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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 6.2. Costs of the transition

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Abstract

This document describes the energy transition costs in energy, material, social and economic terms. Quantification of energy transition costs is the main object of Deliverable 6.2 of the MEDEAS project, according with tasks 6.2a (energy costs), 6.2b (raw material costs), 6.2c (social costs) and 6.2d (Economic costs) in the Work Package 6 about Impacts of energy transition. In energy terms, the model illustrates a decrease in EROI (from 12:1 to 7:1 or even 4:1, depending on scenarios) due to an increase in the energy invested within the system. The decrease in the EROI requires an overdemand and energy intensity increase between 6 to 70 %, and 6 to 40 %, respectively, depending on the scenario chosen. Simulations and risk analysis carried out with raw materials suggest that by the end of the period, the cumulated demand will be higher than the current estimated level of reserves for 11 minerals in at least one of the considered scenarios: indium, tellurium, gallium, cadmium, tin, chromium, silver, lithium, lead, zinc and manganese. Three more minerals would require at least ½ of the current reserves: molybdenum, copper and nickel. By the end of the period, the cumulated demand will be higher than the current estimated level of resources for 2 minerals in at least one of the considered scenarios: tellurium and indium. Three more minerals would require at least ½ of the current resources: silver, molybdenum and manganese. Simulations also suggest that education levels seem to correlate strongly with energy intensities of economic sectors, i.e. the higher skilled labour employed by a sector, the lower its energy intensity. Also, the model suggests that scenarios of transition with GDP growth will promote the employment until 2030, and after that the employment will decrease, presenting also negative impacts on the environment. Regarding the economic costs, the BAU scenario shows that the added-value associated with electricity production will increase 31 % in 2030, and 160 % by 2050, with similar growths for the labour compensation, and fixed capital. Instead, the Green growth scenario presents decreases of 10 % and 43 % in the added-value of electricity production for 2030 and 2050, respectively. Thus, the labour compensation will also decrease 27 % and 55 %, and the capital input will initially increase by 11 % and finally decrease by 33 % from 2030 and 2050, as a consequence of the reduction in total electricity production.

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List of abbreviations and acronyms

BAU	Business As Usual
CED	Cumulative Energy Demand
CF	Capacity factor
CSP	Concentrated Solar Power
EJ	ExaJoule (x 10^{18} J)
EnU	Energy Used
EROI	Energy return on energy investment
EROIext	Extended EROI
EROIpou	Point of use EROI
EROIst	Standard EROI
ESOI	Energy Stored on energy invested
EU	European Union 28 countries
EV	Electric vehicle
EXIOBASE	Multi-regional Environmentally Extended Supply and Use / Input Output (MR EE SUT/IOT) database
FE	Fixed Effects
FEI	Final energy invested
GDP	Gross Domestic Product
GDPpc	GDP Per Capita
GFCF	Gross Fixed Capital Formation
GG	Green Growth
GHG	Greenhouse gas
HVDC	High-Voltage Direct Current
IEA	International Energy Agency
IOA	Input-output analysis
IOT	Input-output tables
IRENA	International Renewable Energy Agency

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ISCED	International Standard Classification of Education
LCA	Life-cycle assessment
Mha	Million hectares
MLT	Mid-Level Transition scenario
MRIO	Multi-Regional Input-Output Tables
NACE	Statistical Classification of Economic Activities in the European Community
OECD	Organisation for Economic Co-operation and Development
OEU	Own-energy use
O&M	Operation and maintenance
OLS	Ordinary Least Squares
OLT	Optimal Level Transition scenario
OTEC	Ocean Thermal Energy Conversion
PHS	Pumped Hydro Storage
PV	Photovoltaic
RES	Renewable Energy Sources
RNE	Renewable and New Energy
SSP	Shared Socioeconomic Pathway
TFEC	Total Final Energy consumption
TWe	Tera-Watt of electricity
TWth	Thermal Tera-Watt
UNEP	United Nations Environmental Program
USGS	United States Geological Service
WIOD	World Input-Output Database
WP	Work Package

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Executive summary

The objective of the MEDEAS project is to provide simulation tools that facilitate the design of energy policies in the European Union to achieve a transition to a low-carbon economy. Task 6.2 analyses the costs of the energy transition from different perspectives, taking into account energetic, raw material, social and economic costs, and showing different scenarios.

In particular, subtask 6.2a is devoted to energy costs for transition. Since energy needs energy to be produced, the key concept used here is Energy Return On Investment (EROI), quantifying energy invested per unit of energy produced. Thus, the dynamic evolution of the EROI has been simulated for three 2060 scenarios (system EROI) and the EROI of the different RES technologies used for electricity generation: wind onshore, wind offshore, Solar Photovoltaic (PV) and Solar Concentrated Power (CSP). The EROIst of the system decreases while the EROIst of the individual RES variable technologies increases due to the fact that the EROI of the latter is lower than the current EROI of the full system, and their share increases over time in the simulated scenarios. The decrease in the EROI of the system (from 12:1 to 7:1 or even 4:1, depending on scenarios) has implications for the rest of the system: in order to satisfy the same level of final net energy consumption, the system needs to process more energy and materials. It has been modelled by an overdemand function. Overdemand and energy intensity increases 6 to 70 %, and about 6 to 40 %, respectively, depending on the scenario chosen.

Subtask 6.2b illustrates the raw materials needed for energy transition. The most affected technologies would be some solar PV technologies (tellurium, indium, silver, manganese), solar CSP (silver, manganese) and Li batteries (lithium, manganese). Also, transition to alternative technologies will intensify global copper demand. Furthermore, a sensitivity analysis has been performed considering the rest of the economy, so that the risk results worsen: by the end of the period, the cumulated demand is higher than the current estimated level of reserves for 11 minerals in at least one of the considered scenarios: indium, tellurium, gallium, cadmium, tin, chromium, silver, lithium, lead, zinc and manganese. Three more minerals would require at least ½ of the current reserves: molybdenum, copper and nickel. By the end of the period, the cumulated demand is higher than the current estimated level of resources for 2 minerals in at least one of the considered scenarios: tellurium and indium. Three more minerals would require at least ½ of the current resources: silver, molybdenum and manganese.

Subtask 6.2c focuses specifically on the socially necessary adaptations of the energy system transformation. Unemployment rates, consumption patterns and collaborative versus competitive

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behaviours are critical aspects that are considered to evaluate the societal influence of the transition towards a 2050 framework. Associated with these social indicators, behavioural social patterns helping to reach the objectives of 2050 are explored. A possible pattern of societal changes is analysed as bottom up as well as top-down. This means, from small groups and self-organising patterns to policy makers (bottom up) or from policy-makers to citizens and small groups (top down). This aspect is explored introducing the selected social behaviour in the MEDEAS nested model approach. Simulations suggest that education levels seem to correlate strongly with energy intensities of economic sectors, i.e. the higher skilled labour employed by a sector, the lower its energy intensity. Also, the model suggests that scenarios of transition with GDP growth promote the employment until 2030, and after that the employment decreases, and the growth levels present also negative impacts on the environment.

Subtask 6.2d tries to understand the economic costs of the energy transition to a low-carbon society by considering the changes in the added-value for two scenarios: the BAU and Green Growth (OLT), and according to three factors: total electricity production, labour compensation and capital input. The BAU scenario shows that the added-value associated with electricity production will increase 31 % in 2030, and 160 % by 2050, with similar growths for the labour compensation, and fixed capital. Instead, the Green growth (OLT) scenario presents decreases of 10 % and 43 % in the added-value of electricity production for 2030 and 2050, respectively. Thus, the labour compensation will also decrease 27 % and 55 %, and the capital input will initially increase by 11 % and finally decrease by 33 % from 2030 and 2050, as a consequence of the reduction in total electricity production.

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1. Introduction

The main result of this deliverable is the quantification of the transition costs to renewables in terms of energy, material, and social costs, according with the tasks 6.2a, 6.2b, and 6.2c.

In terms of energy and material costs, this work focuses on the global level, whose results are also qualitatively translatable to regional and national level given the similarities between current electricity systems in different countries (i.e. centralized systems highly dependent on fossil fuels) and the common challenges they face to successfully achieve the transition to Renewable Energy Sources (RES). Analyses focusing on the regional/national scale might refine the results given that those ultimately depend on geographical conditions such as the potential and quality of each RES technology as well as on national policy decisions such as the selected strategy to deal with the variability and intermittency of RES variables.

Regarding scenarios, in general, MEDEAS models use three scenarios: Business as Usual (BAU), Medium Level Transition (MLT), and Optimum Level Transition (OLT). MLT is different from OLT only by the delay on the star-up of the RES implementation policies. As a consequence, BAU and OLT are the most relevant scenarios, and they will be the most used in this report. On the other hand, in the specialized literature, the OLT scenario is frequently referred as Green Growth (GG). Thus, in this work, OLT scenario is often called GG too.

Furthermore, since the relevant environmental impacts often occur at worldwide level, many of the scenarios have been developed at this level. In any case, the scheme could be easily replicated at any level (EU or country-level models), since the structure is essentially the same in the models.

Finally, although the scenarios usually have 2050 as the horizon, sometimes the model has been run until 2060 in order to look at the future patterns in 2050.

Section 3.1. focuses on the energy investments associated to the transition to RES, including the resulting Energy Return On Investment (EROI) of the system, its systemic implications and a comparison with the literature. Section 3.2 reports the main results in relation to the material requirements associated to the transition to alternative technologies.

Also, this document presents results on necessary social adaptations of the energy system transformation as well as social costs induced by the expected transition to the low-carbon economy (section 3.3). Possible future employment structure and energy intensity linked to labour skills are critical aspects that are considered to evaluate the societal impacts and influence of the transition towards a 2050 framework.

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In section 3.3.1., social adaptions in terms of education (linked to energy intensity) necessary for the energy system transformation are explored. Economic implications helping to reach the objectives of 2050 are derived, and the associated transition patterns are considered. This subtask should follow and build on our contribution to D2.2, where we studied the links between energy and social indicators.

In section 3.3.2, critical aspects for the energy system transformation are elaborated, namely in terms of labour market changes (effects on employment structure in various sectors of the economy at the country level, impacts to low-, medium- and high-skilled labour, and also gender impacts). This part consists of literature review of the past transitions and an analysis of the current situation in terms of employment structure in the sector of electricity production.

In section 3.3.3, social patterns helping to reach 2050 objectives are researched. Based on the analyses in section 3.3.2, social patterns helping to reach the 2050 energy transition are elaborated. The analyses of predictive relations of GDP (total output of the economy), gradual shift from using fossil fuels in the sector of electricity production, and potential employment effects, using input-output analysis and World Input-Output Database's (or other suitable source such as EXIOBASE) social accounts as data source, are carried out.

The focus on labour market effects is also done in terms of impacts of the transition on skilled/unskilled labour and on gender (male/female). This focus is necessary to make sure that the transition is feasible and sustainable not only in terms of environment, but also in terms of human activity to be performed.

Section 3.4. deals with the Economic costs of transition by using key socio-economic indices and variables, such as added-value, operating surplus, fix capital consumption, labour compensation (section 3.4.1). Also, it illustrates the allocation of financial and material resources in different electricity sectors by presenting the economic input of materials, employment, capital and other primary factors to produce one unit of electricity production (section 3.4.2). In addition, total economic cost of switching fossil fuels to renewables by 2030 and 2050 has been calculated under two future scenarios, the Business-as-usual (BAU) scenario and the green growth (OLT) scenario using the estimated future EU IO tables (sections 3.4.3 and 3.4.4).

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2. Methodology

2.1. Energy Return on Investment

The transition from fossil fuels to RES is an indispensable condition to achieve sustainable socio-economic systems. Despite their indisputable environmental and social benefits (e.g. lower pollution (IPCC, 2014)) and the possibility to be managed at local, participative level (Becker and Kunze, 2014), the technical performance of RES technologies can be, in some cases, worse than those of fossil fuels. In fact, fossil fuels are characterized by favourable physical-chemical properties (e.g. high-power density, storable, inert at standard ambient conditions, etc.) that allow manageable, high-quality energy flows to easily supply human societies. In contrast, RES technologies generally require more land surface (i.e. lower power density, (Capellán-Pérez et al., 2017b; MacKay, 2013; Scheidel and Sorman, 2012)), their use competes with other processes of the biosphere, while those with a higher potential (i.e. wind, solar) are critically affected by their intermittence and variability (MacKay, 2013; Trainer, 2012; Wagner, 2014) and have been generally found to have lower EROI, the energy delivered from a process divided by the energy required to get it over its lifetime, than fossil fuels (Hall, 2017a; Hall et al., 2014) (see Eq. 1).

$$EROI = \frac{energy\ returned}{energy\ invested} \qquad \text{(Eq.1)}$$

$$Net\ energy = energy\ returned \cdot (1 - \frac{1}{EROI}) \qquad \text{(Eq.2)}$$

Considering the EROI allows to take a “net energy” approach in energy systems analysis (see Eq. 2), which represents a number of advantages in relation to the conventional “gross energy” approach:

- From a societal/metabolic point of view, the relevant dimension is the energy available to the society (not the energy produced by power plants). In fact, a favourable EROI over the long-term has been identified as an historical driver of evolution and increasing complexity (Hall, 2017b; Hall and Klitgaard, 2012; King, 2016).

- From a technical point of view, the EROI metric allows to internalize factors that affect the whole energy system that are not captured by the monetary costs of individual power plants (such as the additional costs for the system related with distribution, intermittency of RES, etc.). In fact, the energy transition to new energy resources and new energy conversion and storage devices will affect the fraction of energy reinvestment, which may have significant

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economic impacts (Barnhart et al., 2013; Carbajales-Dale et al., 2014b, 2014a; Dale et al., 2012a; Day et al., 2018; Hall et al., 2009; Palmer, 2017; Sers and Victor, 2018)

- Computing the EROI of each technology endogenously and dynamically allows to detect potential harmful situations of increasing gross energy output while decreasing the net energy delivered to the society, i.e. the so-called "energy trap" (Kessides and Wade, 2011; Zenzey, 2013). The relationship of EROI to net energy is non-linear, and consequently its impact can potentially be misjudged. In extreme cases, a too low EROI, even if the gross energy consumption is increasing, may even trigger a collapse of the full system. In this sense, the net energy approach allows to endogenize the concept of minimum EROI for maintaining the level of prosperity of a given society (Brandt, 2017; Hall et al., 2009)

Much work has been carried out to estimate the EROI of individual RES technologies (Bhandari et al., 2015; de Castro et al., 2014; De Castro and Capellán-Pérez, 2018; Hall et al., 2014; Kubiszewski et al., 2010; Price and Kendall, 2012; Prieto and Hall, 2013; Weißbach et al., 2013); however important differences exist depending on the technology, system design and location, and the field is plagued with methodological discrepancies related with the functional units (e.g., a MJ of heat energy versus a MJ of grid electricity) or the boundaries of the analysis (i.e. mine-mouth vs end use or energy technology vs energy system) (De Castro and Capellán-Pérez, 2018; Ferroni and Hopkirk, 2016; Hall and Klitgaard, 2012; Murphy et al., 2016; Prieto and Hall, 2013; Raugei et al., 2017). In relation to the boundaries of the analysis, different EROI categories have been defined (Hall et al., 2014):

- Standard EROI (EROIst): it includes the direct (i.e. on site) and indirect (i.e. offsite energy needed to make the products used on site) energy requirements to get the energy (e.g. build, operate and maintain a power plant). This EROI calculation is applied to fuel at the point where it leaves the extraction or production facility (well-head, mine mouth, farm gate, etc.). This approach allows for the comparison of different fuels even when the analysts do not agree on the rest of the methodology that should be used (Murphy et al., 2011).

- Point of Use EROI (EROIpou): it includes the energy costs to get and deliver the fuel to the point of use of society (e.g. transportation, etc.).

- Extended EROI (EROIext): it considers the energy required to get, deliver and use a unit of energy, i.e. the energy required to produce the machinery and devices used to build, operate and maintain a power plant or a transportation facility (tank truck, pipeline, etc.) as well as

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the energy required for exploration, investment, communication, labour, etc. in the energy system.

As the boundaries of the analysis are expanded, the energy cost of getting it to that point increases, resulting in a reduced EROI (EROIst > EROIpou > EROIext). In parallel, the complexities and uncertainties to estimate each EROI category also increase by expanding the boundaries.

Thus, it is of key importance to understand both the socioeconomic and technical consequences of the large-scale replacement of fossil fuels with RES. In this sense, it is important to properly estimate the future trends in the EROI of future energy fuels, and in particular of renewable energy systems, which will be affected by factors of opposite sign: on the one hand, the EROI may increase due to technological innovation (not to confound with learning rates (Pillai, 2015) or improved mineral recycling rates. On the other hand, different factors will tend to decrease the future EROI of the system, such as the need for increased back-up generation, grids and storage (Clack et al., 2017; Hall, 2017a; Raugei et al., 2015; Weißbach et al., 2013), the increase in energy requirements due to the ore decrease of minerals (Calvo et al., 2016; Mudd, 2010), the need to allocate increasing resources as defensive expenditures to adapt and overcome climate change impacts (Capellán-Pérez and de Castro, 2017; Dietz and Stern, 2015), etc.

The literature review reveals that recent work has been directed to estimate both (1) the historic evolution EROI of existing national energy systems, and (2) the EROI associated to high RES penetration scenarios. A diversity of methodologies is being applied. In relation to the estimation of the historic evolution of the EROI of national energy systems, Lambert et al., (Lambert et al., 2014) developed a proxy method to estimate the standard EROI of a country including all domestic and imported energy fuel sources that a nation uses, considering that there is a relation between EROI and fuel prices. The method was then applied to numerous countries, finding a wide range between 5:1 and 40:1. Brand-Correa et al. (2017) estimated the evolution of the EROI of UK (standard developing a novel method combining physical and monetary data using Multi-Regional Input-Output data and an energy extension, finding that the EROIext of the country has declined from ~14:1 in 2000 to below 6:1 in 2012 (with an equivalent EROIst of 17:1 and 9:1, respectively).

