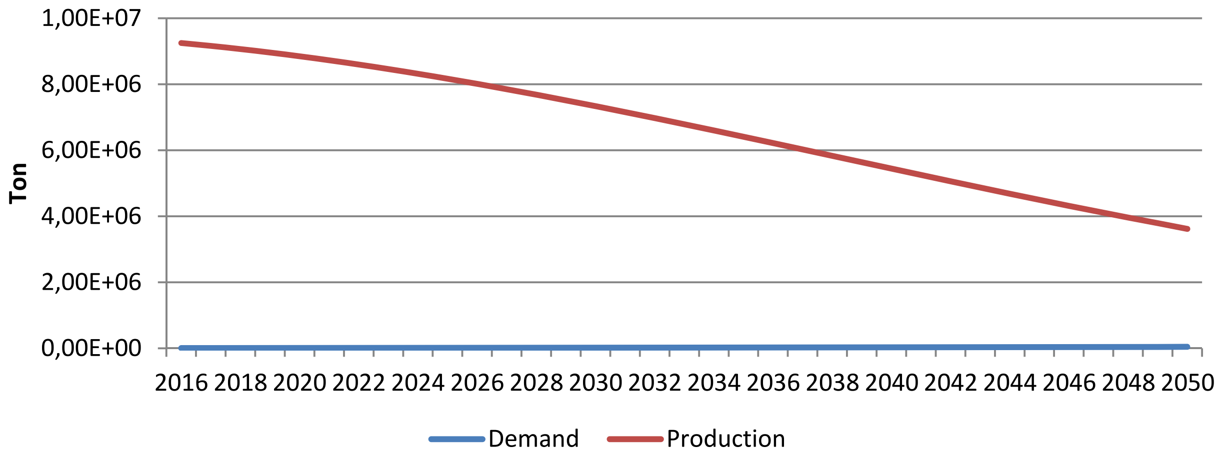

Figure 20. Zn world production and solar thermal power demand projections from 2015 to 2050.

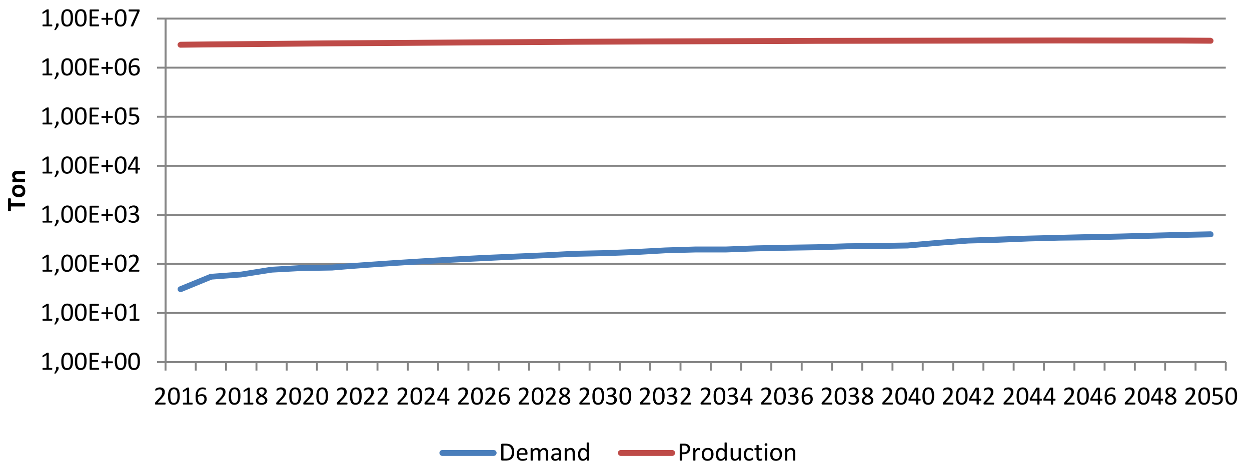

Figure 21. Ti world production and solar thermal power demand projections from 2015 to 2050.

Figure 22 and Figure 23 show the ratios between demand and production for the major metals used in STP. Although there are no expected supply problems by the technology itself, it can be seen how the share of Ni, Ag and Mo demand caused by STP

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will grow from 1.27 %; 0.25 % and 0.17 % to 14 %; 5.69 % and 2.54 %, respectively. Cr and Mn demand in STP meanwhile, will require over 1.5 % of 2050 total production.

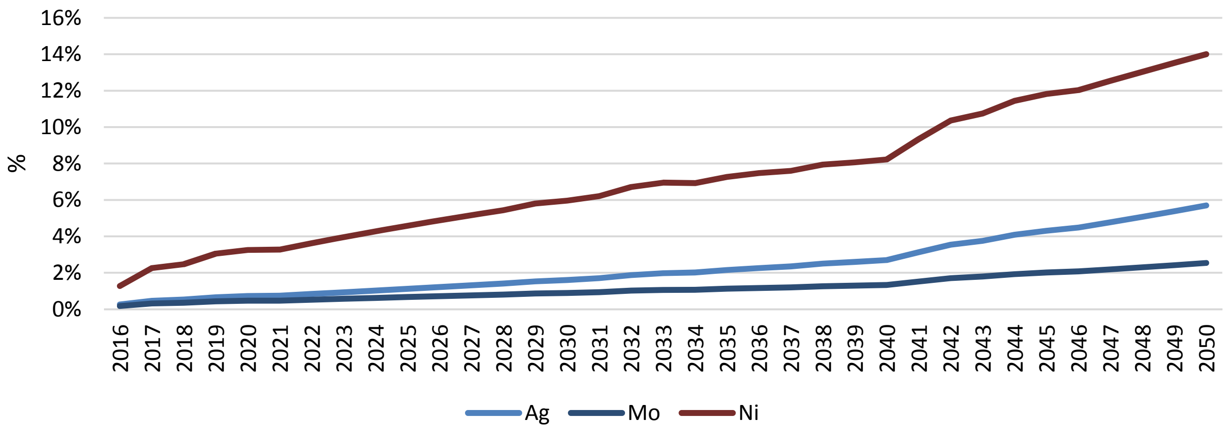

Figure 22. Ag, Mo and Ni world solar thermal power demand with respect to world production from 2015 to 2050.

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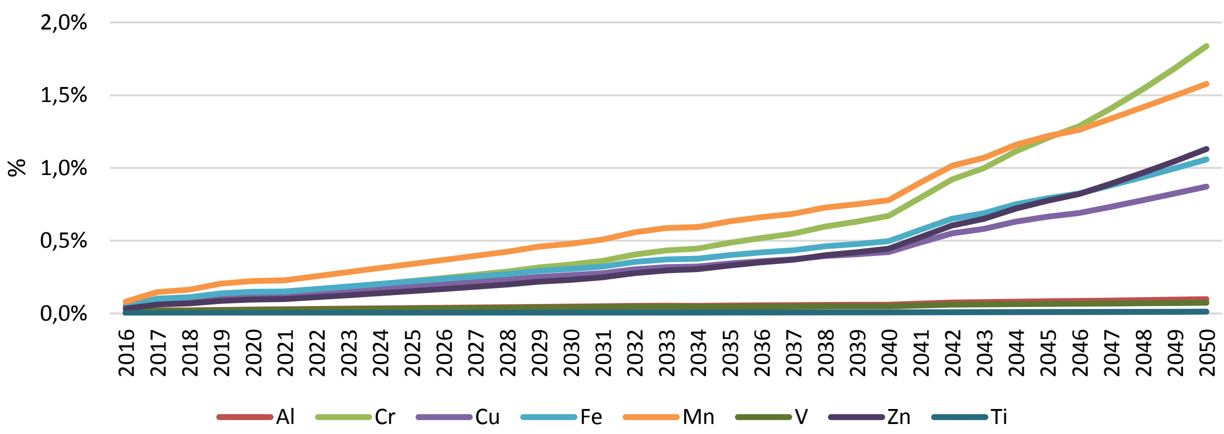

Figure 23. Al, Cr, Cu, Fe, Mn, V, Zn and Ti world solar thermal power demand with respect to world production from 2015 to 2050.

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Finally, considering the cumulative primary material demand from 2016 to 2050 (taking into account recycling figures of studied materials) and comparing these values with current reserves, it can be seen how solar thermal power will not likely be constrained by material supply risk. The higher cumulative demand versus reserves values is found for Ag, where demand is expected to constitute around 1.84 % of current 2015 reserves values.

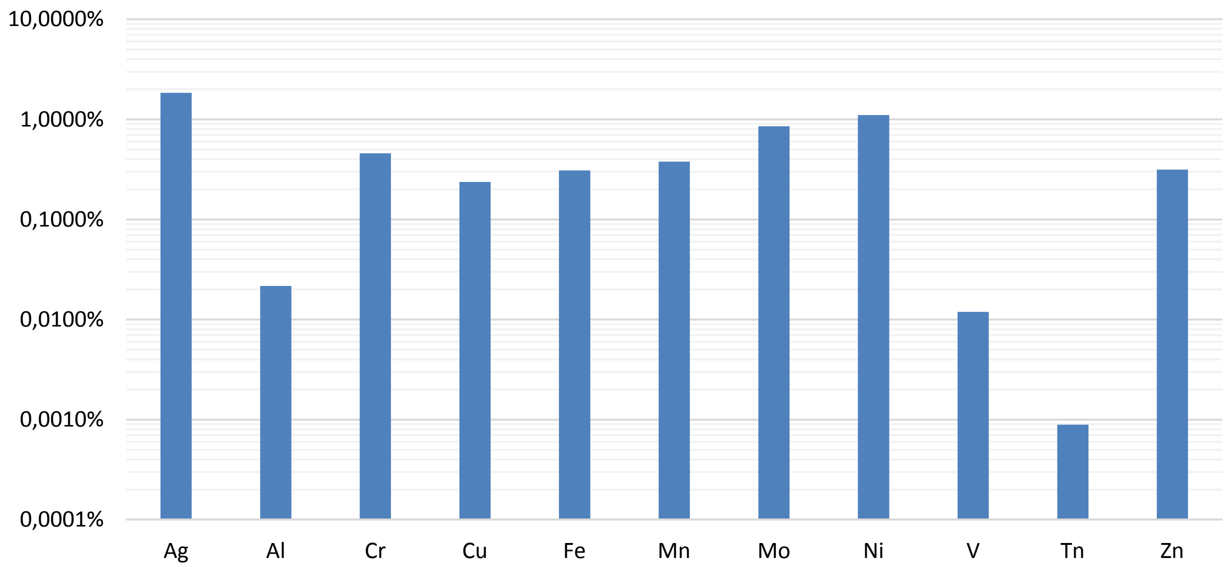

Figure 24. 2015-2050 world demand/reserves.

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8. Conclusions

The most demanded metals in STP from an exergy-rarity (considering the physical criticality of minerals) point of view are: Al, Cu, Fe and Ni. Considering the type and again only considering their material content, PT technologies are more sustainable than CRS. PT has a rarity content of around 14,500 GJ/MW while CRS about 23,900 GJ/MW (i.e. the latter require less quantity of raw materials – 34% less, but 60% more exergy than the first).

In solar thermal power manufacturing and considering a BAU scenario for metal production using a Hubbert-like tendency assessed with reserves data, there are presumably no materials which could be considered critical from a physical availability perspective.

However it is important to highlight that under a BAU scenario, solar thermoelectric installations could demand near 14 %, 4 % and 2 % of Ni, Ag and Mo world production in 2050.

Assessing the different components the most critical are mirrors and energy storage systems.

Taking into consideration these facts, in can be stated that the most critical components in STP are the generator and mirrors and the energy storage systems. This result is a guideline for future design and recycling policies in the solar thermal power sector.

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D2.1: *Report with an analysis of the main limitations of variables and indicators selected to represent the pathways and scenarios.*

Annex 11: *RES for heat generation and physical constraints. Solar Thermal Energy.*

Grant agreement: 691287

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Document info sheet

Responsible partner: (CIRCE – Research Centre for Energy Resources and Consumption)

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TABLE AND FIGURE INDEX

1. Scope and goal

This document is part of MEDEAS Deliverable 2.1. The main aim of this report is to explain in depth which physical constraints are expected in heat generation through solar thermal energy from 2015 to 2050 from the point of view of raw materials.

This activity is done through an assessment of the materials required to manufacture different types of solar thermal absorbers from 2015 to 2050.