In relation to the estimation of the EROI associated to high RES penetration scenarios, Trainer (Trainer, 2018), considering usual EROIst values by technology from the literature, estimated at 5.9:1 the EROI of the electricity system of Australia associated with the 100% renewables electricity mix proposed by Lenzen et al. (2016). Limpens and Jeanmart (2018) have developed a novel and more sophisticated approach in which the maximization of the EROI of the Belgian electricity system allows to find an optimal mix of generation and storage technologies (pumped hydro storage,

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batteries and power to gas) with 1-hour resolution. The found values for the EROI of the system range 9.7:1 (“net EROI” following their nomenclature) for a penetration of RES of 20%, and decrease to 5.4:1 for 100%. Palmer (Palmer, 2017) developed a framework for estimating EROI of energy systems including storage options, and Barnhart et al., (Barnhart et al., 2013) included both storage and curtailment. The GEMBA model (Dale et al., 2012b) considers a dynamic function over time of the EROI of each renewable and non-renewable resources, assuming a peaking function which is a product of two components: one technological that serves to increase energy returns as a function of production (which may serve as a proxy measure of experience), i.e. technological learning; and the other diminishing energy returns due to declining physical resource quality (for more details see (Dale et al., 2011)). The main finding of the GEMBA model is that growth of the renewable energy sector may impact investment in other areas of the economy and thereby hinder economic growth.

The aforementioned studies apply the EROI as a static concept, i.e. assuming that the energy invested is proportional to the energy obtained along the lifespan of the functioning power plant. However, in reality power plants require energy investments upfront to construct, providing energy returns only over the lifespan of the facility.[1] This representation worsens the negative implications of potential “energy trap” scenarios. In this sense, different works have focused on the dynamic integration of EROI to obtain more realistic results (Kessides and Wade, 2011; Neumeyer and Goldston, 2016; Rye and Jackson, 2018; Sers and Victor, 2018; Sgouridis et al., 2016). Sgouridis et al. (2016) build a global energy model dynamically accounting for the up-front energetic costs of CSP, PV and wind based on standard EROI values from the literature, and focused on the estimation of the optimal growth rate of these technologies to achieve system decarbonisation and providing a certain level of per capita net energy available to society. Sers and Victor (2018) construct a model that includes the EROI metric (considering a decline with cumulated installed capacity) and the energy characteristics of renewable generation into a macroeconomic framework, finding that renewable investment rate has the potential to crowd out other forms of investment leading to a declining economic growth rate in scenarios of strong emissions mitigation as the ones required to avoid dangerous climate change, in accordance with results presented in Dale et al. (2012b). King and van den Bergh (King and van den Bergh, 2018) analysed the implications in terms of net energy use of the scenarios proposed by the IEA & IRENA (IEA and IRENA, 2017) (framed in gross energy),

[1] In the words of Sers and Victor (2018): “Renewables, which require energy investment upfront to construct, provide energy returns only over the lifespan of the technology. In simple terms, a unit of energy invested in oil might provide 20 units of energy returned if used immediately; this same unit of energy, if invested in photovoltaics, might provide an energy return of 10 but only over time. That the energy return on renewables is not fully available “upfront” but available only over some life-cycle presents a substantial difficulty in the rapid transition to renewables as a large energetic investment must be made initially without a commensurate energy return.”

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considering a range of EROI for energy technologies, identifying a potential “energy trap” scenario when considering EROI of technologies from the lower range of the literature. Additionally, they analysed the additional growth of solar and wind to maintain the present net energy returns, concluding that these power sources should grow two to three times faster than in other proposals.

The representation of the net energy approach in the MEDEAS model is currently implemented in the electricity sector and includes 3 key novelties which go beyond the current state-of-the-art of the field by including:

1. Dynamic and endogenous calculation of the EROIst of each RES variable technologies for electricity generation taking as a starting point the materials required in the construction, operation, maintenance and dismantling phases and combining this data with the energy consumption per unit of material consumption from Life Cycle Analysis (LCA). For RES dispatchables, the EROI static approach is taken.

2. Dynamic and endogenous computation of the EROIst of the whole energy system. Given that in energy systems operating technologies are complementary and dependent, it is not possible to allocate the requirements of overgrids, storages and overcapacities to any specific technology (Trainer, 2018). Hence, it is not appropriate to estimate the EROI of full energy systems by using estimates of “buffered” EROIs for each individual renewable technology (Capellán-Pérez et al., 2017b; De Castro and Capellán-Pérez, 2018; Weißbach et al., 2013), although this approach may be useful for other purposes such as identification of the implications for intermittency management that these technologies introduce in the system). In this work a step further is performed in relation to previous works by jointly considering the implications of complementarity and intermittence of different RES sources for the EROI of the system. This way, the required overcapacities, storage and overgrids are not assigned to a particular technology but to the whole energy system.

3. Incorporation of the implications of the variations in the EROI of the system for the whole system due to the use of an energy-economy-environment model with interlinks between different dimensions allowing to account for the net energy actually available for the society.

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2.2. EROI of the energy system

Figure 1 represents the energy metabolism of our society with different energy flows and conversions, from primary sources to the energy delivered to society. Each arrow from Figure 1 represents: (0) Primary sources of energy available to society; (1) Useful energy used by society; (2) Direct (i.e. on site) and indirect (i.e. offsite energy needed to make the products used on site) energy requirements to build, operate, maintain and disposal the plant of energy generation; (3) Additional energy requirements so the system correctly manages RES intermittency; (4) Energy used for distribution of energy; (5) Energy requirements to build the machines and infrastructure required to construct the machines and infrastructure, which allows making the energy investments (2), (3) and (4). Note that, in fact, this is a recursive process and a Taylor series can be identified (Capellán-Pérez et al., 2017b).

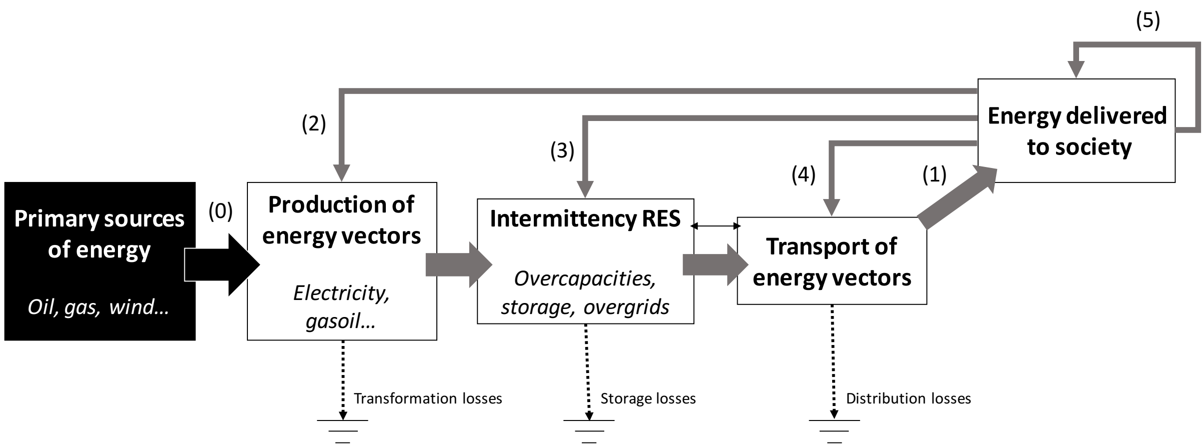

Figure 1. Representation of the energetic metabolism of our society.

At the same time, grey arrows refer to energy flows that are usable by human societies. The black arrow on the left-hand side (0) is a flux of materials with potential energy, which can be transformed into usable energy. Dashed vertical arrows represent energy losses at each phase of the chain (transformation, storage and distribution losses). An exosomatic intermediary (arrows 2, 3, 4 and 5) is always required to transform the potential energy into useful exosomatic energy usable by the society (1) (excluding non-energy uses). White color refers to the anthroposphere and black color to the biosphere, which encompasses it. The thin arrow between "Intermittency RES" and "Transport of energy vectors" represents the fact that the electricity transmission and distribution losses are dependent on the share of RES in the electricity mix. (Size of arrows is not at scale).

The EROIst of the system is defined in this work as the ratio between the final energy delivered to society and two factors: the energy requirements to build, operate, maintain and dispose the plant

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of energy generation, as well as the energy requirements so the system correctly manages RES intermittency ($EROI_{system}^{st}$, Eq.3):

$$EROI_{system}^{st} = \frac{(1)}{(2)+(3)} \tag{Eq.3}$$

Note that for an individual technology, its EROIst is usually defined in the literature as (1)/(2) (De Castro and Capellán-Pérez, 2018; Raugei et al., 2017).

If extending the boundaries, i.e., including more factors such as the energy required for the distribution of the final energy to the point of use, the EROI of the system from a "point of use" approach ($EROI_{system}^{pou}$, Eq.4) can be defined as follows:

$$EROI_{system}^{pou} = \frac{(1)}{(2)+(3)+(4)} \tag{Eq.4}$$

A step further would be to account for the total energy requirements (Eq. 5, see Figure 1) to make the energy investments (2), (3) and (4). This way we would arrive to an "extended" definition of the EROI of the system:

$$EROI_{system}^{ext} = \frac{(1)}{(2)+(3)+(4)+(5)} \tag{Eq.5}$$

The resulting net energy available to society can be obtained as (Eq.6):

$$Net\ Energy = (1) - (2+3+4)) \tag{Eq.6}$$

Discretionary uses of the energy are not energy system related uses of energy, will be:

Discretionary energy uses = Net energy – (5) = (1) – (2+3+4+5)

To be viable, any system requires that Net Energy>0. Additionally, any complex system requires that discretionary energy uses>0 in order to allow for the system to have energy available for other uses than self-maintaining the system.

What are the implications of different EROI of the system levels for the net energy and discretionary uses delivered to society? Figure 2 represents at scale the energy flows to deliver the same net energy to society associated to a "high" (EROIpou=12 and g=0.7) and "low" (EROIpou=2.5 and g=0.8) EROI of the system, respectively. At "high" EROI system levels, the energy investments for delivering

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energy to the consumers are relatively small, and there is not a large difference between final and net energy delivered to society. However, at "low" EROI system levels, the energy investments have reached such a relative size that the primary energy supply have to increase substantially (hence increasing the associated environmental impacts). In the case of accounting for (5)[2], the discretionary energy uses for society would be even smaller.

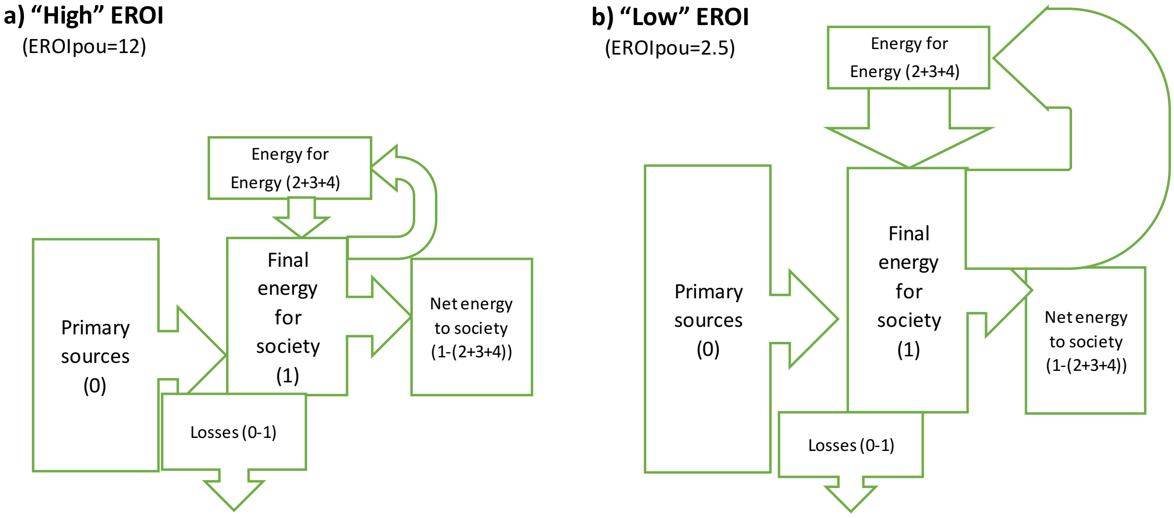

Figure 2. Representation at scale of the energy flows associated to the same level of net energy delivered to the society in the case of (a) "High" EROI, and (b) "Low" EROI.

As aforementioned, ideally, the concept of EROIext should be used when assessing systemic implications of the variation of EROI over time. However, the practical estimation of EROIext is very complex and subject to many uncertainties. To date, few studies have attempted to evaluate it estimating the economic costs associated with the construction of the energy system, and using average energy intensities to transform monetary costs to energy inputs (Ferroni and Hopkirk, 2016; Prieto and Hall, 2013). This methodology and their results are questioned by other authors given the uncertainties in these calculations (Raugei et al., 2017; Raugei and Leccisi, 2016). The EROIpou of the system also faces methodological challenges given the difficulties to consistently estimate the energy investments associated with the transportation of energy vectors, such as pipelines, electric grids, fuels for tank trucks, oil tankers and gas tankers, but also the share attributable to energy distribution of energy investments to build and maintain roads, railways and other transportation methods which have double uses (Hall et al., 2009). Acknowledging the difficulties to compute the EROIext based solely in physical terms (i.e. avoiding the controversy of the energy intensities

[2] Numbers refer to Figure 1.

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methodology) as well as the EROIpou, a first step, conservative approach, is taken in this work estimating the EROI of the system from a standard ($EROI_{system}^{st}$) approach.

The following assumptions are taken to compute the $EROI_{system}^{st}$ in this work:

- For the sake of simplicity, the EROIst of non-renewable energy sources (oil, gas, coal and uranium) is assumed to be constant over time. This simplification can be considered as conservative, given that in the long term the EROI of these fuels will tend to decrease. Indeed, recent analyses have found that the trend is already decreasing for fuels such as oil and gas (Gagnon et al., 2009; Hall et al., 2014).

- The EROIst is dynamically estimated for renewable technologies for the generation of electricity. The EROIst of other renewables such as liquid biofuels or technologies for heat generation is considered to be constant over time.

- Option of allocation of technologies based on their relative EROIst buffered with energy investments to manage intermittency (higher EROI technologies tend to cover a larger share of the energy capacity demand).

- Overcapacities and overgrids[3] related to the increasing penetration of variable renewable technologies in the system are endogenously obtained in the model (see Supplementary Online Material). Overcapacities reduce the effective capacity factor of each technology (Capacity Factor (CF), i.e., the ratio of the actual electrical energy output over a given period of time to the maximum possible electrical energy output over the same amount of time), which also reduces its EROI. Overgrids (high power and High-Voltage Direct Current (HVDC)) are modelled as an additional component of the material intensity (kg/MW) of the construction of new capacity for each RES variable technology, as described in Capellán-Pérez et al. (2017a)..

- Additional losses due to storage use are modelled following Barnhart et al. (2013). The reduction of EROIst at grid scale depends on the ratio of electrical energy stored over the lifetime of a storage device to the amount of embodied electrical energy required to build

[3] Overgrids related to the increasing penetration of variable renewable technologies would more precisely correspond to the concept of EROIpou. However, given that most of energy investments associated to the EROIpou are missing in this work, the nomenclature of EROIst of the system is kept. Moreover, sensitivity analysis shows that overgrids contribution to the EROI is substantially lower than other components (see section 3 on Results).

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the device (i.e. an analogy to EROI for storage technologies, the Energy Stored on Energy Invested (ESOI)); the stored fraction (φ) energy that would have been curtailed without storage[4] and the efficiency of the electric storage (η). In particular, for a given RES variable technology i, the following equation is applied (Eq.7).

$$EROIst_i^{grid} = \frac{1-\varphi_i+\varphi_i\eta_c}{\frac{1}{EROIst_i}+\frac{\varphi_i\eta_c}{ESOI_c}} \quad \text{(Eq.7)}$$

η_c represents the combined storage efficiency of PHS (Pumped Hydro Storage) and EV (Electric Vehicle) batteries and $ESOI_c$ represents the combined energy stored on electrical energy invested of PHS and EV batteries. φ is fixed at 20%.

Points 1 and 2 are modelled assuming that the ratio of energy industry own-energy use in relation to the total final energy consumption (excluding non-energy uses) is constant over time (data from IEA Balances (IEA, 2016)).

Summarizing, MEDEAS dynamically accounts for the EROIst of the system as follows:

$$EROI(t)_{system}^{st} = \frac{TFEC(t)}{g(t)\cdot(OEU(t)+TFEI(t)_{RES\ elec}+TFEI(t)_{storage\ elec})} \quad \text{(Eq.8)}$$

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

$TFEI_{RES\ elec}$: total final energy investments for renewable technologies of electricity generation.

$TFEI_{storage\ elec}$: total final energy investments for storage of electricity.