The results of this Deliverable will be implemented in MEDEAS model through PAVs database values. For this reason, the following table shows the information covered in this document and its link to the PAV list specified in Deliverable 2.1.

Table 1. Link between physical constraints in solar thermal energy and PAVs.

D2.1 Results	PAV	PAV description
Capacity factor of RES	51	productivity of each technology according not only technology evolution but also renewable resources potential (solar thermal)
Investment cost of RES*	52	Investment costs for each RES technology (solar thermal)
Thermal energy cost from RES*	53	Levelage Cost of heat for each RES technology (solar thermal)
RES production for termal applications	54	Yearly production of each RES technology (solar thermal)
RES power density from technology point of view	55	Power density of each RES technology (solar thermal)
RES lifetime for thermal applications	57	Life time of each RES technology (solar thermal)
RES EROI	58	EROI of different RES (solar thermal) from LCA point of view
Al, Cr, Cu, Mo, Ni, Pb,Sn, and Zn solar thermal demand evolution from 2015 to 2050	109	Material intensity for RES

* Investment cost and electricity cost for RES have been indirectly taken into account by assessing the potential evolution of Solar Thermal.

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2. Introduction

Solar energy is clean and abundant. Its intermittent nature and dynamics along the Earth makes it a power source to be used by different technologies. Being one of the most used energy sources, it is considered the most advantaged and the mother of all other energies.

The conversion of solar energy consists in a large family of different technologies, with a wide range of application technologies. Among the most important are deliver heat, cooling, natural light, electricity and production of fuels. Specifically in this work the use of solar energy as direct use for heating generation will be taken into account.

The global installed capacity of solar thermal energy by the end of 2013 was 330 GW_{th}, with a yearly production of 281TWh, which is equivalent to having 471 million square meters of solar collectors (International Energy Agency, 2014).

The vast majority of the total operation capacity is installed in China 180.4 GW_{th} and Europe 42.8 GW_{th}, both together account for 83% of the total power installed, where the predominant application is hot water generation (International Energy Agency, 2014).

The energy demand for direct heating is increasing continuously due to growing thermal loads, changes in building architectural modes, and especially due to increasing occupants indoor comfort demand resulting in higher demands. Some of the most known problems associated with this increase are:

- The global energy demand and CO_2 emission are expected to increase almost 60% by 2030 in comparison to the beginning of this century. The European Union (EU) energy import dependency is expected to increase approximately 70% by 2030, being 50% in 2000 (Comission of European Communities, 2006).
- The production of a test solar heat water (SHW) system in Italy was calculated to produce about 700 kg of CO_2 (International Energy Agency, 2012).

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- Higher electricity demands notably during peak loads for air and water heating. This increase of electricity demand is resulting in higher consumption of primary energy sources e.g. fossil fuels (Gaford & Munir, 2014).
- The real challenge lies in the selection of suitable and efficient technologies to utilize maximum heat from the sun to fulfill the required energy demand (Henning HM, 2007).

Yet the deployment of renewable resources and in particular solar thermal energy, will require an increasing demand of materials which might provoke serious bottlenecks. This is why it is crucial to analyze the expected production trend of solar thermal energy and its associated material needs in order to define future energy policies.

Indeed, a thorough analysis of the resources required for a certain economic sector needs to include not only the energy used throughout its life cycle, but also the materials required to manufacture the analyzed system. The supply of critical raw materials is an important issue that is currently regarded as a potential threat that may put at risk the so-called "Green Economy". Accordingly, a list of 20 raw materials considered as critical because risks of supply shortage and their impacts on the economy, was recently published by the European Commission (European Comission, 2014).

Some of these materials are Platinum Group Metals and Rare Earth Elements, however there are more materials which currently are not considered as critical in this list but need to be also monitored. The term "critical" as defined by the EC is not static and it changes with the socio-economic circumstances. This means that there is not a specific definition of the term, and hence there are more than 20 raw materials that must be considered when we talk about supply risk.

Going back to the solar thermal, the demand for materials used in solar heating technologies such as cooper, glass, steal, brass, etc. is rapidly increasing.

As an example, the annual newly installed capacity of flat-plate and evacuated tube collectors from the global solar thermal market enjoyed a growth rate of about

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12% in 2005 to 34% growth in 2018 (International Energy Agency, 2014). It is urgent to analyze the use of materials that are in demand in direct thermal generation using solar collector technology to guarantee a real sustainable development.

3. Solar thermal, types of technologies

The responsible for collecting solar irradiation on the surface is the solar absorber which must be dark in color to maximize the absorption. Most collectors have an absorber that also reduces the release of the infrared radiation, ensuring that as much heat as possible is retained.

There are mainly three types of absorbers. The following chart shows the classification:

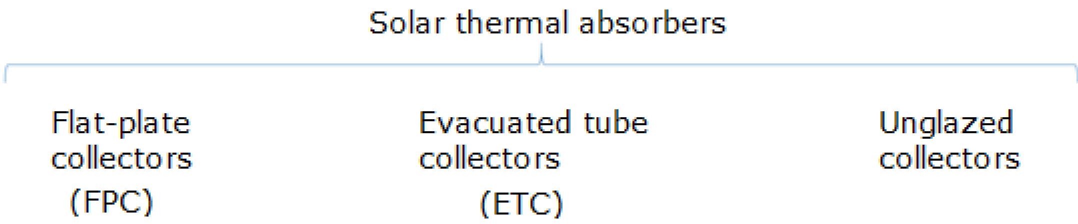

Figure 1. Solar thermal absorbers classification.

FPC collectors, where the housing is a shallow box, comprising a casing (aluminum, steel, plastic or sometimes wood), insulation material (mineral or rock wool) or vacuum to reduce thermal losses on the back of the collector, and one or two transparent layers of low iron, tempered solar glass (sometimes including an antireflective coating which increases transmissivity of the cover) (International Energy Agency, 2012)

ETC, where the housing is a glass tube with vacuum inside, so that the heat losses to the environment are very low.

Evacuated tube collectors can be classified as direct flow tubes and heat pipe tubes. The most popular direct flow tube is the Sydney tube, also known as a twin-

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glass tube or thermos flask tube, which is the main solar thermal product in China. Its main feature is that the vacuum is located between two glass tubes fused together. The outside of the inner tube is coated with a selective surface (International Energy Agency, 2012).

Unglazed collectors consist mainly of plastic absorber without covering, and are primarily used to heat ambient (outside), water-air instead of recirculated building air for commercial, swimming pool heating, industrial, agriculture and process applications.

Of all the capacity, solar collectors are divided into planes with (FPC): 71 GW_{th}, vacuum tubes (ETC): 174.1 GW_{th}, unglazed colectors 22.7 GW_{th}, and indoor air collectors and without cover 1.6 GW_{th} (International Energy Agency, 2014). Worldwide predominant technology is ETC representing 65%, then 26 % correspond to FPC and last unglazed collectors accounting for 8%. In contrast to the world tendency, the most widely used technology in Europe are FPC with a share of 84.9 % (International Energy Agency, 2012).

For these reasons in the present study FPC and ETC are going to be studied. On the other hand, unglazed collectors are made of plastic and don't present a risk from a raw material point of view.

The worldwide market of glazed water collectors is characterized by a steady growth over the past 12 years with China as the main driver for this positive development. Between 2000 and 2012 the average growth rate worldwide was around 20% and between 2006 and 2012 the annual installed glazed water collector area worldwide tripled. Compared to 2011, the growth rate has dropped from 15.3% to 9.6% in 2012 (International Energy Agency, 2014).

4. Materials demand in solar thermal

To identify which materials are used in FPC and ETC a state of the art analysis obtained from the bibliography has been undertaken. In the following table (Table 2)

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an inventory of materials used to produce them, identified by different authors is shown.

Table 2. List of materials for each solar thermal system (in kg).

		Ardente et al. (2004)	Hang, et al. (2011)
Part	**Material**	**kg**[1]	**kg**[2]
FPC	Copper	8.2	2.82
	Thermal fluid (Propylene glycol)	0.9	1.01
	Epoxy dust	0.3	
	Copper	0.46	2.82
	HDPE	0.87	
	Brass	0.04	
	PVC	0.01	
	Welding rod	0.1	
	Rock wool		2.43
	Glass	10.5	9.12
	Rigid PUR	4.2	
	Flexible PUR	0.01	
	Aluminum	4	1.8
	Stainless Steel	6.1	4.14
	Galvanized Steel	33.9	
ETC	Copper Absorber		2.8
	Steel		4
	Rock wool		2.03
	Corrugated board		3.33
	Glass tube		14.2
	Thermal fluid (Propylene glycol)		0.654
	Copper (coating)		2.8
Hot Storage Tank	Galvanized Steel	50	
	Stainless Steel	21	
	Cooper	3.8	
	Brass	0.1	
	Magnesium	0.2	
	Rigid PUR	4.8	
	Thermal fluid (Propylene glycol)	5.4	

[1] Based on an absorber of 2.13 m^2

[2] Based on an absorber of 2.4 m^2

		Ardente et al. (2004)	Hang, et al. (2011)
	Epoxy dust	0.7	
	Welding rod	0.2	
Support	Galvanized Steel	27	
	Stainless Steel	0.5	

The materials presented in the table above help us to identify the elements used in the two different technologies. To cover all the expected physical constraints it is necessary to analyze not only critical materials as defined by the EC, but also more conventional materials like Fe, Al or Cu.

It should be stated that the organic materials presented in Table 2 are not taken into account in this study. Therefore, we can consider a new list of the elements needed for the 2 different technologies. Another important factor is to know the materials of the compounds and the typical composition of the elements for both collectors: steel, welding wool and brass.

The following table (Table 3) summarizes the materials used by the FPC technologies (area 2.13 m^2) and ETC (area 2.4 m^2), considering in both of them the hot storage tank and the support.

Table 3. Studied materials in solar thermal collectors, contribution in mass (gr) per unit of absorber including HST and support.

	FPC	**ETC**
Al	1,239.29	452.77
Ca	636,56	1,328.66
Cu	9,650.41	9,908.82
Mg	342.41	582.74
Na	752.27	1,408.81
K	74.45	151.60
Fe	86,855.32	9,7057.94
C	119.48	133.18
Mn	995.69	1,109.90
P	44.80	49.94
S	29.87	33.30
Si	3,432.78	6,437.51
Ni	497.95	555.06

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Cr	9,956.50	11,098,59
Mo	497,83	554,93
Ti	20,43	99,48
As	0,03	0,04
Pb	1,12	1,26
Sn	0,12	0,14
Zn	14,39	16,21

5. Evolution of solar thermal

The expected power installed projections from 2015 to 2050 is required for assessing the impact of solar thermal material demand in reserves. To do so, projection values from the International Energy Agency (2012), IPCC (2012), European Renewable Energy Council (2012) and REN21 Renewable Energy Policy Network for the 21st Century (2014) have been consulted.

Considering these data, **Figure 2.** shows the evolution of installed power from 2016 to 2050 by type of installation: FPC and ETC. It can be seen how the ETC installations will grow in market share.

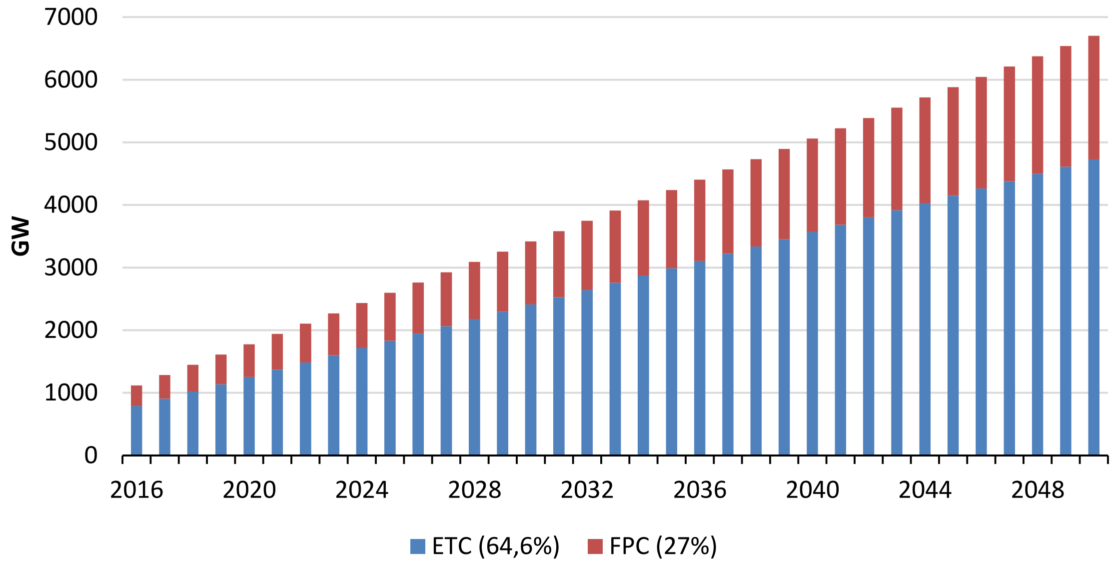

Figure 2. Projection of accumulated power (GWth) in solar thermal by type of installation.

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As it can be seen in the chart above there is a linear growth and the predominant technology is ETC, considering that the percentage of participation will be the same until 2050.

In this case the repowering effect has not been considered because its lifetime is longer. According to life-cycle of solar thermal installations, it ranges from 20 to over 30 years (Great Britain Parliament: House of Lords: Science Technology Commite, 2005-2006). Therefore, for the study period (from 2016 to 2050) the effects of repowering are not significant. On the other hand these types of installations are easier to be repaired than RES for electricity generation and frequently maintenance operation contributes to increase their lifetime.

6. Methodology

To assess the impact of different used materials, the methodology developed by Valero and Valero (2014) is used. This methodology covers the total life cycle, from cradle to gate including the grave to cradle approach.

- **Cradle to Gate approach:** assess the exergy cost to produce a refined metal from the mine to be used in industrial applications.
- **Grave to Cradle:** assess the exergy replacement cost to return raw materials from a dispersed state (i.e.: landfills) to the initial state in mines.

This methodology uses the concept of thermodynamic rarity (Valero and Valero, 2014). The thermodynamic rarity indicator is a rigorous exergy measure of a mineral´s quality considering physical aspects of the minerals such as natural concentration, chemical composition, comminution and energy requirements to beneficiate the given mineral.

This approach gives an additional dimension to the criticality of minerals taking into account physical aspects (scarcity in the crust and energy intensity to mine and beneficiate the mineral). Note that this new dimension is not yet included in current

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criticality assessments which are focused on supply risk and economic importance. Whereas the thermodynamic rarity concept is universal and absolute, the socio-economic criticality assessment is country-dependent and variable. For more information on the methodology, see Annex 5.

To identify physical constraints for solar thermal energy sector a combination of bottom-up and top-down approaches will be used:

- **Bottom-up**: assess the estimated evolution of material production according to current reserves and past production values. This method uses the Hubbert curve methodology traditionally used to assess peak oil. Reserves and production data comes from (Calvo, 2015) and are included in Annex 6.
- **Top-down**: assess the estimated demand of materials from different studied absorbers according to material´s demand and expected sales by type of absorber and recycling current figures of different studied materials.

The values used to assess material rarity are included in the following table:

Table 4. Exergy values used (GJ/ton).

	(A) Grave-Cradle	(B) Cradle-Gate	(A)+(B) Rarity
Al	627.24	10.5	637.74
As	400	9	409
Cr	4.54	0.1	4.64
Cu	291.7	35.3	327
Fe	17.75	0.7	18.45
K	1.224.2	3.1	1.227.3
Mn	15.64	0.2	15.84
Mo	907.91	136	1.043.91
Na	44.1	3.3	47.4
Ni	523.61	9.98	533.59
P	0.4	0.3	0.7
Pb	37	0.9	37.9
Sn	426	15.2	441.2
Ti	9	13.8	22.8

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Zn	25	1.5	26.5

Considering these values and from a rarity point of view, it can be seen for instance that it is not the same to use 1kg of Fe (with a rarity of 18 GJ) than the same quantity of Ni (533 GJ).

The values of current recycling rates are included in the following table:

Table 5. Recycling rates by element (UNEP, 2011).

Element	Recycling rate	Element	Recycling rate
Al	36%	S	0%
Ca	0%	Si	0%
Cu	30%	Ni	29%
Mg	33%	Cr	20%
Na	0%	Mo	33%
K	0%	Ti	52%
Fe	50%	As	1%
C	0%	Pb	51%
Mn	37%	Sn	22%
P	0%	Zn	23%

7. Results

7.1. Rarity analysis per type of solar thermal collector

Figure 3 shows a comparison between a mass and exergy (rarity) analysis in a FPC absorber. From a mass point of view, Fe constitutes around 79 % of the absorbers. However in rarity terms, Fe only constitutes 34 %. This is because more valuable metals (such as Cu, Al and Mo contained in absorbers construction) have a greater exergy content.

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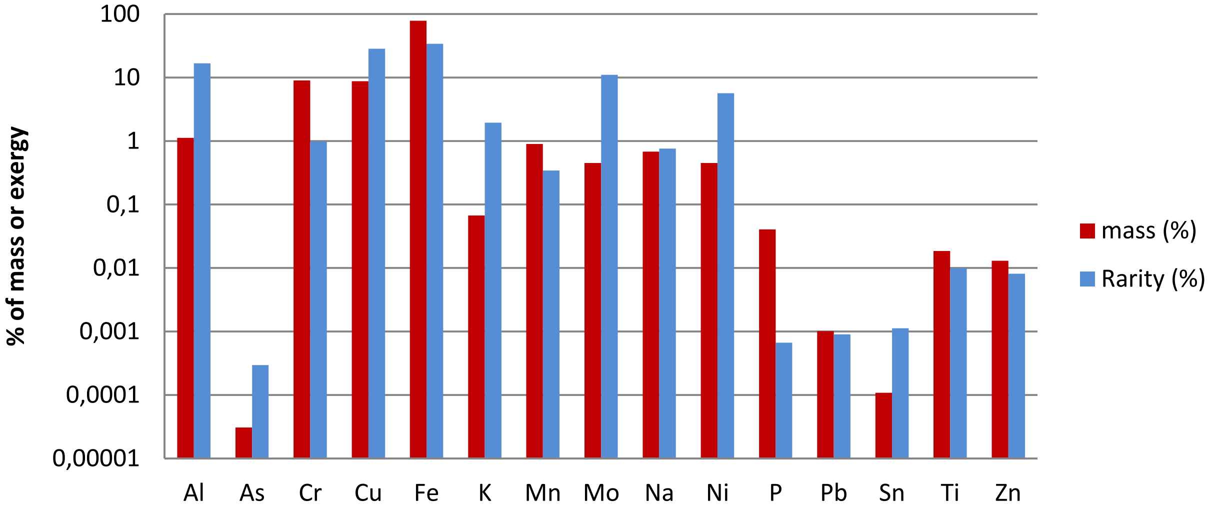

Figure 3. Mass and Exergy-rarity comparison in a FPC Absorber.

Figure 4 shows the results for an ETC absorber. As in the previous case, Fe is more relevant, but in exergy (rarity), Cu, Al and Mo become the most relevant from all.

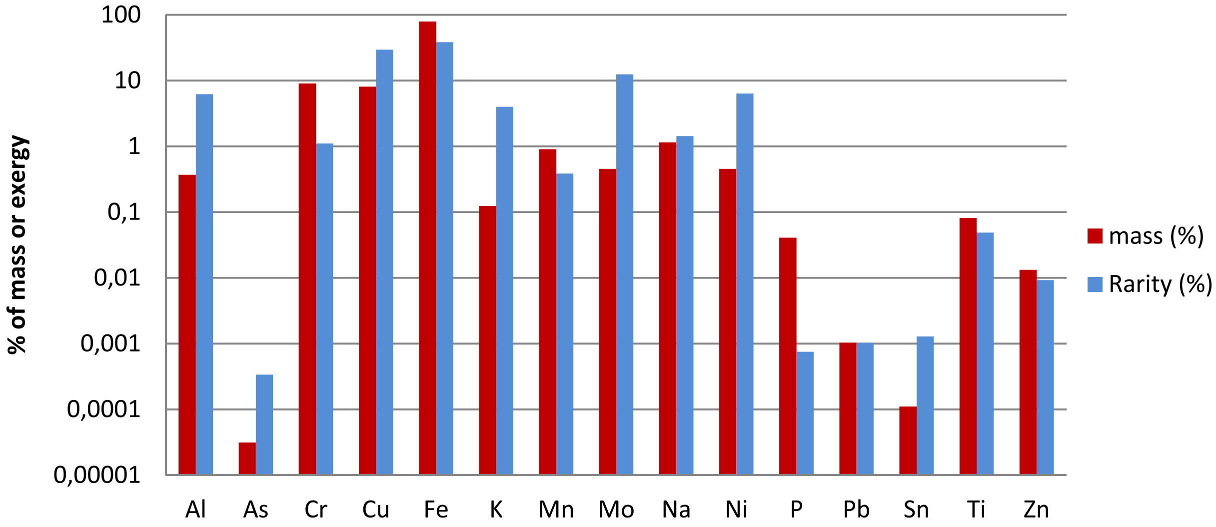

Figure 4. Mass and Exergy-rarity comparison in an ETC absorber.

Figure 5 shows the result for FPC absorbers. Here Cu, Al, Mo acquire a more relevant role in exergy (rarity) terms compared with the mass cumulative contribution.

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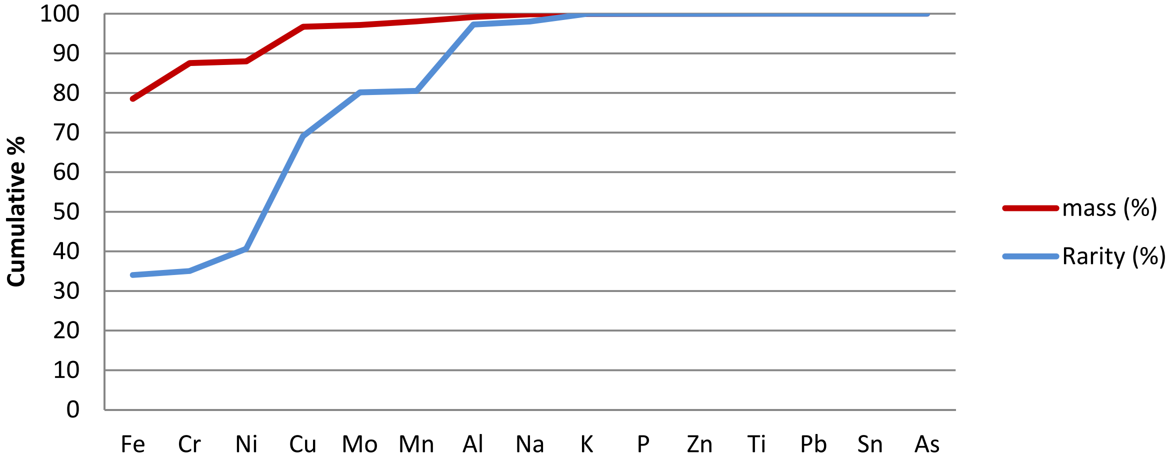

Figure 5. Mass and Exergy-rarity comparison in a FPC.

Figure 6 shows the behavior for ETC. As in the previous case, Cu, Al and Mo have a more relevant contribution in exergy (rarity).

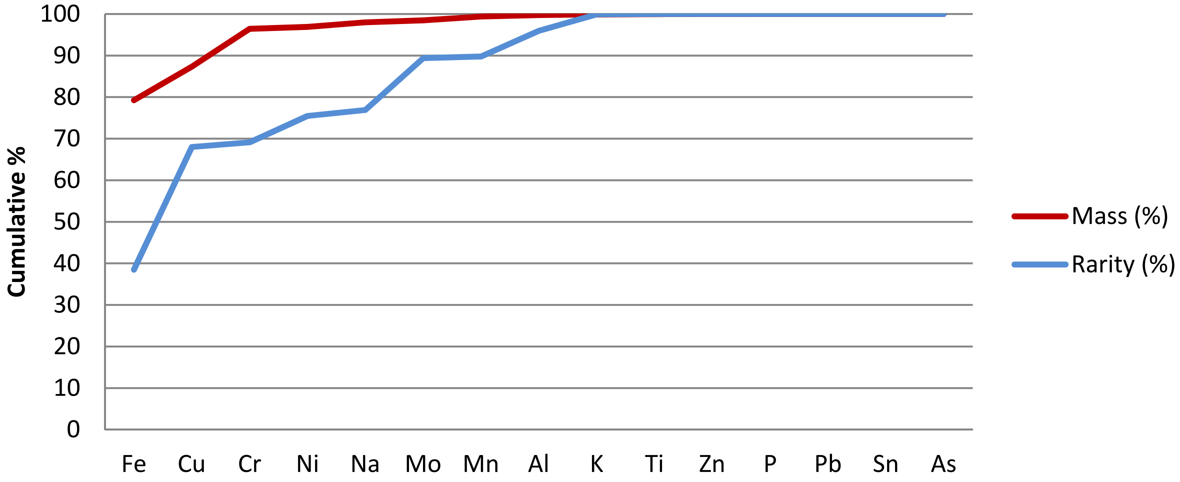

Figure 6. Mass and Exergy-rarity comparison in an ETC.