OEU: Energy industry own energy use.

g = final to primary energy (1)/(0) (see Figure 1).Different authors use different criteria for the value of g depending on the assumption about the quality of the electricity in relation to the rest of the energy consumed. Since we start for the calculation of the EROI from the final energy (1) and the electricity is not the only final form of energy in the system it is inferred that to give the same energy services to the society less final energy (1) will be required as the system evolves towards sources of greater exergy (e. g. the share of electricity in the full energy mix increases); to be able then to compare between evolving energy systems, here, we follow the approach defined in (De Castro and Capellán-Pérez, 2018) and compute g as the ratio between the final energy and the primary energy

[4] This factor is exogenously set ad hoc to 0.2 in all simulations. Sensitivity analysis showed that results are not sensitive to this factor. Sgouridis et al. (2016) consider a similar (*ad hoc*) value of 10% for this parameter.

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consumed in the whole system (excluding the energy dedicated to non-energy uses). The dynamic implementation in a full energy model allows to endogenize the g factor dynamically, given that the transformation of primary energy to final energy will change during the transition to renewables.

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2.3. EROIst of RES technologies for electricity generation

The construction of power plants requires a large upfront energy investment, providing energy returns only over the lifespan of the facility partially compensated by the energy requirements of the operation and maintenance activities, which is followed by another phase of energy investment for decommissioning of the facility. In cases where the information about the energy required in each phase are available, a dynamic approach can be applied for the estimation of the EROI of the technology (Kessides and Wade, 2011; Neumeyer and Goldston, 2016; Sgouridis et al., 2016). Otherwise, a static approach assuming that the energy invested is proportional to the energy obtained along the lifespan of the functioning power plant has to be adopted.

2.3.1. Dynamic expression of EROIst per technology

To estimate the EROI of RES technologies for electricity generation we apply the classic definition of standard EROI (Hall et al., 2014) assuming g=1. For a technology i, the EROI over the whole lifetime of the infrastructure is defined from a "static" perspective (Eq.9), and the annual electricity output is given by Eq.10:

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

$$= \frac{Annual\ elec\ output_i \cdot lifetime_i}{\left(EnU_i^{New\ cap} \cdot (1 + Decomm + GCF_i) + EnU_i^{O\&M} \cdot lifetime_i\right) + Annual\ elec\ output_i \cdot lifetime \cdot SC_i} \quad \text{(Eq.9)}$$

$$Annual\ elec\ output_i = CF_i \cdot Installed\ new\ cap_i \cdot 8760\frac{h}{yr} \quad \text{(Eq.10)}$$

Where,

i: electricity generation technology; Annual elec output: Annual electricity output; CF: capacity factor; Installed new cap: installed new capacity; Lifetime: lifetime of the installed infrastructure; $EnU^{New\ cap+OG}$: energy used in the construction of new capacity and overgrids for RES variables (EnU in this work corresponds to "Cumulative Energy Demand" (CED) in most EROI-related literature, see section 0 for clarification); $EnU^{Decom\ wear\ cap}$: energy used for decommissioning those infrastructures that have ended their lifetime. We assume a fixed share in relation to the EnU of the energy required for the construction of each power plant of 10% following (Hertwich et al., 2015), i.e. Decomm=0.1;

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EnU^{GCF}: energy used to consider the losses due to the effect Joule of each power plant (grid-correction factor). Depending on the power plant a different share of the EnU of the energy required for the construction of each power plant is assumed (GCF); $EnU^{O\&M}$: annual energy used for the operation and maintenance; SC: electricity self-consumption of the power plant as a share of the electricity output.

The above equation can be simplified removing the annual installed electricity capacity and expressing the EnU as energy per installed capacity (Eq.11):

$$EROI_i = \\ = \frac{Cp_i \cdot 8760 \frac{h}{yr} \cdot lifetime_i}{\left(EnU_i^{New\ cap+OG}\ per\ TW \cdot (1 + Decomm + GCF_i) + EnU_i^{O\&M}\ per\ TW \cdot lifetime_i\right) + CF_i \cdot 8760 \frac{h}{yr} \cdot l} \quad \text{(Eq.11)}$$

The previous equation can be directly applied for those technologies of electricity generation for which the material requirements for both new installed capacities and O&M are explicitly modelled since MEDEAS dynamically estimates their $EnU^{New\ cap+OG}$ and $EnU^{O\&M}$. However, given that these data are not available for the dispatchable technologies (hydroelectricity, geothermal, biomass&waste and oceanic), the static approach of EROI has to be applied. For this, some assumptions have to be made in order to adapt Eq.9: that the operation and maintenance are independent of the CF and the self-consumption losses are negligible. The current total EnU per capacity (EJ/TW) per technology over the lifetime of the infrastructure is then (Eq.12):

$$Total\ EnU_i\ per\ TW\ over\ lifetime = \frac{CF_i^{initial} \cdot lifetime_i \cdot 8760 \frac{h}{yr} \cdot EJ\ per\ TWh}{EROI_i^{initial}.} \quad \text{(Eq.12)}$$

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

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

Thus, once estimated the current total EnU per TW for each technology, and assuming that its value will remain constant during the timeframe of MEDEAS, the evolution of EROI over time of the dispatchable electricity generation sources can be expressed by the Eq.13. Note that, despite being defined following a “static” approach, the EROI) can still evolve over time considering the dynamic evolution of the capacity factor of each technology $CF_i(t)$ and the quality factor of the electricity g(t):

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$$EROI_i(t) = \frac{CF_i(t) \cdot lifetime_i \cdot 8760\frac{h}{yr} \cdot EJ\ per\ TWh}{Total\ CED_i\ per\ TW\ over\ lifetime} \qquad \text{(Eq.13)}$$

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

For those technologies of electricity generation for which the material requirements for both new installed capacities and O&M (Operation and Manteinance) are explicitly modelled (which correspond with the RES variables: solar PV, solar CSP, wind onshore and wind offshore), the EROI can be endogenously and dynamically estimated in the model for each time period t (i.e. independently of the lifetime of the infrastructure) (see Eq.14):

$$EROI_i(t) = \frac{Annual\ elec\ output_i(t) \cdot EJ\ per\ TWh}{(EnU_i^{New\ cap+OG}(t) \cdot (1 + GCF_i) + EnU_i^{decom\ wear\ cap}(t) + EnU_i^{O\&M}(t)) + Annual\ elec\ output_i(t) \cdot} \qquad \text{(Eq.14)}$$

CF(t) depends on the level of overcapacity.

$EnU^{New\ cap+OG}(t)$ and $EnU_{O\&M}(t)$ depend on the recycling rates of the minerals.

g(t) is the dynamic final to primary energy (1)/(0) (for the meaning of numbers, see Figure 1).

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

$$EnU_i^{decom\ wear\ cap}(t) = 10\% \cdot EnU_i^{New\ cap+OG}(t) \cdot \frac{wear\ cap_i(t)}{Instaled\ new\ cap_i(t)} \cdot \qquad \text{(Eq.15)}$$

2.3.2. Demand of materials per technology

The demand of materials in MEDEAS-W is split in 2 categories: (1) materials demanded by alternative technologies solar PV, solar CSP, wind onshore, wind offshore, electric vehicle batteries and electric grids (which is the focus of this section), and (2) materials demanded by the rest of the economy.

A literature review was performed in order to identify the material intensity (kg/MW) required by 6 key technologies for the transition towards fully RES-based energy systems: solar PV, solar CSP, wind

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onshore, wind offshore, electric vehicle batteries and electric grids. For the electricity generation technologies, both new installed capacity and operation and maintenance activities are considered.

A total of 58 materials, of which 19 minerals (aluminium, cadmium, chromium, copper, gallium, indium, iron, lead, lithium, magnesium, manganese, molybdenum, nickel, silver, tellurium, tin, titanium, vanadium and zinc) were reviewed. Selection criteria was made on the basis of potential critical materials identified in the literature (EC, 2010; Elshkaki and Graedel, 2013; García-Olivares et al., 2012; Prior et al., 2012; Valero et al., 2018), as well as on specific assessments (Capellán-Pérez et al., 2017a). A comprehensive literature review was performed in order to collate the most robust and accurate data about material requirements for each technology. This approach differs from published meta-analyses which tend to focus on the average values of the range of parameters found in the literature (Bhandari et al., 2015; Dale, 2013; Hall et al., 2014; Kubiszewski et al., 2010; Trainer, 2018). In the cases where published data for an element/phase of the manufacture/installation of the technology was not found, the material requirements have conservatively been estimated from available data from other technologies (instead of being assumed 0 as most commonly performed in the literature). For example, since no data about the material requirements for fences for CSP power plants were found, the data estimated by Prieto and Hall (Prieto and Hall, 2013) for fences for PV were considered; similarly, since no data about ground removal for PV were found, so data for ground removal for CSP was applied instead (De Castro and Capellán-Pérez, 2018; Pihl et al., 2012), etc. In relation to the electric grids, the additional requirement of grids (i.e. “overgrids”) were estimated considering that the RES reach a high penetration in the electric mix, the losses due to Joule effect and the maintenance of grids. All considered data are energy data, i.e. no energy values were derived from monetary costs. Additionally, in the case of uncertainty about potential double accounting, material requirements were not included. Hence, our estimations can be considered conservative/optimistic.

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

- CSP with molten-salt storage without back-up: most efficient and used technology (De Castro and Capellán-Pérez, 2018). Back-up option is not considered since it is usually powered by non-renewable fuels such as natural gas.

- Fixed-tilt silicon PV: better performance in terms of EnU and EROI (Prieto and Hall, 2013) and subject to less mineral availability constraints (de Castro et al., 2013).

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- 2MW onshore wind turbines: currently the global average wind onshore turbine capacity is ~1.4 MW (GWEC, 2017).

- 3.6MW offshore wind turbines taking as reference the current average size in Europe (GWEC, 2017).

- $LiMn_2O_4$ electric vehicle batteries: although they are less efficient than other alternatives (e.g. $LiCoO_2$), the embodied energy for their fabrication is substantially lower (Barnhart and Benson, 2013).

For more details on the estimation of material intensity per technology, see (Capellán-Pérez et al., 2017a; De Castro and Capellán-Pérez, 2018).

2.3.3. Energy used (EnU)

The energy used (EnU)[5] for the construction of new capacity and operation and maintenance activities (O&M) for each RES variable technology for which the material requirements are explicitly modelled (solar PV, solar CSP, wind onshore, wind offshore) is estimated for virgin and recycled materials from LCA (Hammond and Jones, 2011). This part of their EnU is estimated multiplying the material intensity of each technology (assumed constant) by the energy consumption per unit of material consumption (MJ per kg), whose current values constitute a starting point for the dynamic analysis. Values of Hammond and Jones (Hammond and Jones, 2011) are cradle to gate or at most to point of use. The change of recycling rate makes them evolve dynamically. Thus, the EnU of each technology i evolves endogenously for each material j (Eq.16):

$$EnU_i(t) = Material\ intensity_i^j \left[\frac{kg}{MW}\right] \cdot Energy\ consumption\ per\ unit\ of\ material\ consumption^j \left[\frac{MJ}{kg}\right](t) \quad \text{(Eq.16)}$$

For the sake of simplicity, it was decided not to model the increase in energy requirements due to ore decrease of minerals in this analysis, although this effect may be important for some minerals in the future (Calvo et al., 2016; Harmsen et al., 2013; Mudd, 2010).

[5] CED is a term with origin in the LCA community, where it is defined including all the primary energy harvested in the operation phase. However, this definition is not valid to calculate EROI or the Energy Payback time. To avoid confusion of the different "CEDs" being used in the literature, and given priority to the historical precedence to the CED defined by LCA community, we apply in this report the term Energy Used (EnU) instead of Cumulative Energy Demand (CED).

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2.4. Feedback of EROI variation to the economic and energy subsystems

The aforementioned variation of the EROI of the system implies an increase in the energy intensity of the economic sectors linked to the generation, transformation and transport of energy. (see (Nieto et al., 2018) and (Capellán-Pérez et al., 2017a) for a full description of the Economy module of MEDEAS). This feedback effect between the energy system and the economic system has also been modeled in MEDEAS-W, but it has been necessary to do it indirectly, due to the grouping of economic sectors used in the World Input-Output Database (WIOD) (Dietzenbacher et al., 2013).

Thus, the adopted solution to model the change of the EROI has been to consider it an additional effect on the total final energy required and consumed by the system in relation to a reference year. This way, a decrease (increase) of the EROI in relation to the reference year will induce an increase (decrease) of the demand of total final energy. The application of this approach assures that the final net energy initially demanded is maintained after accounting for the EROI of the system dynamic feedback. We judge that the potential double accounting due to the combination of LCA of technologies with national accounts is more than compensated by using the EROIst of the system metric instead of EROIext.

For practical use, we name N_{eds} the net energy delivered to society (flow (1) in section **Error! Reference source not found.**), E_{inv} the energy invested to supply N_{eds} (flow (2)+(3) in section **Error! Reference source not found.**), and E_{ret} as the total energy returned (flow (1)+(2)+(3) in section **Error! Reference source not found.**) corresponding to E_{inv}+N_{eds}. Thus, the EROI can be defined as:

$$EROI = \frac{Eret}{Einv} = \frac{Neds + Einv}{Einv} \qquad \text{(Eq.17)}$$

Operating:

$$Neds = EROI \cdot Einv - Einv = Einv \cdot (EROI - 1)$$

$$Einv = \frac{Neds}{EROI - 1}$$

From the point of view of the energy demand (D), introducing time dependency and combining with the previous Eq.17:

$$D(t) = Eret(t) = Neds(t) + Einv(t)$$

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

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

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

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

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

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

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

Setting both previous expressions for D(t+1) and dividing we obtain the EROI feedback factor (EROI FC), as expressed by Eq.18:

$$EROI\ FC(t) = \left(\frac{EROI(t)}{EROI(t) - 1}\right) \cdot \left(\frac{EROI(t_0) - 1}{EROI(t_0)}\right) \qquad \text{(Eq.18)}$$

And setting t_0=2015

With this coefficient, the modified demand (D^m) to include the effect of the EROIst of the system change, from the original demand (D), and considering i the 5 different final fuels modelled in MEDEAS, is obtained as:

$$D_i^m(t+1) = D_i(t+1) \cdot EROI\ FC(t+1) \qquad \text{(Eq.19)}$$

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2.5. Raw material costs

This work focuses both on energy and material requirements associated to the transition to RES. In fact, there is a tight link between both, given that energy is required to extract, process and concentrate materials; and materials are required to construct the energy generation and transportation facilities. Although metal recycling and technological change may contribute to future supply, mining will likely have to continue growing for the foreseeable future to ensure that such minerals remain available to industry (Ali et al., 2017; UNEP, 2013). Hence, the endogenization of the EROI of the individual technologies in MEDEAS-W requires data on the actual material intensity (kg/MW) of these technologies. An extensive literature review has been performed to identify the materials required to construct, operate and maintain the so-called “scalable” RES technologies for electricity generation, i.e. (solar CSP, solar PV, wind onshore and wind offshore), i.e. those renewable sources characterized by a higher techno-sustainable potential (IPCC, 2011; Smil, 2010). Two more technologies are considered in this bottom-up assessment of material requirements which are also considered key for the large-scale deployment of RES: electric batteries and overgrids. Requirements for a total of 58 materials, of which 19 minerals, have been reviewed (Capellán-Pérez et al., 2017a). This way, the model allows to compute the mineral requirements related with the expansion of alternative energy technologies. This assessment is of great importance given recent works highlighting the dependence of the current economic system and alternative technologies on minerals (EC, 2010; Elshkaki and Graedel, 2013; García-Olivares et al., 2012; Prior et al., 2012; Valero et al., 2018). In particular, García-Olivares et al. (2012) proposed a global alternative mix to fossil fuels based on proven RES technologies, power transport and for some future transport systems not relying on scarce materials. They found that the proposed alternative would still be strongly constrained by the availability of metals such as lithium, nickel, zinc and platinum; requiring 60–70% of the copper reserves. Valero et al. (2018) analysed potential bottlenecks for 31 raw materials in the 2016–2050 time period under a business as usual scenario for wind power, solar photovoltaic, solar CSP and passenger electric vehicles, identifying 13 elements having very high or high risk: cadmium, chromium, cobalt, copper, gallium, indium, lithium, manganese, nickel, silver, tellurium, tin and zinc. Although this work is focused on the implications of the energy transition on the EROI of the system, it also contributes to this emerging research topic highlighting the vulnerability due to the potential scarcity of some minerals.

The importance of dynamic and endogenously computing the material requirements and the EROI of the system in modelling projections is illustrated by the simulation of three scenarios with different targets of penetration of renewables in the electricity mix within a global Environmental

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Integrated Assessment Model (MEDEAS-W) to 2060 under a *Green Growth* narrative (GG)[6], which is an alternative paradigm frequently assumed to avoid the adverse impacts on human societies of the global environmental change (European Commission, 2011; Jacobs, 2012; OECD, 2018, 2011; UNEP, 2011a; World Bank, 2012).

The material requirements (kg/MW) considered in MEDEAS for each RES variable electricity generation technologies are fully documented in Capellán-Pérez et al. (2017a). Given the difficulty and time-intensiveness to estimate the material requirements for each technology, a selection of key technologies was performed. This way, the scalable RES for electricity generation were selected (solar PV, solar CSP, wind onshore, wind offshore; note that these are variable intermittent RES), as well as the electric storage and overgrids requirements. All the estimates are thus derived from physical inputs, and no indirect estimates based on associated economic costs are considered. The energy requirements for the construction of the rest of RES technologies for electricity generation (which correspond to the dispatchable technologies: hydroelectricity[7], geothermal, biomass & waste and oceanic[8]) as well as other storage systems such as pumped hydro storage were also included but in a simplified (static) manner.

[6] Green growth scenario is equivalent to the OLT scenario in MEDEAS models.

[7] The intermittence and seasonal variability of the rains, as well as the requirements of other water resources such as irrigation, may limit the capacity of hydroelectric energy to be considered as 100% dispatchable. This limitation has not been considered.

[8] A great diversity of marine technologies exists and some of them could be considered as dispatchable (e.g. Ocean Thermal Energy Conversion (OTEC)) while others are subject to variability (e.g. tidal & wave). For example, the wave plant of Mutriku (Spain) presents a factor of almost 5 in its seasonal variability comparing summer and winter (Torre-Enciso et al., 2009). For the sake of simplicity and thus from a conservative point of view, we assume that all oceanic power is dispatchable. Moreover its importance in the model is reduced given its low potential and EROI (Capellán-Pérez et al., 2017a).

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2.6. Scenario assumptions for energy and materials

Three scenarios with different penetration of renewables in the electricity mix are simulated in MEDEAS global model to 2060 under a *Green Growth* narrative (GG or OLT), which is the alternative paradigm assumed by the establishment to avoid the adverse impacts on human societies of the global environmental change (European Commission, 2011; Jacobs, 2012; OECD, 2018, 2011; UNEP, 2011a; World Bank, 2012). GG narrative focuses on successfully combining economic growth with environmental protection. To reach this aim, they posit achieving an absolute decoupling between economic activities increase and the consumption of energy and materials through a substantial increase in efficiency improvements, the electrification of the system, the transformation of the transportation sector and the rapid transition to low-carbon energy sources (renewables, nuclear and not discarding future technologies such as advanced biofuels and bioenergy combined with carbon capture and storage). These goals are expected to be achieved with a so-called 'inclusive economic growth'. The more or less explicit objective is to undertake a modernization process widely based on the path previously followed by developed countries, but including a technology-based transition to RES and large efficiency improvements (IEA/OECD, 2017; IEA ETP, 2017; SSP db, 2016; van Vuuren et al., 2017). In this scenario, policies are progressively activated (in the period 2020-2025, which given current time (June 2018) it may be considered as an optimistic assumption.

Combined RES currently contributes over 20% of the electricity generation at global level. Three scenarios based on the GG narrative are simulated considering different growth rates of the RES technologies for electricity generation (see Figure 7):

- *GG-50%*: ~50% of RES in electricity mix in 2060,
- *GG-75%*: ~75% of RES in electricity mix in 2060,
- *GG-100%*: ~100% of RES in electricity mix in 2060.

The targets are approximated given that MEDEAS-W is a simulation model. These scenarios allow to assess the implications of RES increasing contribution in the electricity system for the whole system[9]. For the sake of simplicity, in this work, the EROI-based allocation method of renewable energy technologies is not activated.

The quantification of the GG storyline applied in this work has been performed on the basis of a detailed literature review of scientific papers and reports from international institutions, as well as on our assessment. In general, a business-as-usual (BAU) scenario (a narrative which broadly

[9] MEDEAS-W model is used because it is being tested functional structure and relationships in these subjects that are equivalent in the other MEDEAS nested models, i.e. MEDEAS-EU and MEDEAS country-level (Bulgaria and Austria).

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assumes the extrapolation of current trends into the future) is required as an implicit reference, given that the GG narrative is built on alternative assumptions such as a higher Gross Domestic Product per capita (GDPpc) increase and a lower population growth due to higher education levels in this scenario. In particular, data from the Shared Socioeconomic Pathways (SSPs) quantifications' are considered for population (SSP1) and GDPpc (SSP2[10]) evolution (Kc and Lutz, 2017; O'Neill et al., 2017; SSP db, 2016)), a more equitable share of income, as well as an economic structure which tends towards a modern economy such as Denmark ((Nieto et al., 2018) for details on the assumptions applied in the Economy module for this scenario). GG also assumes efficiency improvements 2x faster than historical trends both at productive sectors and households, a global afforestation program based on (Nilsson and Schopfhauser, 1995) as well as an increase in recycling rates of minerals of +5%/year which are in the high range estimated by Valero et al., (Valero et al., 2018) to avoid mineral bottlenecks in alternative technologies in the future. The role of nuclear energy in a global "Green Growth" scenario is challenged by the fact that different countries and organizations/institutions have a different view. In this work, given the challenges that the nuclear industry faces (Schneider and Froggatt, 2014), a slight increase in nuclear capacity is considered in accordance with the most optimistic prospects of alternative scenarios published by the IEA (IEA ETP, 2017). Different views also exist on the role of biofuels in a Green Growth scenario. Similarly as for nuclear, for the sake of simplicity in this report we take as reference the alternative IEA ETP scenarios (IEA ETP, 2017), which assume a slow growth (half of historical trends) for conventional biofuels on cropland given their environmental impacts in parallel with a significant contribution of advanced biofuels in the future. For the renewables dedicated to heat generation we assume a doubling of the annual historic short-term averaged growth rates of installed capacity (with a maximum of +20%/year to avoid unrealistically high growth rates).

Table 1. Overview of the most relevant scenario inputs.

shows the most relevant variables and hypotheses set in MEDEAS-W for simulating the GG scenario in this work.

Table 1. Overview of the most relevant scenario inputs.

Scenario inputs & assumptions	Green Growth	Reference
Desired GDPpc growth (2015-2060 yearly average)	SSP2 (+2.8%/year)	(Capellán-Pérez et al., 2017a; SSP db, 2016)

[10] GDP in SSP is defined in Power Purchasing Parity (PPP), while in MEDEAS GDP is defined in market exchange rates (MER). Given that SSP2 is also a high GDPpc growth scenario (almost +3%/year yearly average over the period 2015-60) and this projection is available in MER after MEDEAS project results (Capellán-Pérez et al., 2017a), SSP2 was chosen instead for running the simulations in this work.

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Scenario inputs & assumptions	Green Growth	Reference
Population growth (2015-2060 yearly average)	SSP1 (+0.4%/year)	(Kc and Lutz, 2017; SSP db, 2016)
Target labour share (2050)	60 %	(Nieto et al., 2018)
Target A matrix (2060)	2009 Denmark IOT (Intput-Output Tables)	(Nieto et al., 2018)
Phase-out oil for electricity and heat?	Yes	Own estimation
Efficiency improvements (Final energy intensity)	2x times increase historical efficiency improvement trends by sector/households and fuel	Own estimation
Global afforestation program?	Yes	(Nilsson and Schopfhauser, 1995)
Nuclear installed capacity	Moderate capacity increase (+2.5%/year)	High range from literature review (IEA ETP, 2017)
Recycling rates of minerals (19 minerals)	+5% annual improvement rate from current recycling rates	Own estimation. Current recycling rates from (UNEP, 2011b).
Renewables		
Annual capacity growth of RES for electricity (see Figure 7)		Potential (Capellán-Pérez et al., 2017a)
Hydroelectric	*Scenario-dependent*	1 TWe
Geothermal	*Scenario-dependent*	0.3 TWth
Bioenergy	*Scenario-dependent*	Shared potential for heat, liquids and electricity (30 EJ)
Oceanic	*Scenario-dependent*	0.05 TWe
Wind onshore	*Scenario-dependent*	1 TWe
Wind offshore	*Scenario-dependent*	0.25 TWe
Solar PV	*Scenario-dependent*	200 Mha shared on land + PV rooftop endogenous depending on available urban land[a]
Solar CSP	*Scenario-dependent*	
Pumped Hydro Storage	*Scenario-dependent*	0.75 TWe
Annual capacity growth of RES for heat (commercial / non-commercial)		Potential (Capellán-Pérez et al., 2017a)
Bioenergy	+11%/yr / +20%/yr	Shared potential for heat and electricity (30 EJ)
Geothermal	+10%/yr / +15%/yr	4.4 TWth
Solar thermal	+20%/yr / +20%/yr	Endogenous depending on urban land[a]
Bioenergy		Potential (Capellán-Pérez et al., 2017a)
2nd Gen cropland	+3.5%/yr	200 Mha
3rd Gen cropland (starting 2025)	20%/yr	
Residues (starting 2025)	20%/yr	25 EJ/year
Non-renewable energies depletion curves		

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Scenario inputs & assumptions	Green Growth	Reference
Oil	(Laherrère, 2013)	
Gas	(Laherrère, 2013)	
Coal	Best Guess (Mohr et al., 2015)	
Uranium	(EWG, 2013)	
Climate Change impacts	Parabolic "soft" damages (dangerous climate change after some years having surpassed +2ºC of temperature increase)	

[a]Share available roof over total urban land: 5% from current 2-3% (Capellán-Pérez et al., 2017b).

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2.7. Social costs

2.7.1. Social and behavioural adaptions necessary for the energy system transformation

The Social and behavioural adaptions necessary for the energy system transformation (subtask 6.2.c.1) in terms of energy intensity related to labour skill levels are explored and analysed. The analyses build upon the work started in WP2, where the relationship between labour skills and energy intensities has already been tested. We are now focusing on developing an econometric model that can be implemented in MEDEAS.

The social dimensions of the renewable energy transition not only matter in terms of effects on labour demand and related skills, but also fundamentally influence the renewable energy transition itself. Skilled labour facilitates the adoption of energy-efficient and renewable energy technologies, and therefore fundamentally affects the energy intensities of industries. The social costs of the transition are therefore endogenous and provide an inherent feedback loop in the system that can facilitate, but also inhibit the low-carbon transition.

This can be explained with a simple example: If the demand for labour skills and related human capital for the adoption of energy-efficient and renewable energy technologies increases, then this human capital feeds back by facilitating further technology adoption. As a consequence, the energy intensities of each sector reduce.

The skill classification used in this analysis is based on the International Standard Classification of Education (ISCED) 1997, which is linked with the input-output structure of WIOD. Accordingly, three skill classes are separated:

- Low skill level: Primary education up to lower secondary education (first 9 years).
- Medium skill level: Upper secondary up to post-secondary, non-tertiary (e.g. from age 14-16, high schools, gymnasiums, etc.).
- High skill level: First and second stage of tertiary education (universities, colleges, but also vocational training).

The energy intensity of sectors is a fundamental variable in MEDEAS. Figure 3 illustrates how energy intensities are modelled in MEDEAS.

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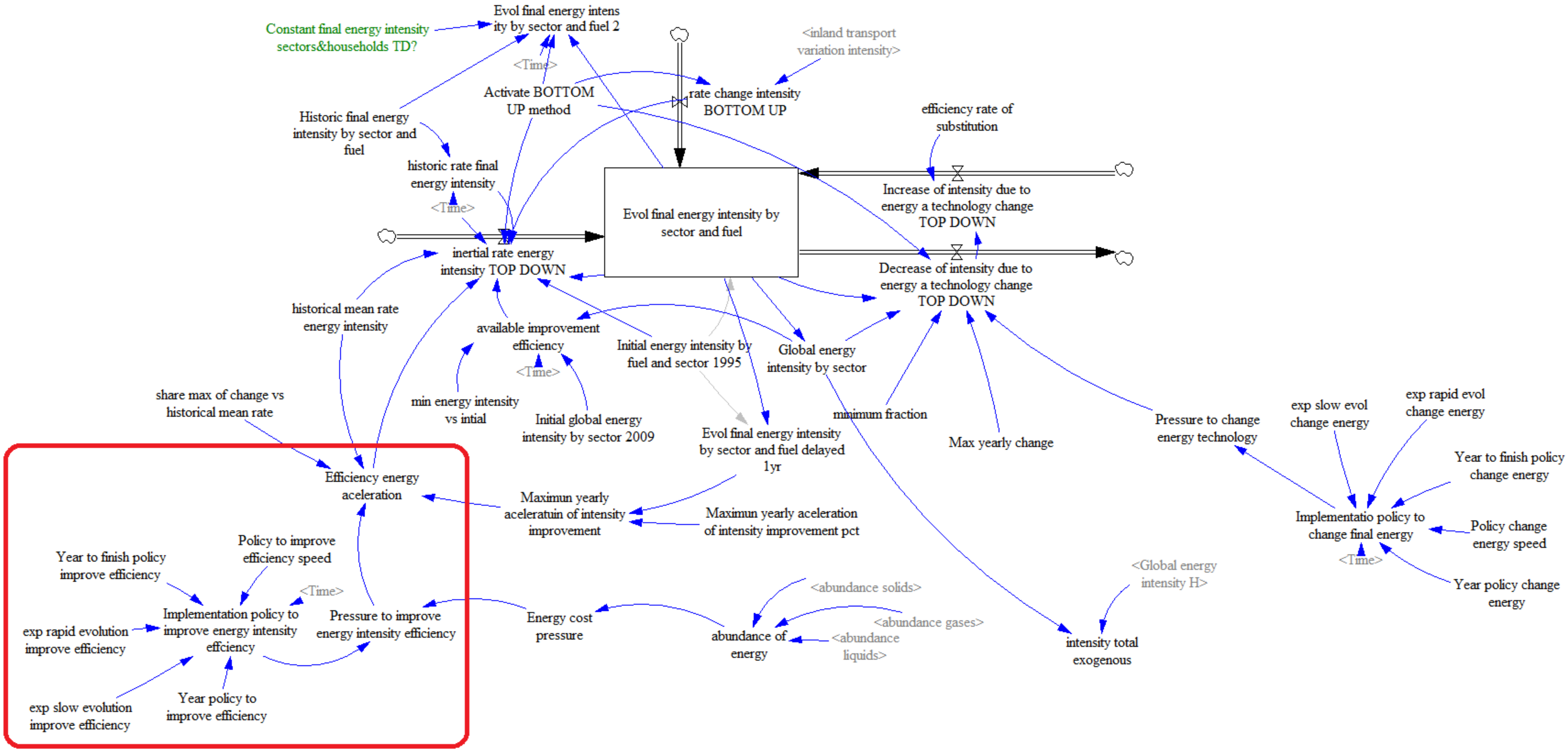

Figure 3. Energy intensities modelled in MEDEAS.

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2.7.2. Critical aspects for the energy system transformation and social patterns helping to reach 2050 objectives

Recently, the EU has adopted the **Energy Roadmap 2050** (European Commission, 2014) with the aim of reducing greenhouse gas emissions by 80-95% (from 1990 levels), a binding target (at EU level) to boost the share of renewables to at least 75% of EU energy consumption and to establish the share of RES in electricity consumption reaching 97% ("Energy roadmap 2050," 2012).

Our study reacts to the EU's efforts but goes further in two regards. First, we aim to detect what implications for the economy in terms of monetary fluxes between the sectors and specifically for the labour market would a 100**% transition from fossil fuels to renewable energy sources** (RES) have in one particular sector. We conduct the analysis for the sector of **electricity generation**, one of the sectors that are still now-a-days heavily dependent on fossil fuels even though the trend is radically changing, especially in the last decade.

Critical aspects for the energy system transformation in terms of labour market changes (effects on employment structure in various sectors of the economy at average country level, impacts to skilled and unskilled labour and employment by gender). The results presented below are an analysis of the critical aspects of the transformation in terms of 1) literature review of other analyses dealing with the similar topic, and 2) input-output analysis of the current employment situation in the sector of electricity production (direct and indirect labour demand generated by the sector of electricity production).

Also, we have modelled a gradual replacement of the electricity production based on fossil fuels. The model counts with a significant (100%) decline of the fossil fuels-based production of electricity, while the demand is kept constant, implying that the electricity generation needs to be replaced by RES, namely one third by wind onshore, one third by solar PV, hydropower, and the rest by biomass and waste. While the share of each wind, solar PV and biomass increases, we keep the share of electricity by hydro constant, assuming that the capacity for new hydroelectricity power plants is becoming limited.

Second, we analyse the impacts of the transition in terms of job creation and destruction, trying to detect **distributional employment effects**, i.e. what types of labour will be required due to the transition. In other words, our analysis is trying to detect what types of labour (low-skilled, medium-skilled, and high-skilled) will be required due to the transition to RES in terms of assumed job destruction and creation, using input-output analysis and its social accounts with data on labour

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requirements from WIOD and EXIOBASE. While modelling employment effects of the post-carbon transition, particularly in the context of the EU Energy Roadmap, has been abundant, the impacts of a complete shift of one sector towards RES together with distributional employment effects on different groups of labour force has been rare.

2.7.3. Input-Output Analysis

We apply input-output analysis (IOA) to see the structural changes throughout the economy. IOA allows capturing inter-industry linkages and measuring their direct and also indirect effects of externally imposed changes (Kerschner and Hubacek, 2009). The basic input-output transaction table consists of rows showing "Who gives to whom?" and columns showing "Who receives from whom?" in an economy, as shown in Figure 4 below (i.e. each cell shows € or $ worth of deliveries FROM for example agriculture TO industry).

Industry to industry input-output table			
From↓ | To→	**Agriculture**	**Industry**	**Services**
Agriculture		*„What Industry pays for commodities delivered by Agriculture"*	
Industry			*„What Services pay for commodities delivered by Industrial sectors"*
Services		*„What Industry pays to Services" (marketing?)*	

Figure 4. Simple input-output structure of an economy with three sectors (Agriculture, Industry, Services).