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7.2. Stock in use per solar thermal absorbers

In this stage the importance of assessing stock in use materials is analyzed as a guideline for recycling polices. The following figures show stock in use evolution measured in exergy of the main studied materials for EPC and FPC jointly.

Figure 7 shows the evolution of stock in use in the case of Cu and Fe. In 2050 Fe and Cu stocks in use values will be multiplied by 7 and 5.5 with respect to current values.

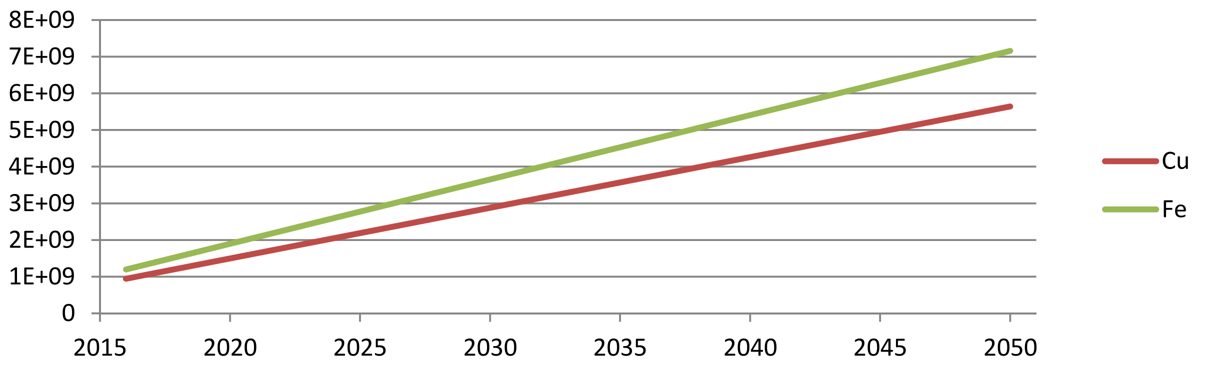

Figure 7. Fe and Cu stock in use evolution (GJ).

Figure 8 shows the evolution of stock in use in the case of Al, Cr, Mo and Ni. In all cases 2050 stocks in use values will be higher.

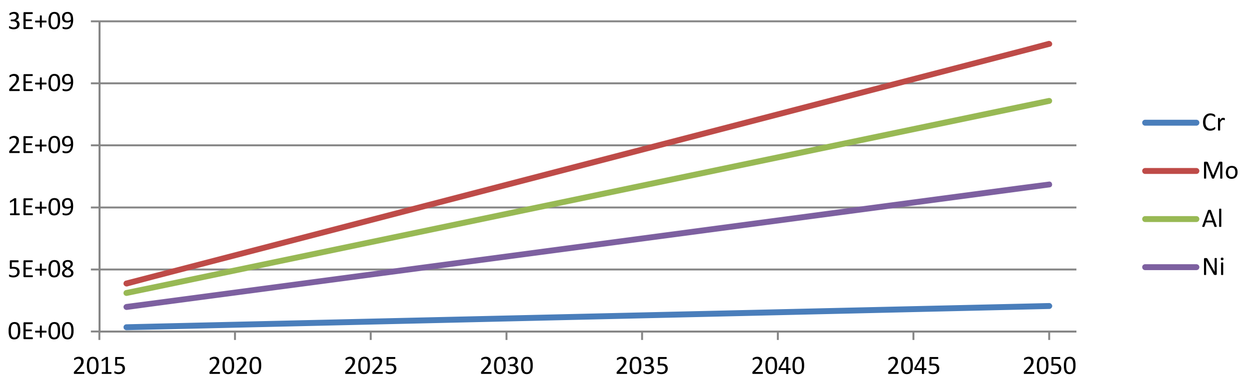

Figure 8. Al, Cr, Mo and Ni stock in use evolution (GJ).

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7.3 Material shortages due to solar thermal installations

Once different solar thermal installations are studied from a material point of view, the expected demand of materials from 2015 to 2050 can be assessed. The aim is to identify possible material shortages due to the use of solar thermal energy under a "Business as Usual" scenario. It is important to mention that the BAU scenario for material production has been built assuming that it will follow a Hubbert-curve trend.

Figure 9 compares Cu, Cr, Mo and Ni demand to manufacture solar thermal absorbers with their respective estimated production of materials.

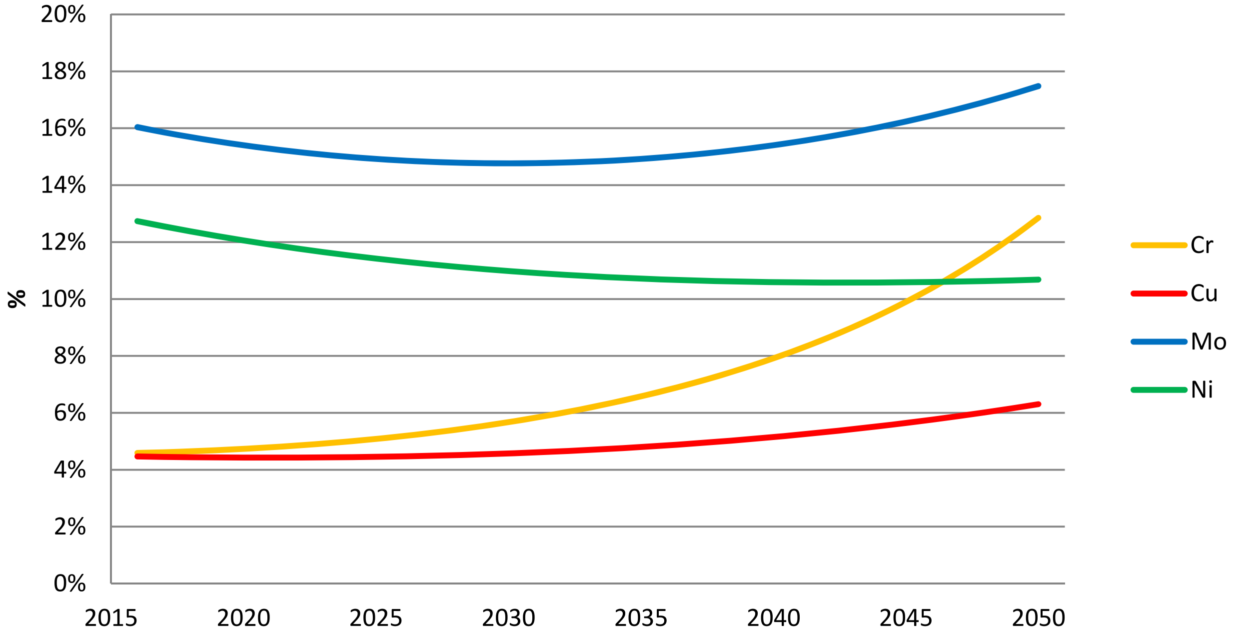

Figure 9. Cu, Cr, Mo and Ni world production and solar thermal demand projections from 2015 to 2050.

Considering just solar thermal, there is no physical constraint envisaged until 2050 for the selected materials. But it is clear that in many of these materials, the production will decrease and it will become increasingly difficult to meet the needs involving the solar thermal collectors. In addition, those metals will not only be used for this particular application and solar thermal will need to compete with other sectors for its proper development.

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Figure 10 shows the values for the rest of the materials. As in the previous case, there is no physical constraint envisages, as the comparison between demand and production does not even exceed 1%.

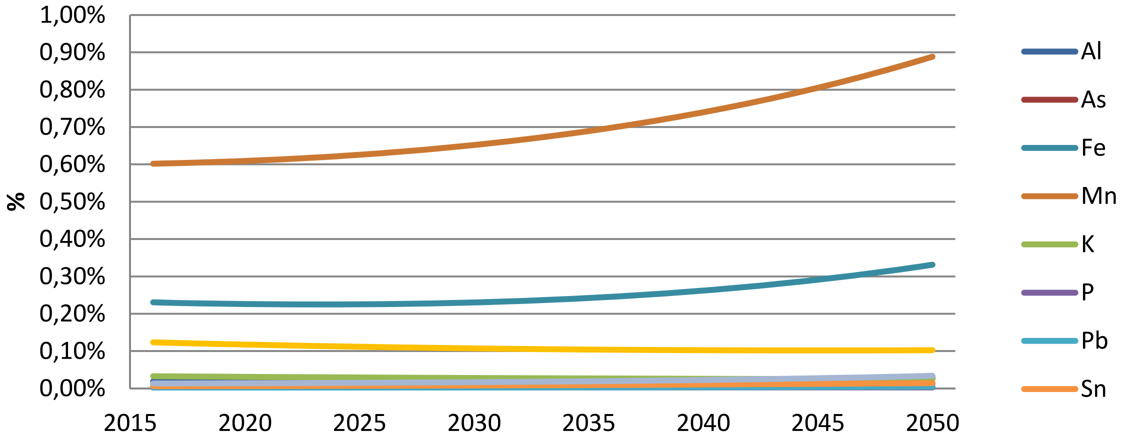

Figure 10. Rest of materials world production and solar thermal demand projections from 2015 to 2050.

The following figure shows the ratio between expecteddemand from 2015 to 2050 and current reserves values of the studied materials.

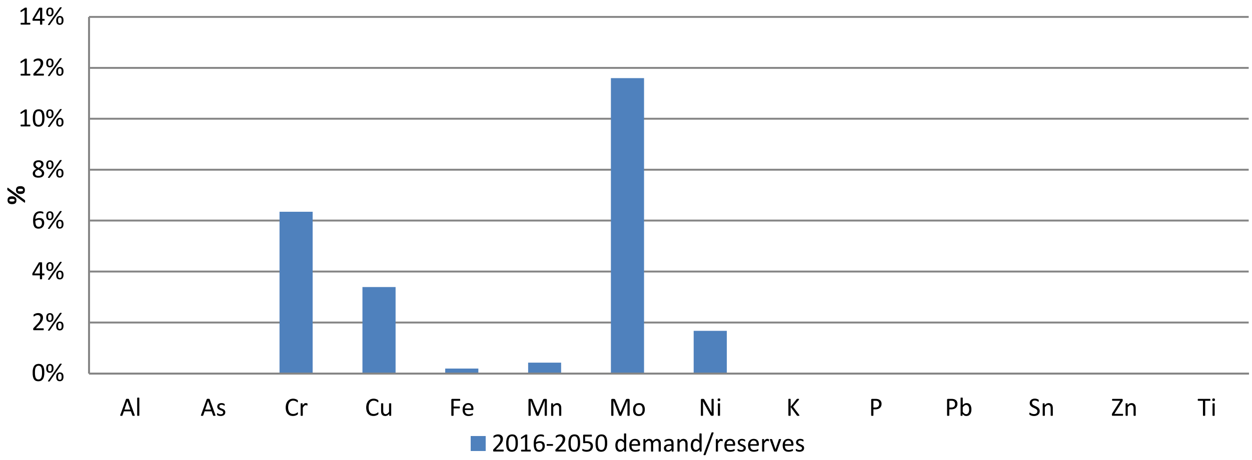

Figure 11. 2015-2050 world demand/reserves.

As can be seen from the figure, Ni, Cu, Cr, Mo demand constitute about 1.5, 4 %, 6.5 % and 12 % of their reserves value, respectively.

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7. Conclusions

The most demanded metals from an exergy - rarity (considering the criticality of minerals through exergy) point of view are: Al, Cu, Cr, Fe, Mo and Ni for FPC and ETC absorbers.

In particular, FPC and ETC have approximately the same content of exergy. FPC has a rarity content of 4.7 GJ and ETC demands 4.6 GJ.

In solar thermal absorbers manufacturing and considering a BAU scenario for metal production using a Hubbert-like tendency, there are no materials with high risk of creating bottlenecks in the future. Yet solar thermal will need to strongly compete with other applications for especially Ni, Cr and Mo used as alloying elements in steel. This is why recycling should be a priority.

On the other hand, without considering the steel alloy materials, Cu represents the material with higher demand in solar thermal absorbers manufacturing. In the same way, it should be considered within the recycling policies.

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D2.1: *Report with an analysis of the main limitations of variables and indicators selected to represent the pathways and scenarios.*

Annex 12: *Domestic storage applications and physical constraints*

Grant agreement: 691287

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TABLE AND FIGURE INDEX

1. Scope and goal

This document is part of the MEDEAS Deliverable 2.1. The main aim of this annex is to highlight some of the possible physical constraints in the electricity storage sector applied to residential uses expected from 2015 to 2050 from a material point of view.

This activity is done through an assessment of materials which will be necessary to manufacture different types of Li-based batteries from 2015 to 2050.

The results of this Deliverable will be implemented in MEDEAS model through PAVs database values. For this reason, the following table shows the information covered in this document and its link to the PAV list specified in Deliverable 2.1.

Table 1. PAVs related to storage applications and covered in this Annex.

D2.1 Results	PAV	PAV description
Energy density storage system evolution	98	Energy storage density from chemical point of view
Energy storage system evolution	99	Energy storage cost from chemical technologies
Energy density storage system evolution	100	Energy storage density from a second life
Energy storage system evolution	101	Energy storage cost from a second life
Battery Lifetime	102	Energy storage lifetime
Electricity storage linked with RES applications	106	The storage capacity linked with RES domestic applications
Transport and distributed grid material demand	107	Material demand of storage applications

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2. Introduction

The fact that in the last decades the migration to big cities has bind most of the European inhabitants together around urban environments (EEA, 2013), has led to centralize the electricity demands in big nucleus separated through large distances, joined to small population villages with small electricity demands that should be covered.

One of the main worries in the next decades, consequence of this electricity demand agglutination, will be an increase of the pressure level suffered by the transmission grids from generation points (traditional and renewable generation plants that are not usually located in the urban framework) to big cities. The use of smart grids, where renewable energy sources schemes will be integrated in the roof and surroundings of the houses, will help to reduce the grid saturation by means of self-consumption and net metering systems. These systems will also help to cover other consumer's electricity demands with the excess of electricity produced.

One of the major challenges of self-consumption and net metering in households is the disparity between power generation from renewable technologies (mainly PV in roofs) and current demand. Most of the electricity production takes place during the daytime when people are usually out of their homes. This can lead to self-consumption ratios from 17% to 44%, depending on household size and irradiation levels (Roland Berger Strategy Consultants, 2015; Dehler et al., 2015), but there is still a need of covering the rest of the demand.

The imports of electricity from other producers or from the electrical grid is an option, but the possibility to storage the excess of production to cover the peaks and the non-production periods is an alternative that could increase the self-consumption ratios and improve grid flexibility. An example of application is shown in Figure 1.

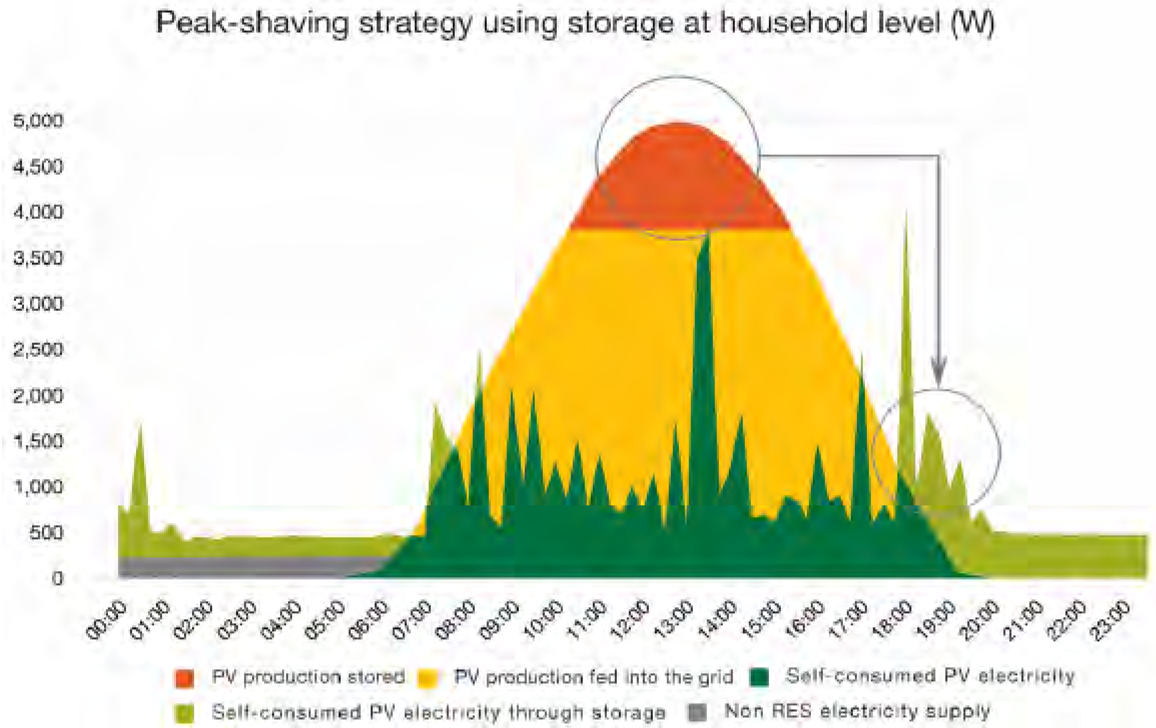

Figure 1. Example of a peak-shaving strategy using power storage (Solar Power Europe, 2015).

Electricity storage systems are made of a good number of many different materials, some of which are considered critical. Indeed, the supply of critical raw materials is an important issue that is currently regarded as a potential threat that may put at risk the so-called "Green Economy". Accordingly, a list of 20 raw materials, considered as critical taking into account risks of supply and their impact on the economy, was recently published by the European Commission (European Commission, 2014).

In the case of electricity storage systems, bromide, cobalt, iron, lead, lithium, manganese, nickel, sodium, sulfur, vanadium and zinc are found in most of the different batteries technologies. Additionally, other forms of storage as hydro storage and air compressed systems use additional metals to manufacture the proper compressors and turbines. The term "critical" as defined by the EC is not static and it can change with the socio-economic circumstances. This means that there is not a specific definition and

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hence there are more than 20 raw materials that must be considered when we talk about supply risk (Cullbrand, 2011).

In this annex, the analysis of the projection of the electricity storage systems coupled to PV roof from 2015 to 2050 have been developed from a material constraint point of view.

3. Electricity storage systems

A market analysis of the potentially electricity storage technologies indicates that there exist many different technologies that can be divided into four categories:

- **Mechanical storage:** Pumped hydro storage (PHS), Compressed air energy storage (CAES) and Flywheel energy storage (FES)
- **Electrical:** Supercapacitors (SC) and Superconduction magnetic energy storage (SMES)
- **Electrochemical:** Sodium-sulfur batteries (NaS), Lithium ion batteries (Li-ion), Flow batteries and Vanadium redox-flow batteries.
- **Chemical:** Hydrogen, Synthetic natural gas (SNG) and other chemicals as methanol, ethanol and so on.

In order to evaluate and generate projections of uses, it is necessary to know the final costs of systems that are right now under development. Establishing the correct costs for these technologies can be particularly difficult because of the limited experience of mass manufacturing. One possible alternative is to use the cost of the materials involved as an indicator because this could be a possible way to evaluate the theoretical cost reduction potential of different storage technologies.

Another factor to bear in mind is the maturity of the technologies. This will indicate the availability in the next years. Figure 2 includes an analysis of the maturity of the electricity and thermal storage systems that is currently available:

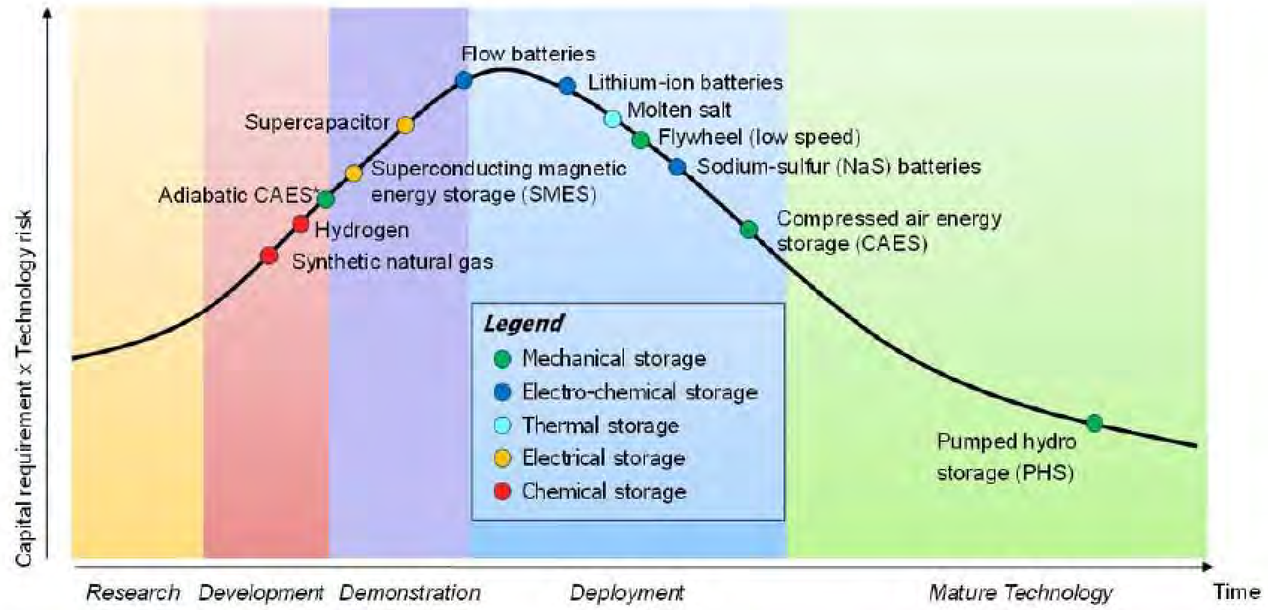

Figure 2. Maturity curve of the storage technologies (SBC Energy Institute, 2013).

As figure 2 indicates, the technologies with higher maturity from a smart grid and transmission grids application point of view are PHS, CAES and NaS batteries. In the case of Li-ion batteries, at this moment it is well established for computers and cellular applications and it is increasingly being applied to electric cars. The technical risk associated to extrapolating the current use of Li-ion to self-consumption applications in the residential sector will be much smaller than using an alternative technology not so mature.

At this moment the use of Lead-acid batteries is commonly found associated with PV off-grid systems due to a lower cost of this kind of batteries. Nevertheless the current introduction of Tesla large batteries, the prevision of a price reduction from the current 800 $/kW up to less than 200 €/kW for 2025 (ENTSOE, 2012; Roland Berger Strategy Consultants, 2015; Dehler et al., 2015) and the quite higher energy density of Li-based batteries, leads to think that this technology will be expected to be predominant in the self-consumption residential sector.

An analysis of the current status of the electricity storage systems currently working in Europe and the World indicates that Li-ion batteries is the major technology used for

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small applications (see Figure 3). Because of this, Li-based technology (and most specifically MNC/C and NCA/C technology because they are the most likely expected technologies to be implemented in the electrical mobility, see corresponding Annex) have been considered and analyzed.