If the economy is divided into ***n*** sectors, and if we denote by X_i the total output (production) of sector ***i*** and by Y_i the total final demand for sector ***i***'s product, we may write sector ***i***'s ***output***:

$$X_i = z_{i1} + z_{i2} + \ldots + z_{ii} + \ldots + z_{in} + Y_i$$

X_i … TOTAL OUTPUT (PRODUCTION) OF SECTOR ***i***

z_{i1} … PRODUCTS GOING FROM SECTOR ***i*** TO SECTOR ***1***

Y_i … TOTAL FINAL DEMAND FOR SECTOR ***i***'s PRODUCT

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The ***z*** terms on the right-hand side represent the interindustry sales by sector ***i***, thus the entire right-hand side is the sum of all sector ***i***'s interindustry sales and its sales to final demand. The above equation represents the distribution of sector ***i***'s output. The following equation reflects the outputs of each of the ***n*** sectors:

$$X_1 = z_{11} + z_{12} + \dots + z_{1i} + \dots + z_{1n} + Y_1$$

$$X_2 = z_{21} + z_{22} + \dots + z_{2i} + \dots + z_{2n} + Y_2$$

…………..

$$X_i = z_{i1} + z_{i2} + \dots + z_{ii} + \dots + z_{in} + Y_i$$

…………..

$$X_n = z_{n1} + z_{n2} + \dots + z_{ni} + \dots + z_{nn} + Y_n$$

Consider the information in the ***i***th column of ***z***'s on the right-hand side – that are ***sales to sector i*** (***i***'s purchases of the products of various producing sectors in the economy):

z_{1i}

z_{2i}

…

z_{ii}

…

z_{ni}

These elements are the sales to sector ***i***, that is, ***i***'s purchases of the products of the various producing sectors in the country; the column thus represents the sources and magnitudes of sector ***i***'s *inputs*. Clearly, in engaging in production, the sector also pays for other items – for example, labour and capital – and uses other inputs as well, such as inventoried items. All of these together are termed the ***value added*** in sector ***i***. In addition, ***imported goods*** may be purchased as inputs by sector ***i***.

All of these inputs (value added and imports) are often lumped together as purchases from what is called the ***payments sector***, whereas the ***z***'s on the right-hand side of the equation serve to record

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the purchases from the ***processing sector***, the so-called ***interindustry inputs***. Since each sector can also use its output as its own input, *inter*industry inputs include ***intra-industry inputs*** as well.

The magnitudes of these interindustry flows can be recorded in a table, with ***sectors of origin (i.e. sellers) listed on the left***, and ***the same sectors, now "destinations" (i.e. purchasers), listed across the top***. From the column point of view, these show each sector's ***inputs***; from the row point of view, the figures are each sector's ***outputs***.

The interindustry flows from sector ***i*** to ***j*** (for a given period – mostly 1 year) depend entirely and exclusively on the total output required from sector ***j*** for the same period. For example, the more cars produced in a year, the more steel will the automobile producers need during that year. The so-called ***technical coefficients*** define the exact nature of this relationship.[11] Technical coefficient is the ratio of input from each other sector to the total output of a given sector (=the Euro's worth of inputs from sector *i* per Euro's worth of output of sector *j*) as shown below in Figure 5 (Miller and Blair, 2009).

To identify key features of the post-carbon input-output economic structure it is necessary to focus on the technical coefficients and their expected evolution over the monitored period. The determinants of the technical coefficients cover technological progress (Leontief, 1983), but also infrastructure policies, substitution due to relative price changes, as well as industrial structure (Peneder, 2003).

[11] Input-output analysis works here with an assumption of **constant returns to scale**, which means that the coefficient does not depend on (and does not change with) the amount of items produced. In addition, input-output analysis requires that a sector use **inputs in fixed proportions**. Suppose that sector 4 from the example above also buys inputs from sector 2, and that, for period of observation, $\mathbf{z_{24}=\$750}$. Therefore, $\mathbf{a_{24}=z_{24}/X_4=\$750/\$15{,}000=0.05}$. For $X_4=\$15{,}000$, inputs from sector 1 and sector 2 were used in the proportion $\mathbf{P_{12}=z_{14}/z_{24}=\$300/\$750=0.4}$. This is simply the reflection of the fact that $\mathbf{P_{12}=z_{14}/z_{24}=a_{14}\times X_4/a_{24}\times X_4=a_{14}/a_{24}=0.02/0.05=0.4}$. P – the proportion – is the RATIO OF THE TECHNICAL COEFFICIENTS, and since the coefficients are fixed (=the production has constant returns to scale), then the input proportion is fixed.

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Industry to industry input-output table					
From↓ | To→	Agriculture	Industry	Services	Final Demand (expenditures)	Total Demand (output) (Y)
Agriculture	0,3	0,2	0,1		
Industry	0,5	0,6	0,4		
Services	0,1	0,1	0,3		
Value added					
Total Supply (X)					

Figure 5. Technical coefficients in a simple input-output structure of an economy with three sectors.

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2.8 Economic cost

2.8.1. Construction of EU input-output table with future energy mix

To capture both direct and supply chain effects of low carbon transition in electricity sector on the EU economy, in this study first constructed the EU input-output model for year 2014 using the EXIOBASE3. Since EXIOBASE3 includes all EU countries' IO tables, to be consistent with the MEDEAS system dynamic model, we merged all EU IO tables into a single region IO table that represents the whole EU economy. However, it's crucial to update the IO tables with the future energy mix in the electricity sector to be able to assess the economic impact of energy transition under different energy development scenarios. Here, we update the IO tables based on two scenarios, the BAU scenario and the OLT scenarios and for each scenario our economic cost assessment focuses on two time points, 2030 and 2050. In the new IO tables, we only adjust technical coefficients for electricity sectors to reflect the new energy mix in electricity production and the technical coefficients for the rest of economic sectors remain the same assuming that production technology remains unchanged in non-electricity sectors. We made such assumption because our analysis only focuses on the low carbon transition in the electricity sectors. Although our IO analysis also captures the upstream supply chain effects of the change in electricity production, it is extremely difficult to project the future economic development at sectoral level and the uncertainty introduced by such sectoral level projection might be too big to be useful for our analysis.

There are two steps to update the technical coefficients to reflect the new energy mix in electricity sectors. First, we update the rows of technical coefficients (or input coefficients) in electricity sectors. Each coefficient shows the electricity input (in monetary value) to each economic sector to produce one-unit output of that sector (a_{ij}). For example, *aij* shows input from electricity sector *i* to economic sector *j* to produce one unit of output in sector *j*. Assuming that the total electricity input to sector *j* is *S* (the summation of inputs from all electricity sector), the new input coefficients from electricity sector should also add up to *S*, but input coefficient from each electricity sub-sector is changed to reflect the new energy mix. In this study, we assume that the production technology efficient remain unchanged meaning that to produce one unit of electricity in each electricity sector in 2030 or 2050 (i.e. coal power plant, natural gas, solar), it requires the same input from each economic sector as it is in 2014. Based on this assumption, the column technical coefficients remain the same except the ones that change on the rows that have been update in the first step. However,

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the new tables need to include the change in total electricity production by energy types and this change reflects in the change in total sectoral output of electricity sectors.

The MEDEAS system dynamic model provides the future projection of electricity output by energy types under different scenarios (i.e. BAU and OLT). We use the electricity generation result from the MEDEAS to project the future total economic output for electricity sector based on the change rate in electricity generation between the two-time point, such as 2014 and 2030. For example, we use 2014 total output of electricity sectors from the IO table as the base, thus the future total outputs of electricity sectors are the 2014 total output multiplied by the change rate of each electricity generation.

2.8.2. Economic impact assessment using input-output model

In this study, we applied input-output model to assess the economic impacts of changing electricity production under BAU and OLT scenarios. Here, the economic impacts include labour compensation, capital consumption (depreciation), and other value-added categories (e.g. operating surplus).

The IO analysis is based on input-output tables. Each entry in the row and column illustrates the flow from the sale sector to the purchase sector. The IO model consists of n linear equations depicting the production of an economy. In this study, we use the input-output table with 160 sectors with detailed electricity sectors (9 energy types). To calculate economic impacts, we extended the standard input-output model with several value-added indicators.

$$T = \hat{e}_k (I - A)^{-1} x_{ele} \qquad \text{(Eq.20)}$$

where T is total factor input (both direct and indirect) driven by the change in electricity production ; $\hat{e}_k$ is a matrix with factor input coefficients of value added category k on its diagonal and k indicate the value added category, e.g. labour compensation, fixed capital consumption, and each factor coefficient is the factor input requirement to produce one unit of a sector's output; $(I - A)^{-1}$ is the Leontief inverse matrix capturing both direct and indirect effects along the entire supply chain; x_{ele} is a vector of sectoral output with economic output for electricity sectors and zeros for other sectors.

Using the Eq.20 we can calculate the total factor input requirements in all economic sectors to satisfy the electricity production under different electricity production scenarios. Therefore, the difference between the *T* base year (2014) and the *T* target year (2030) shows the change in labor comepnsation and other valude added generation due to the change in electricity production.

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3. Results and scenario assessment

3.1. Energy costs of transition

3.1.1. Transition to RES and EROI of the system

Figure 66 shows the dynamic evolution for the three scenarios considered in this work of the EROIst of the variable RES technologies for electricity generation whose EROI has been dynamically modelled: wind onshore, wind offshore, solar PV and solar CSP (see section 0). This figures allows to assess that wind technologies are providing more net energy to the system over time than solar ones. In particular, Figure 66c shows that solar technologies would only be a net contributor to the system by the end of the simulation period. All EROI levels tend to increase by time: this is mainly due to the improving mineral recycling policies assumed within the GG paradigm (i.e., recycling minerals is generally less energy intensive than processing virgin minerals from the mine (Hammond and Jones, 2011). EROI also reaches its maximum value when the full potential of a resource is achieved (i.e. energy investments are directed only to O&M and infrastructure replacement), which is the case for example for wind onshore in scenarios GG-75% (~2050) and GG-100% (~2040).

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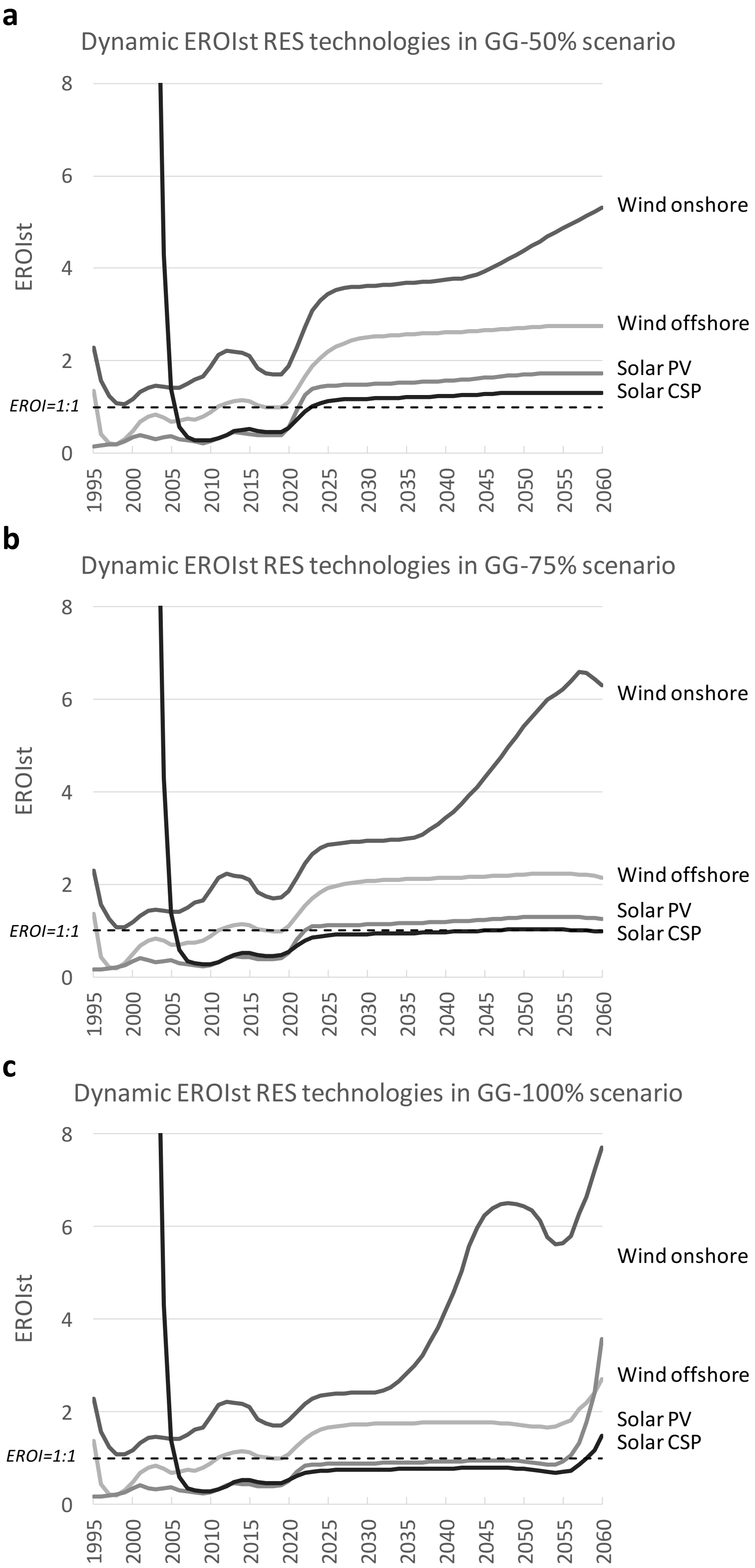

Figure 6. Dynamic EROIst of the RES variable technologies for the scenario (a) GG-50%, (b) GG-75% and (c) GG-100%.

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Figure 77a shows the penetration level of RES in the electricity mix for the 3 scenarios considered, which matches with the targets selected by 2060: ~50%, ~75% and ~100%. Figure 77b shows the dynamic evolution of the EROIst of the system (as defined in section 0). The current EROIst of the global energy system as defined in the Methodology of this report is found to be ~12:1, having decreased from ~15:1 since 1995. As expected, the EROIst of the system decreases faster in those scenarios where the penetration of RES in the electricity system is faster. This way, the EROIst for each scenario in the target year is ~7:1 (GG-50%) and ~4:1 for GG-75% and GG-100%, respectively. The fact that for the latter two scenarios the same EROIst of the system is obtained in the target year is due to the dynamic nature of the transition to renewables: as seen in Figure 77b, the EROIst for the GG-100% scenario decreases faster than the GG-75% reaching a minimum of 2:1 at ~2055, increasing thereafter. This behaviour is due to the fact that the EROIst in a given year is dependent on the energy investments being performed during that year. By 2055, the transition to RES in the electricity sector is almost achieved in the GG-100% scenario and due to this reason the rate of energy investments decreases thereafter thus allowing the EROIst of the system to partially recover until ~4:1. Similarly, scenarios GG-75% and GG-50% also show a “rebound” (although of lower magnitude) during the second half of the 21st century if the timeframe is expanded to 2100. The magnitude of this “rebound” depends on the interaction of different factors which are scenario dependent such as the electricity demand, the promotion of RES, the availability of electric storage, etc.

The EROIst of the system decreases while the EROIst of the individual RES variable technologies increases due to the fact that the EROI of the latter is lower than the current EROI of the full system, and their share increases over time in the simulated scenarios.

The EROIst of the system slightly increases for scenarios GG-50% and GG-75% in the first period of the simulation (2020-2030) due to the fact that the imposed growth rates of RES capacity for the technologies for electricity generation consistent with the 2060-targets are lower than the last historical data. Subsequently, the effect of exponential increase and cumulated capacity drive the EROI of the system to lower levels than historical ones.

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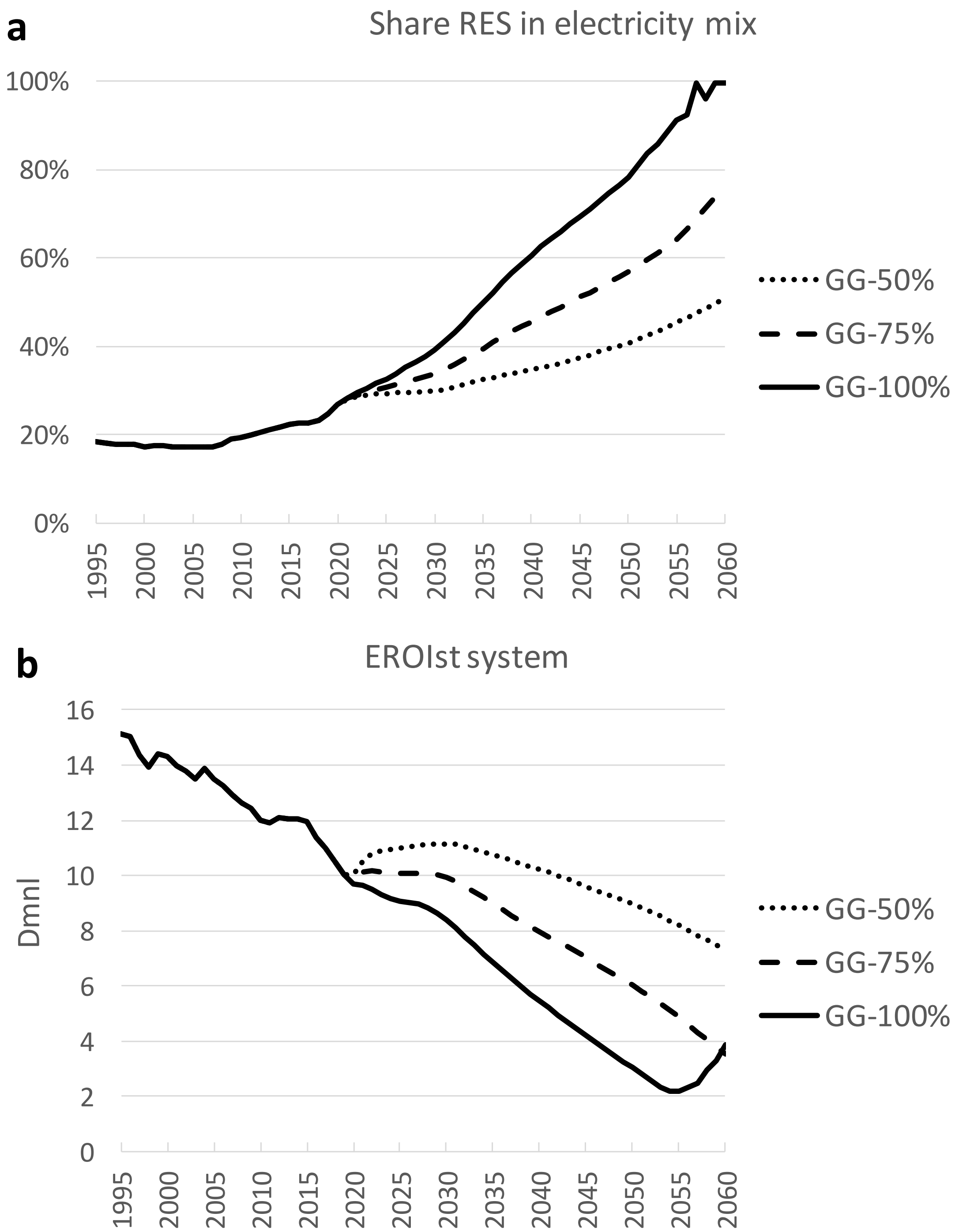

Figure 7. Transition to RES in the electricity system and EROIst of the system for the scenarios GG-50%, GG-75% and GG-100%: (a) share of RES in the electricity generation mix; (b) dynamic evolution of the EROIst of the energy system.