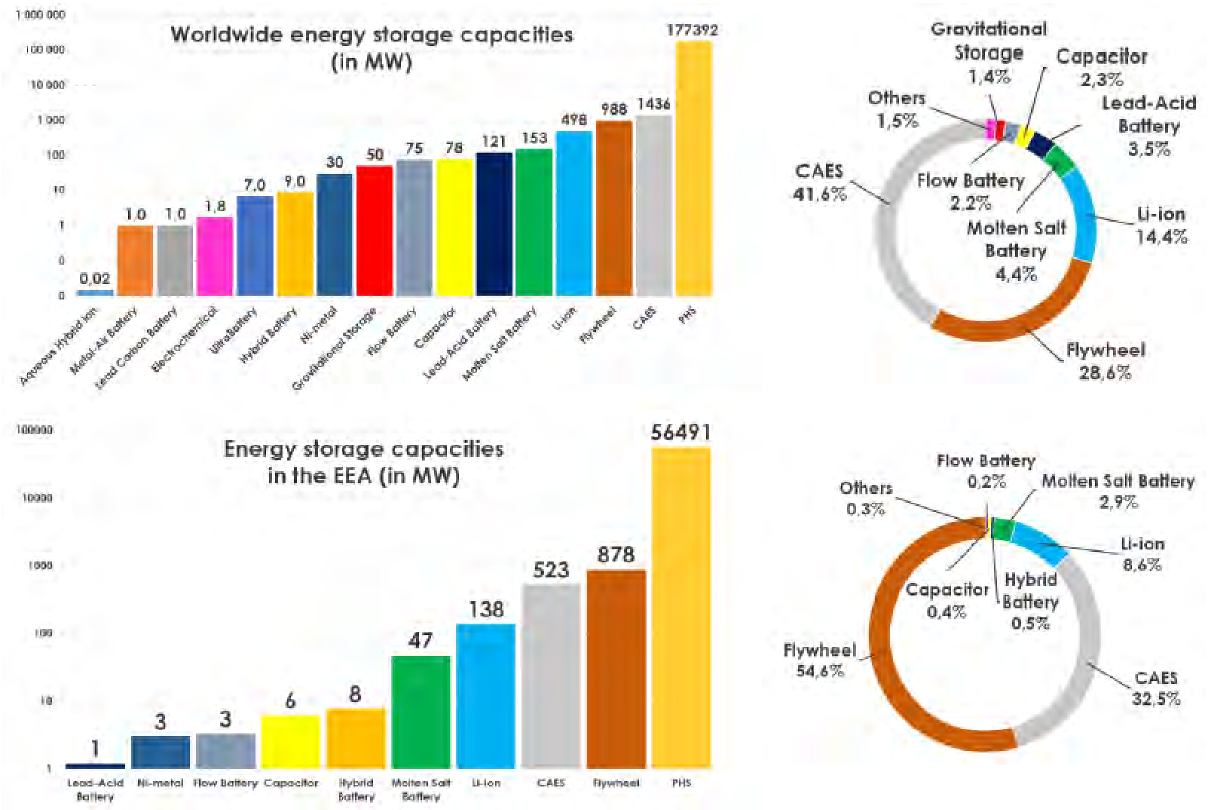

Figure 3. Storage capacity in the World and Europe and share excluding PHS technology (Normark & Faure, 2015).

Alongside maturity, the European regulations currently ruling the self-consumption and PV roof facilities, are aligned to improve the penetration of self-consumption. In the case of Germany, PV self-consumption roof systems are exempt of paying the fraction of the taxes associated to the purchase of electricity to the grid. In the case of France and UK, a reduction of Feed-In-Tariffs associated to renewable systems is the supporting methodology to move towards parity grid PV self-consumption scenarios.

According to Roland Berger Strategy Consultants (2015) and International Energy Agency (2013) the penetration of PV systems in the electrical grid is very promising

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with values up to 15% for Europe and 25% for the World of the whole electric consumption for 2040 and up to 44% of the total electricity consumption for RES systems for 2050. According to these projections, and with increasing electricity and decreasing batteries prices, the expectations of including batteries in PV roofs for self-consumption systems is also high. According to IRENA (2015) and Normark and Faure (2015) studies, values close to 15 GWh of residential power storage capacity for 2025 and 240 GWh for 2050 will be obtained.

4. Evolution of storage systems

To assess the impact of Li-based battery material demand in reserves it is important to assess the projection of storage capacity from 2015 to 2050 used in self consumption systems. According to the information found in different storage energy roadmaps (Normark and Faure, 2015; IRENA, 2015) a strong growth in the capacity of the batteries applied to self-consumption systems in the residential sector is expected in the world (Figure 4):

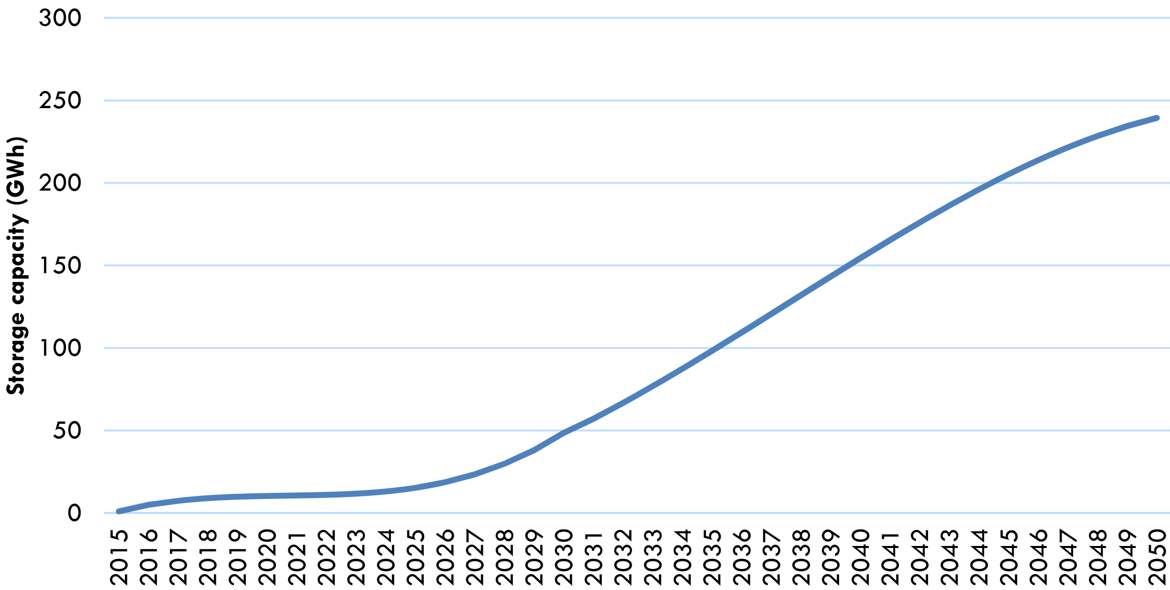

Figure 4. World electricity storage capacity in the residential sector for self-consumption.

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Figure 4 shows that an important storage capacity growth is expected in the world especially from 2030. It is not easy to find storage capacity previsions in Europe except for the current Li-based battery self-consumption inventory (140 MWh mainly located in Germany). In the case of the World, it is possible to find short term previsions but there is a lack of long term information, mainly because long term scenarios are uncertain, but a prevision of approximately 250 GWh for 2050 seems a reasonable value based on the main current manufacturer previsions.

5. Methodology

To assess the impact of different used materials, the methodology developed by (Valero and Valero, 2014) is used. This methodology covers the total life cycle, from cradle to gate including the grave to cradle approach.

- **Cradle to Gate approach:** assess the exergy cost to produce a refined metal from the mine to be used in industrial applications.
- **Grave to Cradle:** assess the exergy replacement cost to return raw materials from a dispersed state (i.e.: landfills) to the initial state in mines.

This methodology uses the concept of thermodynamic rarity (Valero and Valero, 2014). The thermodynamic rarity indicator is a rigorous exergy measure of a mineral´s quality considering physical aspects of the minerals such as natural concentration, chemical composition, comminution and energy requirements to beneficiate the given mineral.

This approach gives an additional dimension to the criticality of minerals taking into account physical aspects (scarcity in the crust and energy intensity to mine and beneficiate the mineral). Note that this new dimension is not yet included in current criticality assessments which are focused on supply risk and economic importance. Whereas the thermodynamic rarity concept is universal and absolute, the socio-economic criticality assessment is country-dependent and variable. For more information on the methodology, see Annex 5.

To identify physical constraints for batteries, a combination of bottom-up and top-down approaches will be used:

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- **Bottom-up:** assess the estimated evolution of material production according to current reserves and past production values. This method uses the Hubbert curve methodology traditionally used to assess peak oil. Reserves and production data comes from (Calvo, 2015) and are included in Annex 6.
- **Top-down**: assess the estimated demand of materials from batteries according to material´s demand and expected installation projections and recycling current figures of different studied materials.

The values used to assess materials in exergy terms are included in the following table:

Table 2. Exergy values used (GJ/ton).

	(A) Grave-Cradle	(B) Cradle-Gate	(A)+(B) Rarity
Co	10,872.00	9.20	10,881.20
Li	545.83	12.50	558.33
Mn	15.64	0.20	15.84
Ni	523.61	9.98	533.59

Considering these values, and from a rarity point of view, it can be observed that Co is by far an extremely critical metal (11 GJ/kg) compared to Mn (16 MJ/kg).

As two main Li-based technologies are expected to be implemented in the residential sector, and without technology allocation provisions, the two extreme cases (just using one technology or the other) and the average value have been analysed.

One of the main restrictions associated to the batteries is that, independently of the technology of the battery, their lifetime duration is by far lower than the lifetime of the PV modules. In order to determine the lifetime of the energy storage systems, different experimental activities have been carried out and have been published in specific literature. As a summary, independently of the type of battery, the useful life time depends on the depth of discharge and the profile of the loads. In general terms, the

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lifetime of the storage systems applied to residential loads are expected to be ranged from 6 to 8 years (Cucchiella, D'adamo, & Gastaldi, 2016), (Layadi, Champenois, Mostefai, & Abbes, 2015) and no longer than 4 years for electrical vehicles (Sarakesta-Zabala, y otros, 2016). To estimate the mass requirements of the rare metals, an optimistic reposition rate value of 8 years has been used.

Finally, the recycling rate should be considered as not the complete demand will be supplied by primary extraction. According to the report UNEP (2011), the recycling ratios for Ni, Li, Co and Mn are 29%, 1%, 32% and 37%, respectively.

6. Results

6.1. Exergy analysis per type of battery

Figure 5 shows the exergy (rarity) of the four major rare metals found in the considered Li-based batteries. The rarity value is used to evaluate the exergy requirements per kWh as the studied materials correspond to a market product.

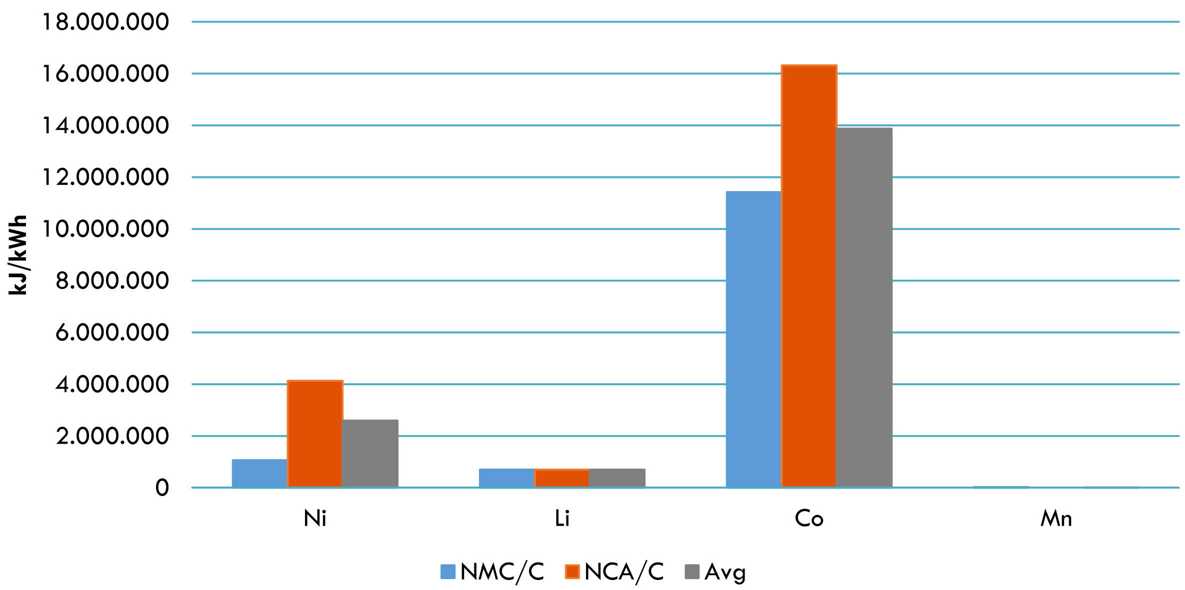

Figure 5: Mass and Exergy comparison for NMC/C and NCA/C batteries.