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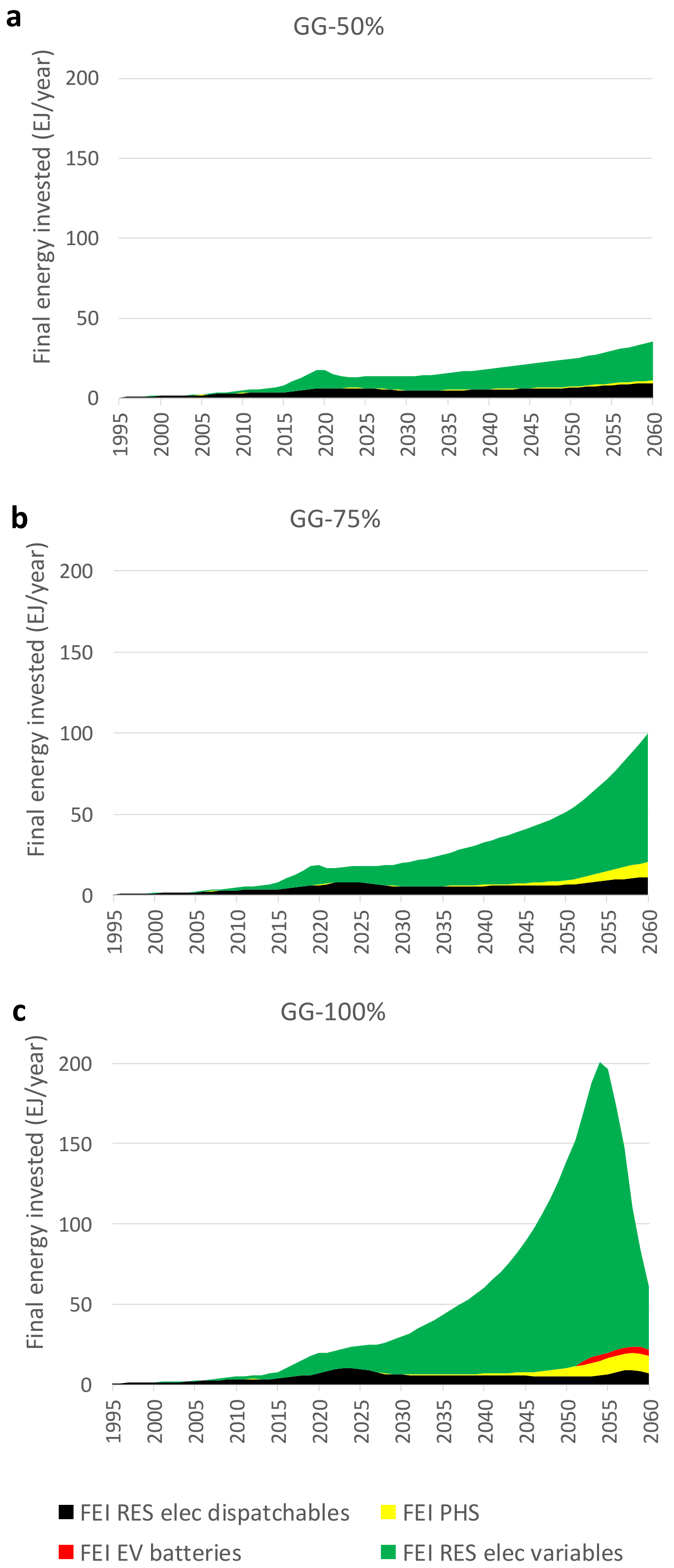

Figure 8. Final energy invested by type for each scenario.

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Figure 87[12] shows that the most important contributing factor to the EROIst of the system evolution is the energy investments associated with the variable renewable technologies for electricty generation (wind, PV and CSP), accounting from 2035 onwards for between the 60 and 90% of the total final energy investments for all scenarios. Overgrids represent just between 5 and 10% of the energy investments attributed to new capacity. As expected, energy storage investments depend on the penetration of RES in the electricity mix, but are however quasi negligible in comparison to the installation of new capacity. The minimum in the EROIst of the system for the scenario GG-100% corresponds with the maximum level of final energy investments, which by 2055 surpass the amount of 200 EJ/yr (Figure 88c). This is a vast amount of energy investments, surpassing 50% of the current level total final energy supply. For scenarios GG-50% and GG-75%, the maximum is reach by 2060 at ~40 and ~100 EJ/yr, respectively (Figures 8a and 8b).

3.1.2. Overdemand estimation and efficiency of the system

The decrease in the EROIst of the system has implications for the rest of the system: in order to satisfy the same level of final net energy consumption, the system needs to process more energy and materials. This phenomenon is modelled in MEDEAS-W through a function of overdemand. Figure 99 shows the increase in final energy demand to compensate for the variation of EROIst of the system up to 2060 for the three simulated scenarios. In GG-50% scenario, the overdemand increases softly reaching around +6% by 2060. In GG-75%, there is a faster increase in the overdemand which surpasses +20% by 2055-60. Finally, in GG-100% the effects are very large: there is a maximum of around +70% by 2055, which corresponds with the aforementioned maximum in final energy invested and the minimum in the EROIst of the system. This means that, in order to satisfy the same final net energy demand in this scenario, the system would need to process 70% more of energy with relation to the case of not accounting to the EROI.

[12] RES dispatchables for electricity generation (RES elec dispatchables), Pumped hydro storage (PHS), electric vehicle batteries (EV batteries) and, RES variables for electricity generation –including overgrids- (RES elec variables).

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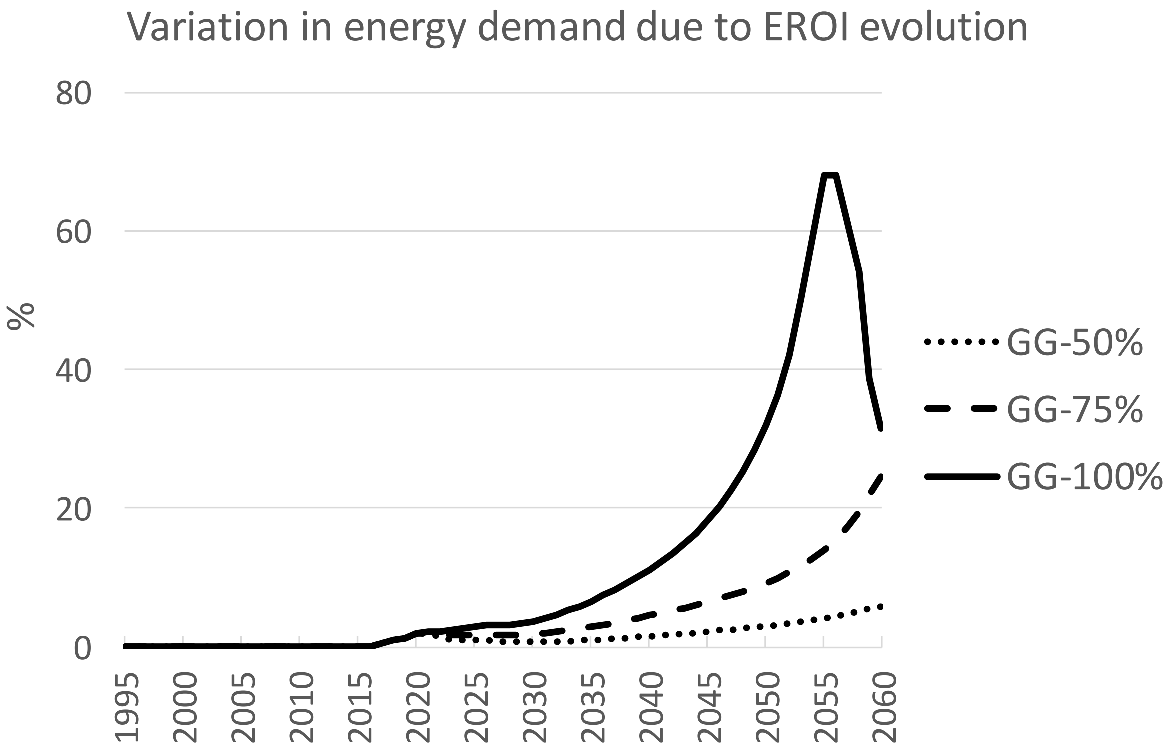

Figure 9. Variation of final energy demand due to EROI dynamic evolution (percentage).

Depending on the growth of renewables, the additional increase of final energy demand can also have significant implications for the efficiency of the system. In fact, the transition to RES in the electricity sector implies a material intensification of the economy which counters the assumed exogenous efficiency improvements for the productive sectors and households assumed within the GG narrative in this study (see Table 1. Overview of the most relevant scenario inputs.

). This means that in each scenario, by 2060, the total final energy intensity increases by 6%, 25% and 40%, for the scenarios GG-50%, GG-75% and GG-100%, respectively, with relation to the case of not accounting with the EROI. This increase is however higher during the period of high growth of RES capacity. Figure 1010 shows that by 2055 the total final energy intensity in the GG-100% scenario would reach the level attained in the years 2000s, while in the case without accounting for the EROI variation, the total final energy intensity steadily decreases over the simulated period (cumulated reduction of 40% between 2020 and 2060). For the scenario GG-75%, the total final energy intensity starts to increase by 2050 and by 2060 it reaches the levels of 25 years before. These results point to a strong re-materialization of the system during the transition to renewable energies.

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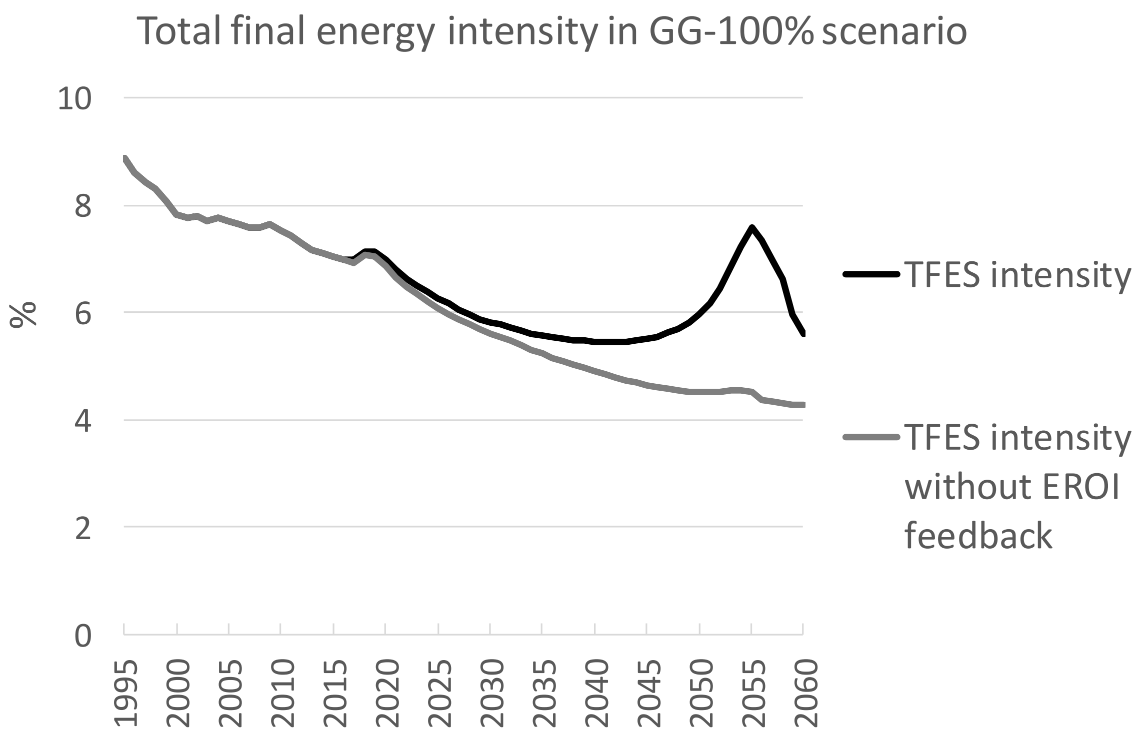

Figure 10. Comparison of the total final energy intensity in scenario GG-100% without accounting for the EROI feedback and accounting for its effect.

3.1.3. EROI of the system: comparison of obtained results with the literature

As aforementioned in the introduction, few studies have up-to-now analysed projections of 100% RES scenarios from a net energy perspective, with some exceptions (Dale et al., 2012b; Sgouridis et al., 2016; Trainer, 2018). Of those, only Sgouridis et al. (2016) dynamically considers the up-front costs of the energy investments and the delayed return of energy generation over the lifetime of the infrastructures. Those works applying a "static" approach for EROI integration downplay the transitory reduction in the net energy delivered to the society during the transition to RES.

Also, all previous works focus on the estimation of a "composite" EROIst of the system obtained as the weighted average of the static EROIst of the different technologies in the energy mix. This approach misses the dynamic nature of the problem as well as the additional infrastructure to manage RES variables intermittency (overgrids, overcapacities and storage). In fact, the representation of the intermittency of variable RES in these works is limited, most focusing on average annual power. Sgouridis et al. (2016) considers additional losses due to the storage of a share of variable generation; however, given the specifications considered (ESOI=125 and storage

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of 10% of average annual generation), its inclusion does not practically affect the results. Trainer (Trainer, 2018) does indirectly take into account the overcapacities required in a scenario of 100% electricity for Australia (Lenzen et al., 2016). The composite EROIst of the system (weighted average of electricity generation and assuming g=1) associated to the simulated scenarios in this work by 2060 is ~16:1 (GG-50%), ~10:1 (GG-75%) and ~8:1 (GG-100%). These are values substantially higher than the EROIst of the system reported in section 0 (~7:1 for GG-50% and ~4:1 for GG-75% and GG-100%). Further differences between studies are also highly dependent on the estimates of EROIst per technology considered, given the wide ranges reported in the literature. In this sense, it should be highlighted that the EROIst of the individual electric RES technologies in this study are in the lower range of the literature (Capellán-Pérez et al., 2017a).

Re-running the previous scenarios GG-50%, GG-75% and GG-100% considering the RES for electricity generation as dispatchable resources and preserving the same levels of exogenous capacity growth for RES technologies for electricity generation to achieve the 2060-targets in the intermittent case allows to compute the EROIst of the system in the conditions assumed by the aforementioned studies. Firstly, the removal of the phenomenon of intermittency of RES considerably facilitates the transition towards a 100% system, coming 10 years earlier for the GG-100% scenario (before 2050). Similarly, the growth of RES capacity which previously drove the system to ~75% of the electricity generation by 2060, is able under the new conditions to achieve 90% RES electricity by 2060.

These results show that those energy models not considering the restrictions in order to take into account the intermittent nature of the scalable RES technologies provide overly optimistic results. Secondly, as expected, the EROIst of the system improves, with the minimum for scenario GG-100% being reached at 3:1 by 2045-50 and stabilizing at ~5:1 when the 100% target is reached.

3.1.4. Implications of the energetic costs of the transition to RES

Which are the systemic implications of the obtained results? It is questionable wheter a complex system such our industrial society would be able to cope with an EROI of the system as low as 2:1, even temporary, as it is the case in the GG-100% scenario. This would put a big stress in the system, requiring to process large amounts of primary energy and materials (see Figure 2 and 9), thus diverting economic (e.g. investments), material and human resources from discretionary uses and simultaneously exacerbating environmental problems. In fact, the current modelling framework does not consistently capture the implications of the drop of the EROI of the system to very low levels (which would even be worse in the case of considering instead EROIpou or EROIext).

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In reality, a sharp drop in the EROI of the system to very low levels should endogenously induce a collapse of the system, as for example in Brandt (2017). Few works have dealt with the intricate issue of the minimum EROI to sustain our society. In the words of Lambert et al. (2014): “Certainly history is littered with cities and entire civilizations that could not maintain a sufficient net energy flow (Tainter, 1990), showing us that certain thresholds of surplus energy must be met in order for a society to exist and flourish. As a civilization flourishes and grows it tends to generate more and more infrastructure which requires additional flows of energy for its maintenance metabolism”.

Different works, applying different methodologies (Fizaine and Court, 2016; Hall et al., 2009; Lambert et al., 2014), have suggested that a minimum EROIst of the system > 10-15:1 is required to sustain advanced industrial societies to support such things as modern healthcare, education, and arts (discretionary spending) in addition to basic needs (e.g., food, shelter, and clothing). This is agreement with other works based on alternative methods (Fizaine and Court, 2016). Brandt (2017), on the other hand, find that the energy return must roughly be > 6:1 (EROIpou) to sustain complex societies, which is roughly equivalent to EROIst > 10:1 and EROIext>2.25:1, although with a large uncertainty.