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As can be seen in figure 5, with the exception of Ni NCA/A battery, the mass content of metals in the batteries are in the same ranges. The conversion of such figures into exergy values through the rarity concept implies a sharp increase in the contribution of cobalt to the total because of its high physical criticality.

In Figures 6-9 the mass requirement evolution and the grave-to-cradle exergy evolution up to 2050 has been represented for each analysed metal. The inclusion of grave-to-cradle term allows shedding some light on the energy requirements to return the materials into the original concentration in the Earth as a measure of the impact that extracting these rare metals has on the environment.

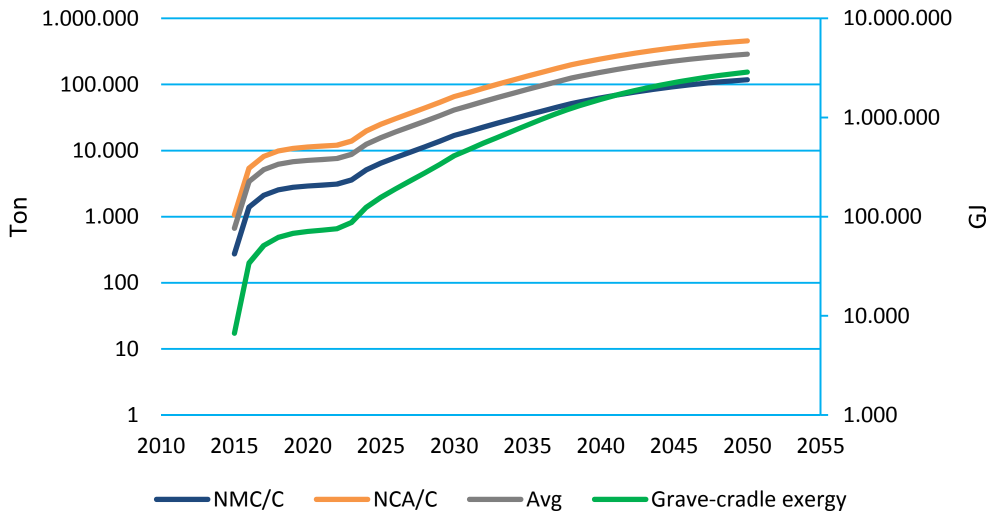

Figure 6. Ni annual requirement.

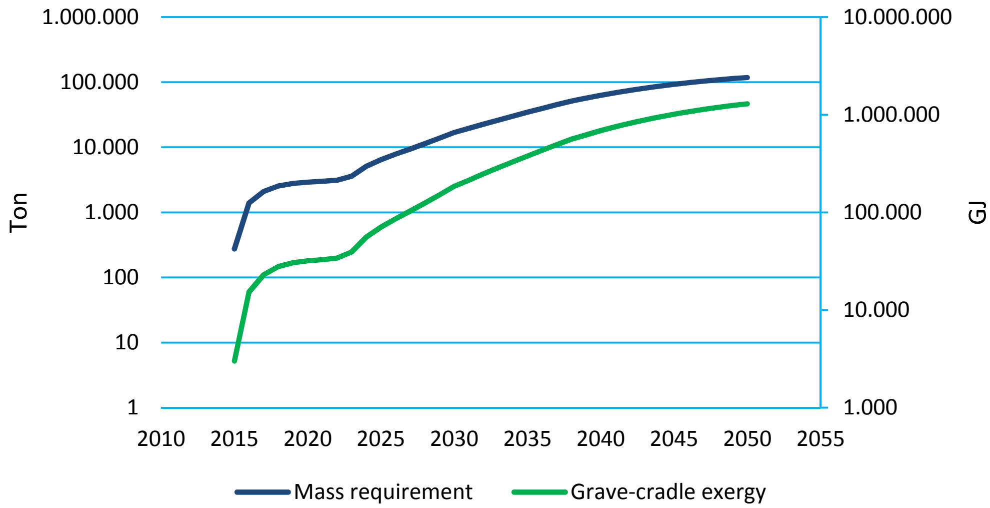

Figure 7. Li annual requirement.

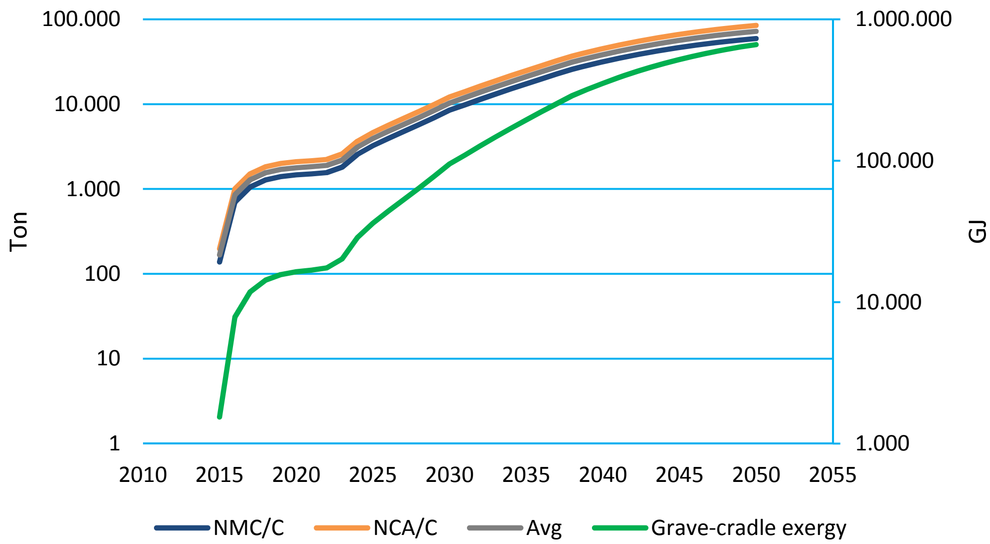

Figure 8. Co annual requirement.

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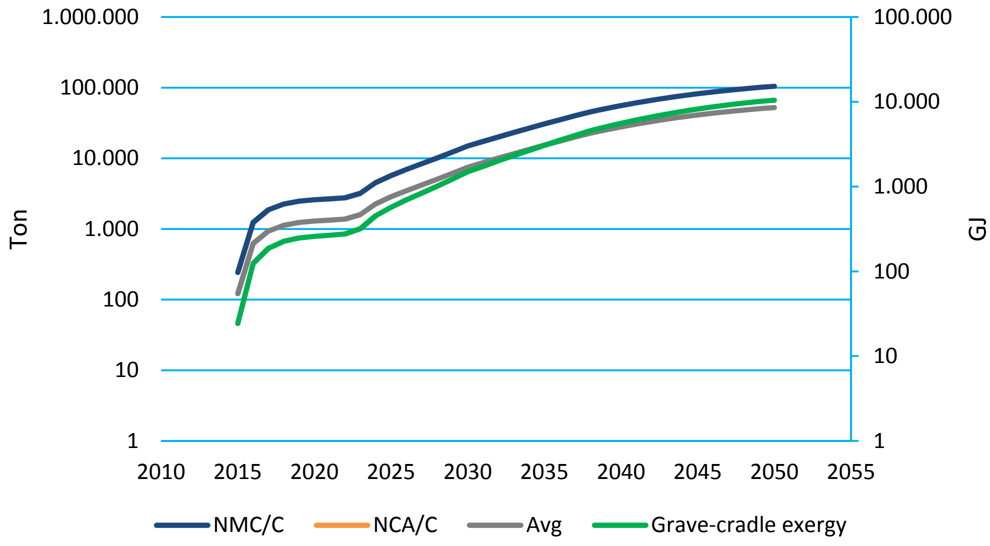

Figure 9. Mn annual requirement.

A qualitative analysis of the previous figures leads to a main conclusion: due to the replacement rate, an important growth of the metals consumption is expected from 2023.

By means of the mass – rarity (exergy) conversion ratio shown in figure 5, it is also possible to account for the embodied exergy of the Li batteries with the addition of the partial effect of each metal. This value represents a quantitative idea of the exergy requirements of extracting, manufacturing and returning the materials in batteries at their end-of-life to the original state in the mines. The annual evolution is depicted in figure 10.

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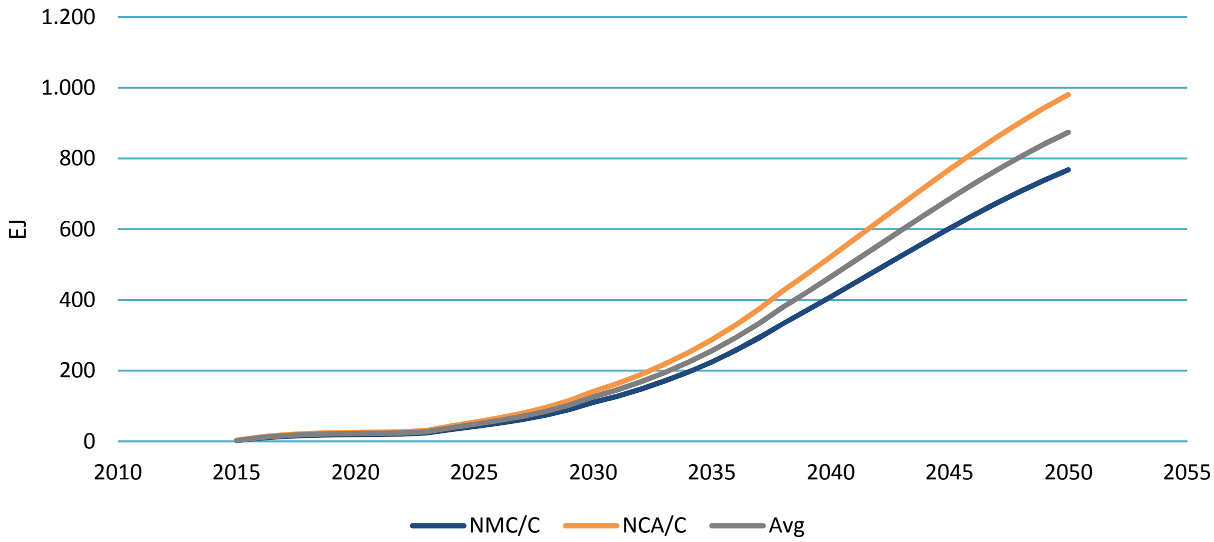

Figure 10. Embodied exergy (rarity) in self-consumption Li-based batteries for the residential sector.

An important difference between the rarity of NCA/C and NMC/C can be seen in this figure. This is due to the lack of Mn (the metal with the lowest exergy) and its replacement with Ni (with higher value) in the NCA/C batteries.

6.2. Material bottlenecks in batteries

Once the Li, Ni, Co and Mn requirements in batteries have been analyzed, expected demand for materials associated to storage systems from 2015 to 2050 are assessed. The aim is to identify possible material shortages due to the installation of batteries under a "Business as Usual" scenario. Recall that the BAU scenario for material production has been built assuming that it will follow a Hubbert-curve trend assuming available reserves as registered in 2015 by the USGS. Note that the same results are obtained using tonnage or exergy values, hence curves are shown in mass terms.

Figure 11 compares Li demand to manufacture batteries with its estimated world production using the Hubbert peak model. It can be seen that in the case of lithium it

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seems that it will not constitute a physical constraint by itself during the analysed period 2050 with the expected projections.

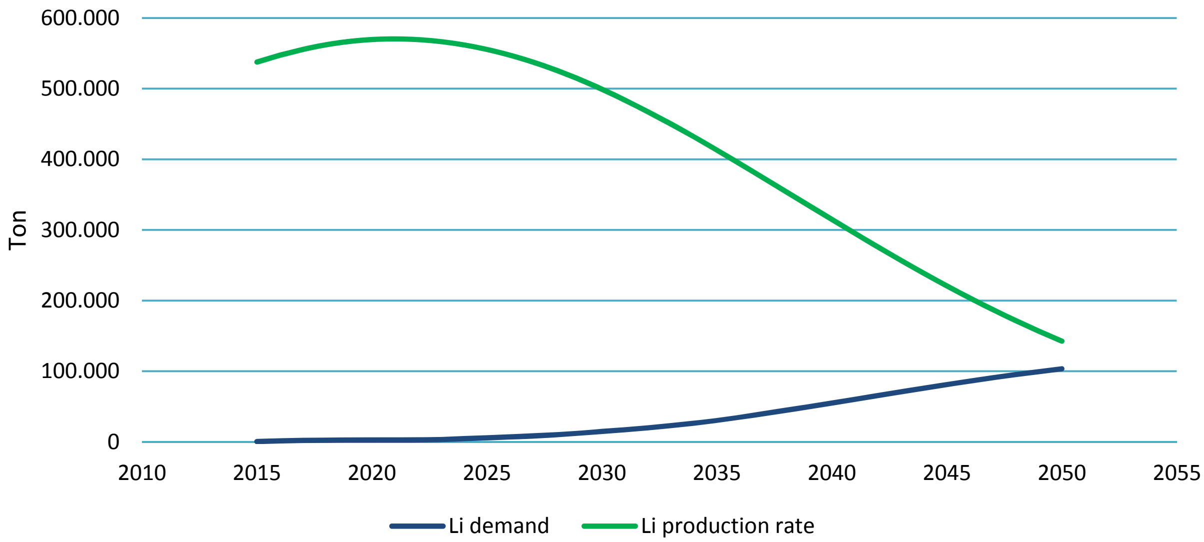

Figure 11. Li world production and demand projections from 2015 to 2050.