Note that a distinct threshold does not exist given that the reduced availability of discretionary outputs as inter-industry operations become less efficient is a process with cascade, increasing consequences over time and the different sectors of the economy. In any case, these numbers are roughly consistent with the current EROIst of the global system obtained in this work (~12:1), given the high inequalities in energy consumption and levels of development at global level (Arto et al., 2016).

Figure 1111 represents the evolution of the EROIst of the system obtained in this work for each scenario and the different levels of systemic-risk as identified in the literature review (Brandt, 2017; Fizaine and Court, 2016; Hall et al., 2009). Given that EROIst > EROIpou > EROIext and the above discussion the following risk levels can be identified depending on the EROIst: >15, no risk; <10-15, low risks; <5-10: very dangerous; <5: very dangerous; <2-3: unfeasible system. These levels are indicative and evidently the risks are inversely proportional to the EROIst, similarly to the risks identified by the IPCC in the “Reasons for Concern” diagrams (IPCC, 2001; Smith et al., 2009). It is noteworthy, that by the mid-century, and even with renewable share in the electricity sector of ~50%, the system would enter in a zone identified as “very dangerous” in the literature.

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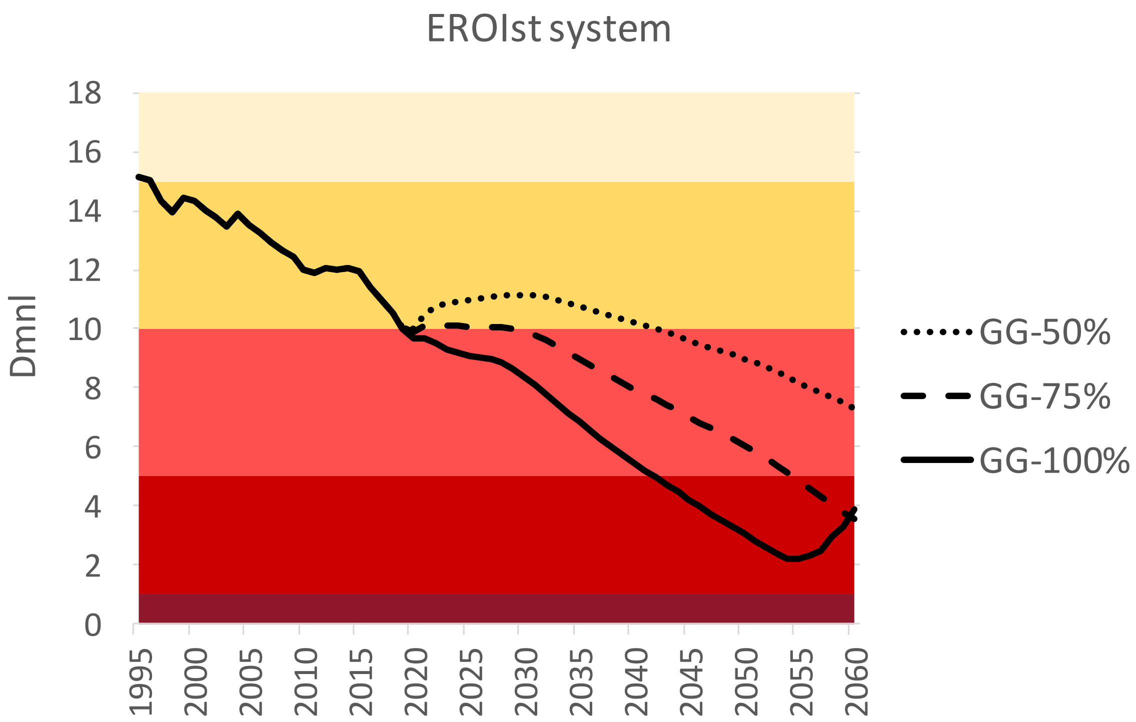

Figure 11. Dynamic evolution of the EROIst of the energy system for the scenarios GG-50%, GG-75% and GG-100% and different levels of systemic-risk as identified in the literature review.

The reported results are even more upsetting taking into account that a number of conservative assumptions likely make the obtained results optimistic:

- EROIst > EROIpou > EROIext,

- Only the dynamic evolution of the EROI of the RES technologies to produce electricity has been considered. However, in the long term the EROI of non-renewable fuels will tend to decrease; indeed, recent analyses have found that this trend is already ongoing (Gagnon et al., 2009; Hall et al., 2014).

- Generous recycling improvement rates of minerals are considered within the GG narrative (+5%/year for all minerals). However, phenomena of opposite trend such as the increase in energy requirements due to the ore decrease of minerals (Calvo et al., 2016; Mudd, 2010) may more than compensate for this in the future.

Finally, the EROI of the system is ultimately dependent on the mix of technologies in the electricity supply as well as on the strategy and options available (e.g. PHS potential) to deal with RES intermittency. Further work may be directed to design a robust technology allocation methodology within the model which takes into account the relative EROIst of different options in order to avoid

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that the EROI of the system is drained by a high participation in the energy mix of those technologies with a lower EROIst. Nevertheless, it should also be kept in mind that the EROI does not capture all the benefits and disadvantages of a given technology. For example, in the case of rooftop PV, despite its lower efficiency in relation to ground-based plants, it does not require additional land.

Further work may also be directed to explore alternative ways to analyse the implications of the evolution of the EROI of the energy system to the whole socio-economic system. In this sense, Input-Output analysis seems a promising approach (Brand-Correa et al., 2017).

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3.2. Material costs of transition

There are large uncertainties in relation to the future availability of minerals, the usual reserves and resources estimates being even more problematic than those of fossil fuels. Robust estimates of their availability in the literature to date are scarce and limited to few minerals (Mohr et al., 2012; Northey et al., 2014). In fact, although the concept of “peak oil” and other fossil fuels has been explored and debated extensively within the literature, there has been comparatively little research examining the concept of “peak minerals” (Bardi, 2014; Bardi and Pagani, 2007). For these reasons, the supply of minerals (conservatively) does not constraint the system in MEDEAS-W, as it is done, for example with fossil fuel availability (Nieto et al., 2018).

In order to assess the implications in terms of eventual future scarcities, the cumulative mineral consumption over the studied period is compared with the current level of reserves and resources of the minerals (as performed by other studies (García-Olivares et al., 2012; Valero et al., 2018)). Generally, the term ‘‘resources’’ is used to represent the amount of energy resources (proven or geologically possible), which cannot currently be exploited for technical and/or economic reasons but may be exploitable in the future. ‘‘Reserves’’ refer to the fraction of the resource base estimated to be economically extractable at the time of determination. Currently, one of the most used sources for reserve, reserve base and resource information is the United States Geological Survey (USGS), as it compiles information from mines and deposits from all over the world and for all the mineral commodities. Yet, the information is sometimes incomplete or inaccurate, and as 2009, the reserve base estimations are no longer provided. Table 1 in (MEDEAS, 2016) shows the reserves and resources information for the commodities selected in this work, which is the result of the comparison of different sources and selection of the best and most accurate data (Emsley, 2001; Frenzel et al., 2016, 2014; Sverdrup and Ragnarsdottir, 2014; USGS, 2015).

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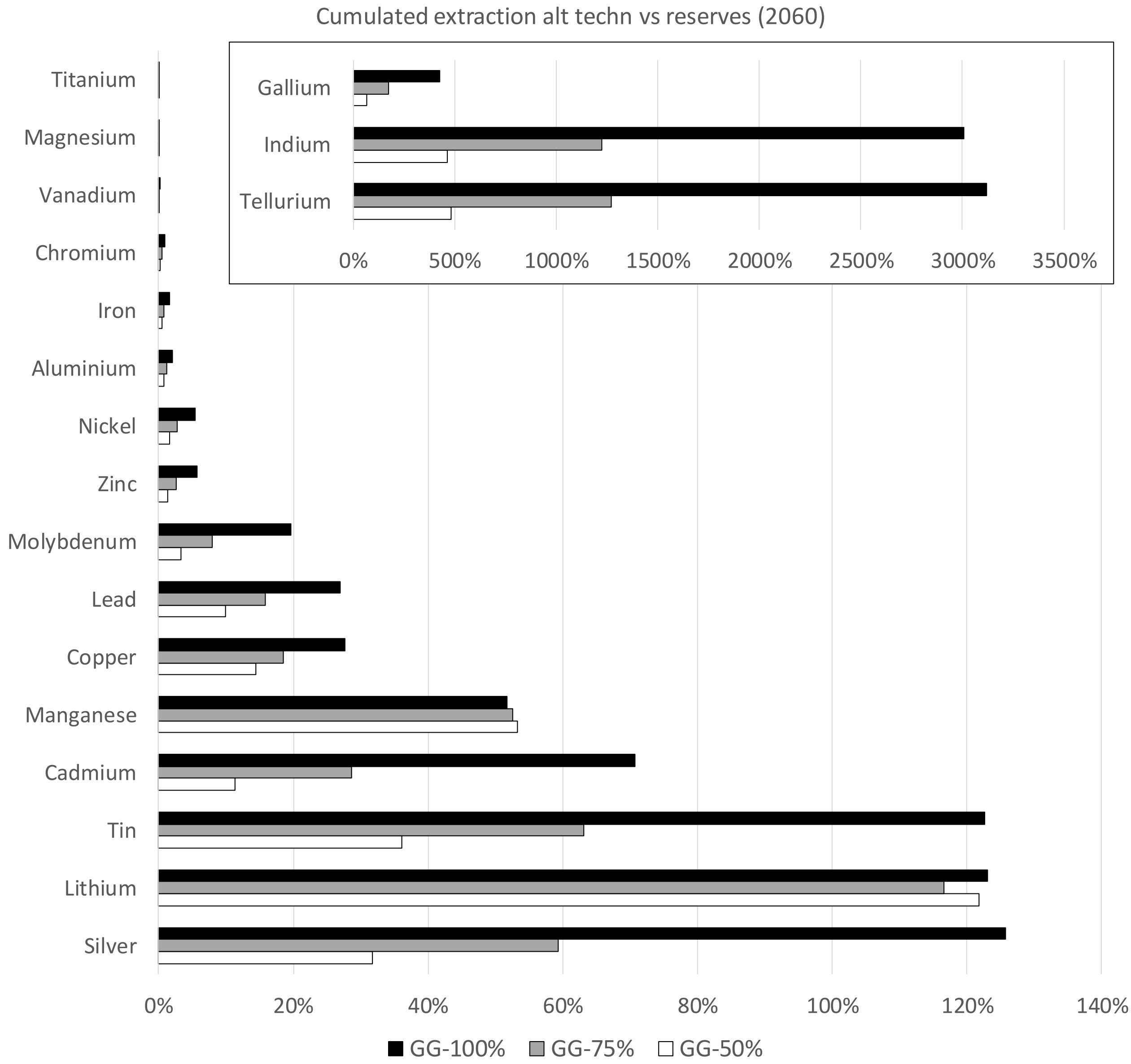

Figure 12. Cumulated extraction (2015-2060) of minerals for alternative technologies vs current reserves for the three scenarios GG-20%, GG-50% and GG-100%.

Figure 122 shows the ratio between the cumulated extraction (2015-2060) of minerals for the alternative technologies considered in this study and the current reserves for the three scenarios considered in this study. By the end of the period, the cumulated demand is higher than the current estimated level of reserves for 6 minerals in at least one of the considered scenarios: tellurium, indium, gallium, silver, lithium and tin. Four more minerals would require at least ¼ of the current reserves: cadmium, manganese, copper and lead.

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Figure 133 shows the ratio between the cumulated extraction (2015-2060) of minerals for alternative technologies and the current resources for the three scenarios considered in this study. By the end of the period, the cumulated demand is higher than the current estimated level of resources for two minerals in at least one of the considered scenarios: tellurium and indium. Three more minerals would require at least ¼ of the current resources: silver, lithium and manganese.

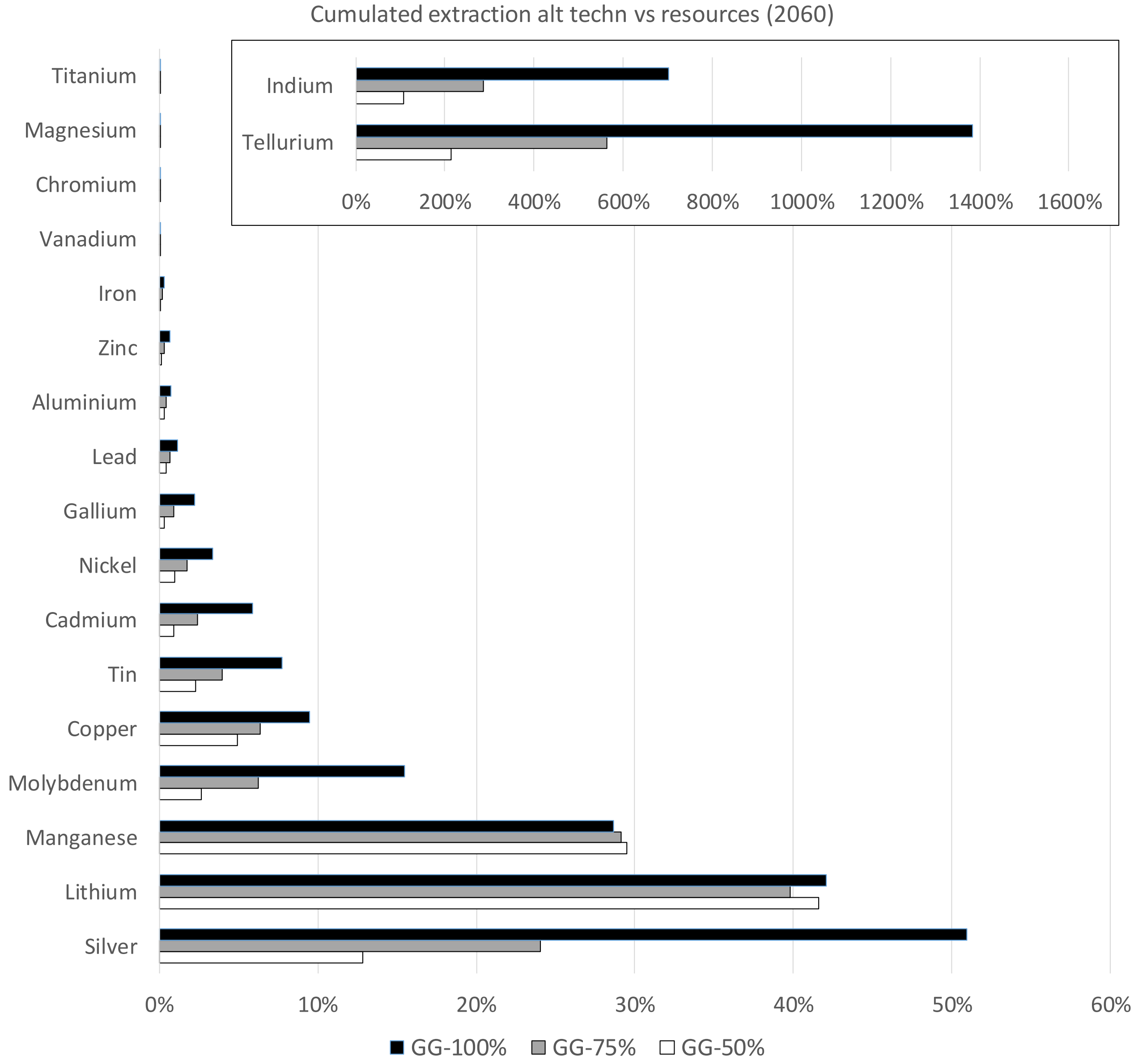

Figure 13. Cumulated extraction (2015-2060) of minerals for alternative technologies vs current resources for the three scenarios GG-20%, GG-50% and GG-100%.

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Following these results, the most affected technologies would be some solar PV technologies (tellurium, indium, silver, manganese), solar CSP (silver, manganese) and Li batteries (lithium, manganese). Wind technologies would be much less affected. Notably, gallium and indium also belong to the list of 14 critical minerals identified by the Raw Material Initiative of the EU (EC, 2010).

These results also show that the transition to alternative technologies will intensify global copper demand, "the backbone of the telecommunications infrastructure in the global North" (Fleissner et al., 2013), by requiring of 15-30% of the current reserves and 5-10% of the current resources of copper globally (note that power supply lines have not been considered excepting for overgrids for variable RES). For example, other studies considering a full transition to 100% RES and considering material requirements for transportation of electricity reach higher levels, e.g., 60-70% of estimated current reserves (García-Olivares et al., 2012).

Ideally, dynamic demand should be compared with dynamic supply, which is beyond the scope of the current work (Calvo et al., 2017; Valero et al., 2018). However, the consideration of static metrics such as reserves and resources provides a conservative, lower bound for risk analysis. Another conservative assumption is the hypothesis of high growth of recycling rates of minerals in the next decades; the maintenance of current recycling rates would imply higher levels of potential mineral scarcity.