In the case of Ni, according to the expected requirements, it seems that in the case of a scenario with NMC/C batteries, demand for this metal could be even greater than world Ni production (Figure 12). For the other two scenarios, even if demand and production do not cross, the quantity required to produce batteries would be so high, that a large part of Ni production would be required just to supply such demand.

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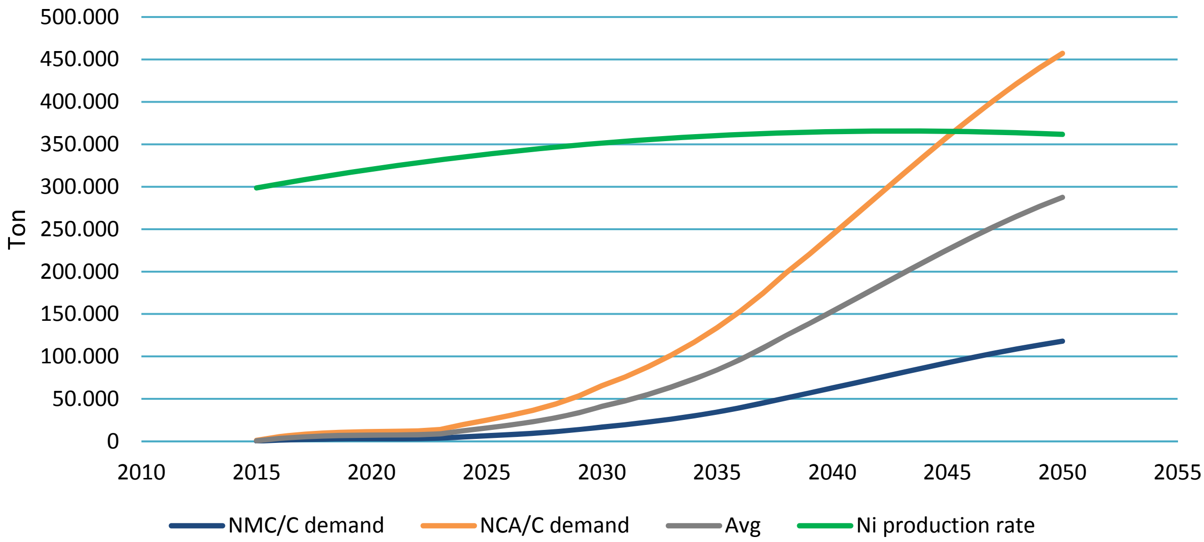

Figure 12. Ni world production and Li-based batteries demand projections from 2015 to 2050.

Figure 13 shows the values for cobalt. As in the case for Ni, most of Co world production would be required to manufacture batteries.

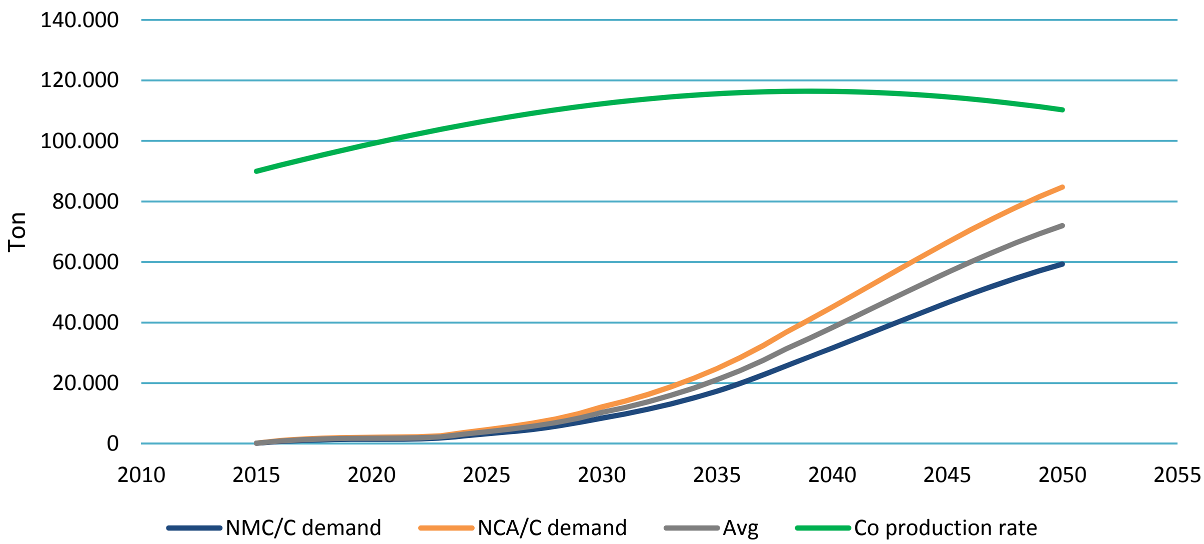

Figure 13. Co world production and Li-based batteries demand projections from 2015 to 2050.

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Finally, in the case of Mn, Figure 14 shows that this metal will not constitute a bottleneck in the analysed period.

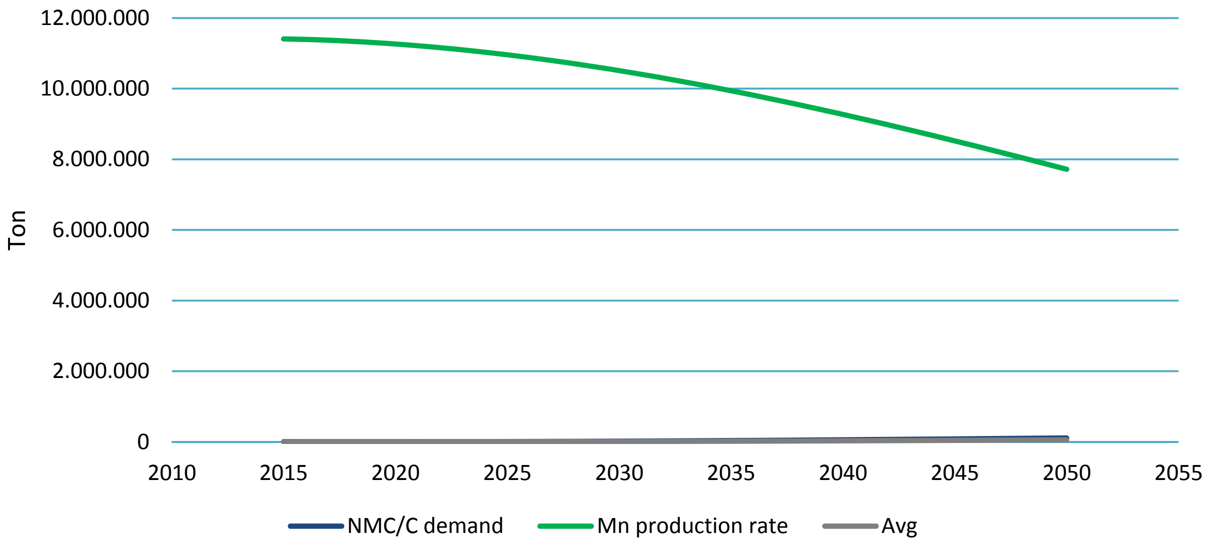

Figure 14: Mn world production and Li-based batteries demand projections from 2015 to 2050.

From the above figures it can be stated that it will be necessary to increase Ni and Co production or their recycling rates in order to fulfil the material requirements for the Li-based batteries projections in the residential sector.

Finally, considering the cumulative primary material demand from 2016 to 2050 (taking into account recycling figures of studied materials) and comparing these values with current reserves, it can be seen that geological reserves will be in principle large enough to supply the required demand (Figure 15).

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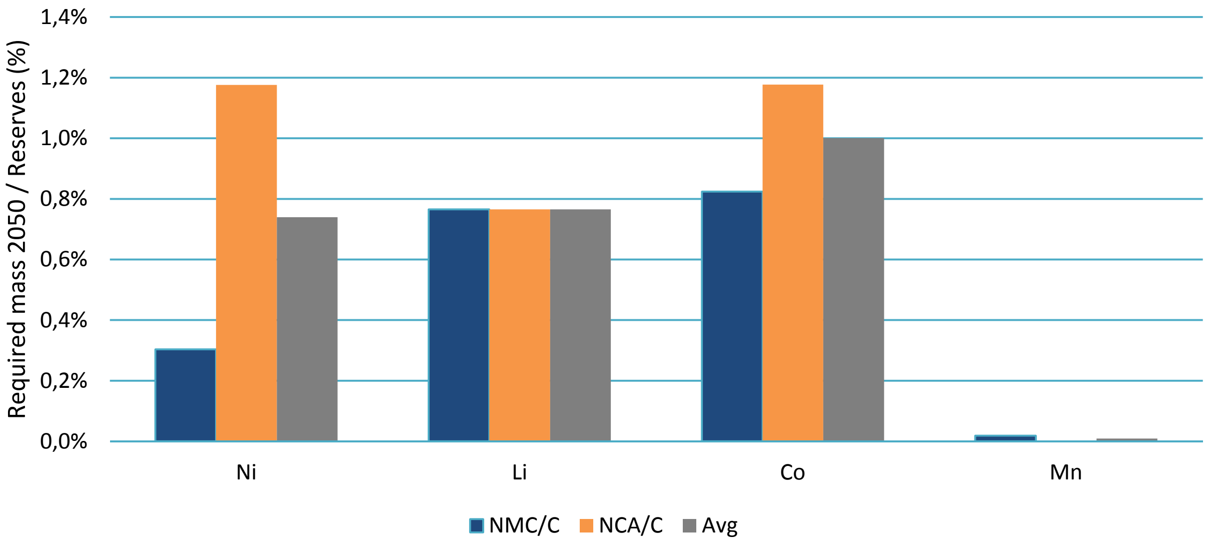

Figure 15. 2015-2050 world demand for batteries/reserves.

7. Conclusions

According to the material evaluation, Li, Ni, Co and Mn (in the case of MNC/C batteries) will be the most used materials for power storage batteries applied to self-consumption in the residential sector from now up to 2050.

In terms of rarity, MNC/C (with 770 EJ for 2050) presents a lower value of embodied exergy than NCA/C (with 980 EJ for 2050) due to the higher use of lithium instead of manganese.

Accordingly to the production provisions, it seems that with the expected projections it will be necessary to increase the cobalt and nickel manufacture rate in order to fulfil the material requirements. In this case, none of the metals present a higher demand than the available information on reserves so the production rate and no the difficulty to obtain the metals will be the limiting variable.

A possible alternative to increase the production ratio could be recycling the batteries used in the electric vehicles. At the end of their useful life, the capacity of the batteries will be enough to be used in residential application where discharge profiles are more stationary than in the case of mobility. The IRENA's report (IRENA, 2015) concludes that in 2030 there will be 250 GW of lithium batteries, being half of them second life

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batteries from electrical vehicles. In the case of reusing only 10% of those batteries to renewable systems almost all the material requirements would be covered without the need of further extraction.

Historically, the analysis of second life uses of batteries have been studied during the first decade of the XXI century (EPRI, 2000; Cready, 2003; Eyer & Corey, 2010). A more deep and recent economic analysis (Bowler, 2014) where different end of lifetime scenarios (3, 5 and 10 years) are evaluated to be integrated in a secondary value chain (i.e. residential applications) in Europe shows how reusing the batteries used in the electrical vehicles will lead to potential profits to the vehicle buyers. According to this, the first reused batteries will be available from 2017 to be completely developed as a reliable alternative at the beginning of 2023.

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