Finally, it should be kept in mind that the interaction with the demand of minerals from other sectors of the economy would worsen the aforementioned assessment. However, the low quality of data in relation to mineral consumption by the whole economy globally prevents from performing a robust projection of these material requirements in the future (Valero et al., 2018). Still, a sensitivity analysis has been performed considering that the current levels of materials demanded by alternative technologies are negligible in comparison with those demands from the rest of the economy, and that the demand of minerals linearly depend from GDP evolution (see Supplementary Online Material for details). We believe this approach allows to consider first-order magnitude effects. Appendix A shows the results in terms of cumulated extraction (2015-2060) vs current reserves (Figure A1) and resources (Figure A2). As expected, the risk analysis substantially worsens: by the end of the period, the cumulated demand is higher than the current estimated level of reserves for 11 minerals in at least one of the considered scenarios: indium, tellurium, gallium, cadmium, tin, chromium, silver, lithium, lead, zinc and manganese. Three more minerals would require at least ½ of the current reserves: molybdenum, copper and nickel. By the end of the period, the cumulated demand is higher than the current estimated level of resources for 2 minerals in at

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least one of the considered scenarios: tellurium and indium. Three more minerals would require at least ½ of the current resources: silver, molybdenum and manganese.

The main way to overcome supply bottlenecks, in a business-as-usual context not considering demand-side options in the line of voluntary material degrowth (Demaria et al., 2013), is through increasing recycling rates. However, improving recycling rates of certain metals can be very difficult, due to several factors such as unappropriated design, special properties which need complex recovery processes and when mixed, thermodynamic limits, etc. (Valero et al., 2018). In this sense, future work may focus on the implications of the recycling rates of minerals on the EROI of the system.

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3.3. Social costs of transition

The results presented below are a list of proposals concerning important analytical relationships of the necessary social adaptations to reach the transition. We link the socioeconomic indicators included in the MEDEAS model with the social indicators that are not part of the model.

3.3.1. Social and behavioural adaptations necessary for the energy system transformation

Energy intensities vary considerably across countries and sectors. As Voigt et al. (2014) point out in their analysis of energy intensities based on WIOD, also the changes in energy intensities during the time period from 1995 to 2011 vary considerably (see Figure 14 and Figure 15[13]).

While energy intensities have reduced for all countries except Brazil, there are four sectors (Electricity, Gas&Water Supply (NACE: “E”), Mining&Quarrying (NACE: “C”), Other supporting and auxiliary transport activities (NACE: “63”), Education (NACE: “M”), where energy intensities have increased when all countries are considered.

There is significant potential of this pathway to improving energy intensities especially in currently highly inefficient countries, as the convergence of mean energy intensities attests (see Figure 16).

[13]Circles depict median changes and squares represent output-weighted mean changes. For sector descriptions, see the WIOD sector and ISIC classifications of WIOD (www.wiod.org).

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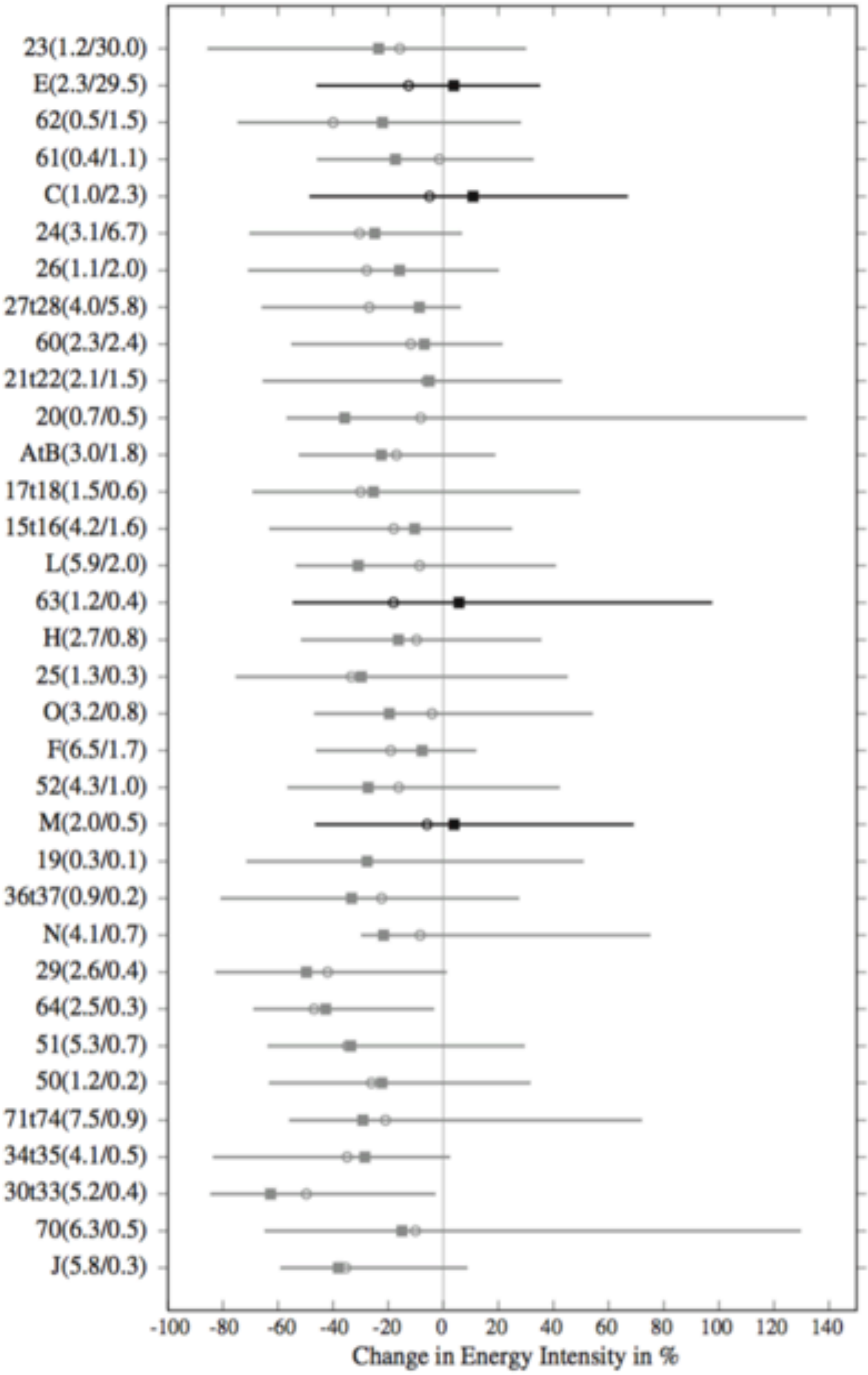

Figure 14. Energy intensity changes between sectors in the period 1995-2011.

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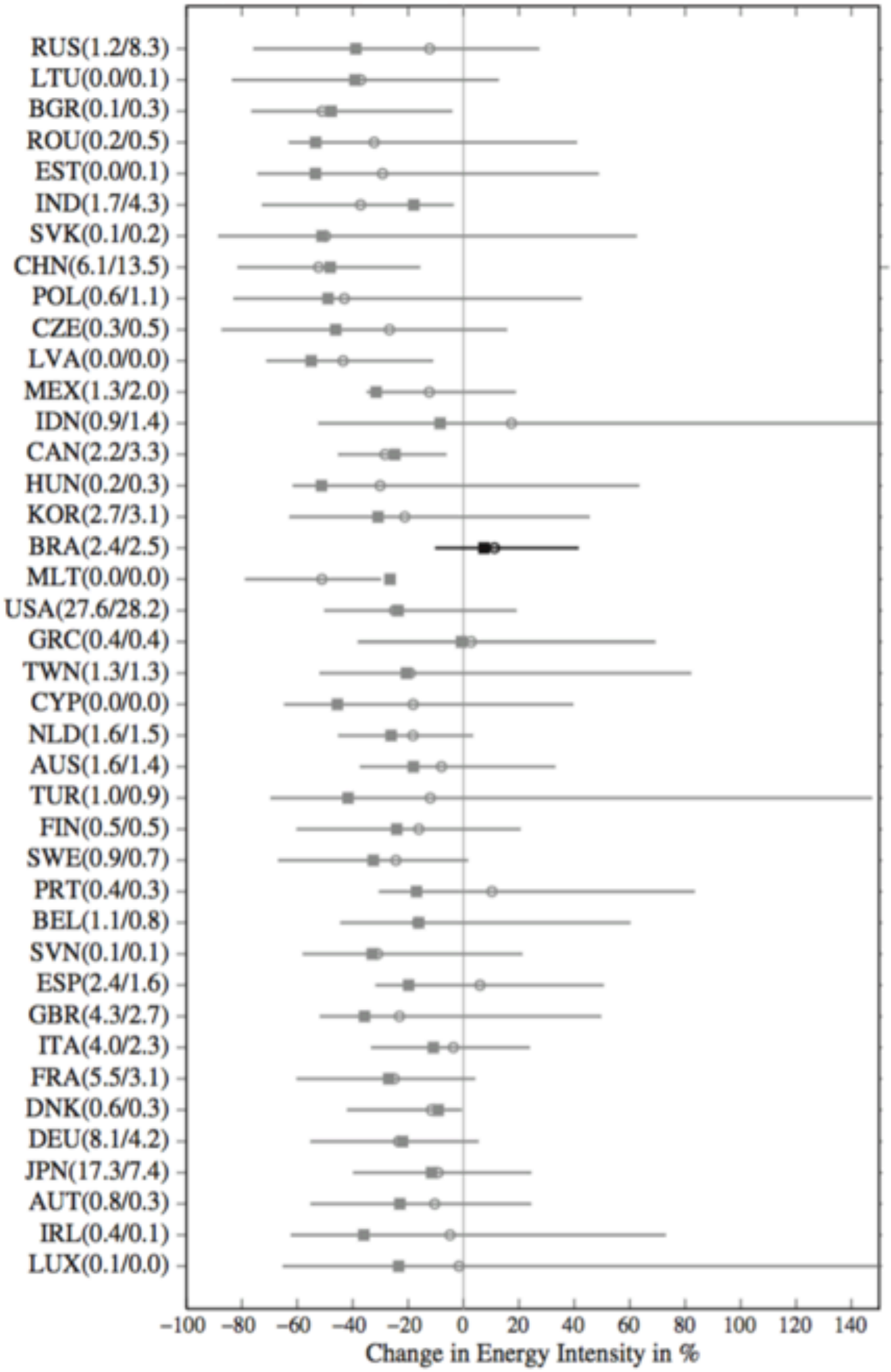

Figure 15. Energy intensity changes between countries in the period 1995-2011.

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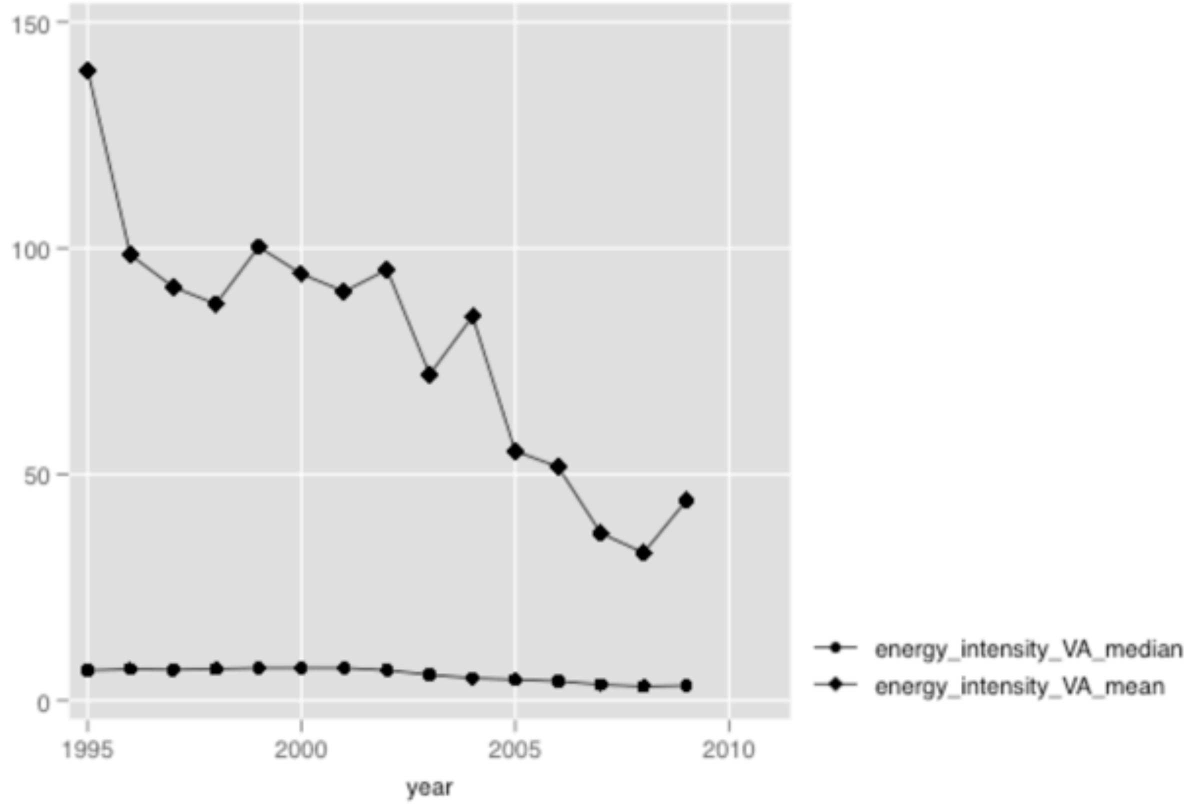

Figure 16. Convergence of mean energy intensity to the median across all countries covered in WIOD.

To recapitulate, the relationship between skills and energy intensities can be found across sectors and countries, with a decreasing energy intensity related to an increase in the share of high-skilled labour employed in a sector (see Figures 17, 18 and 19). There is also an expected u-shaped relationship for the share of medium-skilled labour employed, as the Figure 17 reveals. The figure shows a linear fit curve, which is not the optimal fit, as can be seen. This is to be expected because a larger share of medium-skilled workers naturally reduces the proportion of high- or low-skilled workers.

Before estimating the relationship between energy intensities and labour skills, we need to account for other variables that influence energy intensities and control for these in the econometric estimation.

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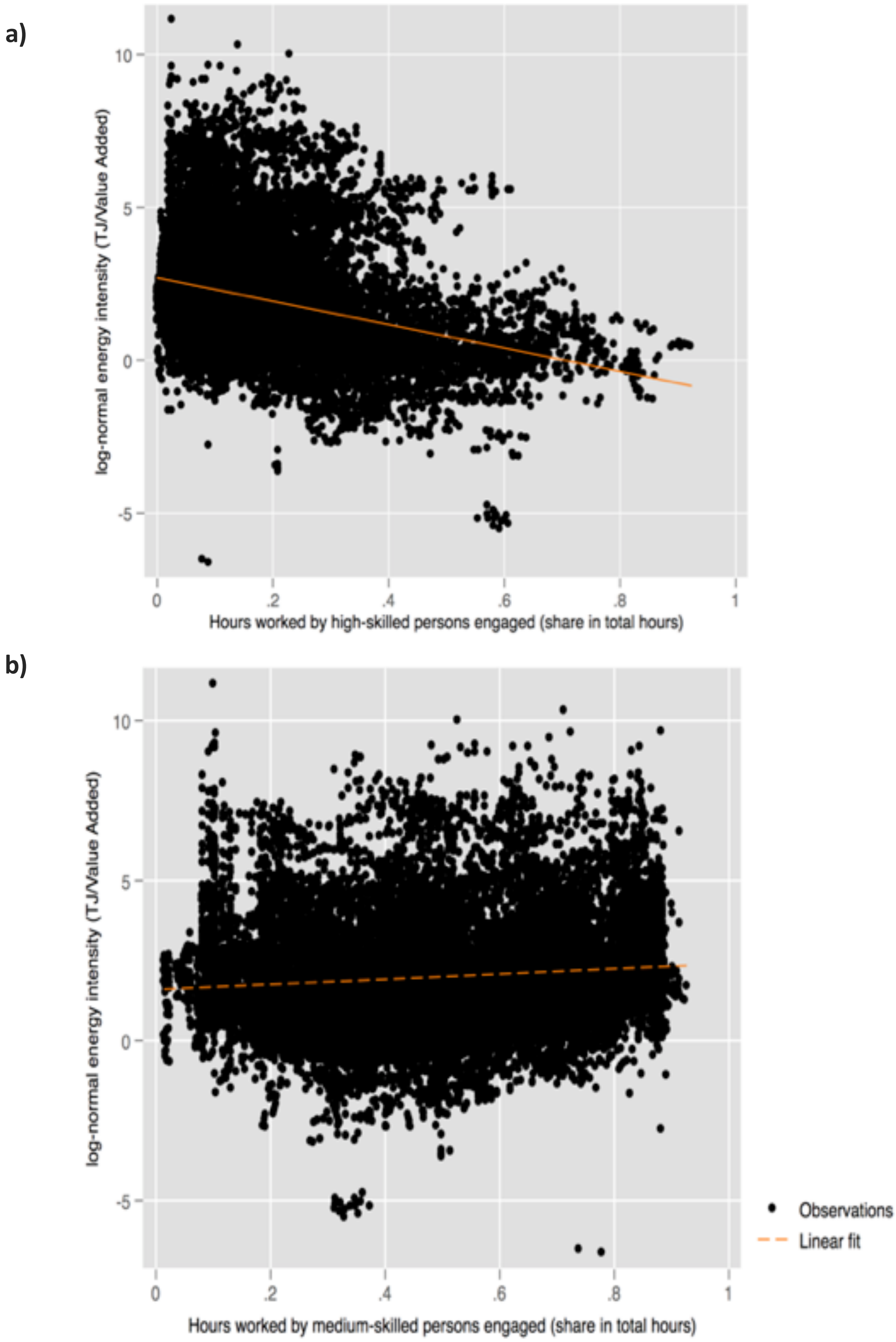

Figure 17. Relation between energy intensity and the share of employed high-skilled labour (a) and medium-skilled labour (b).

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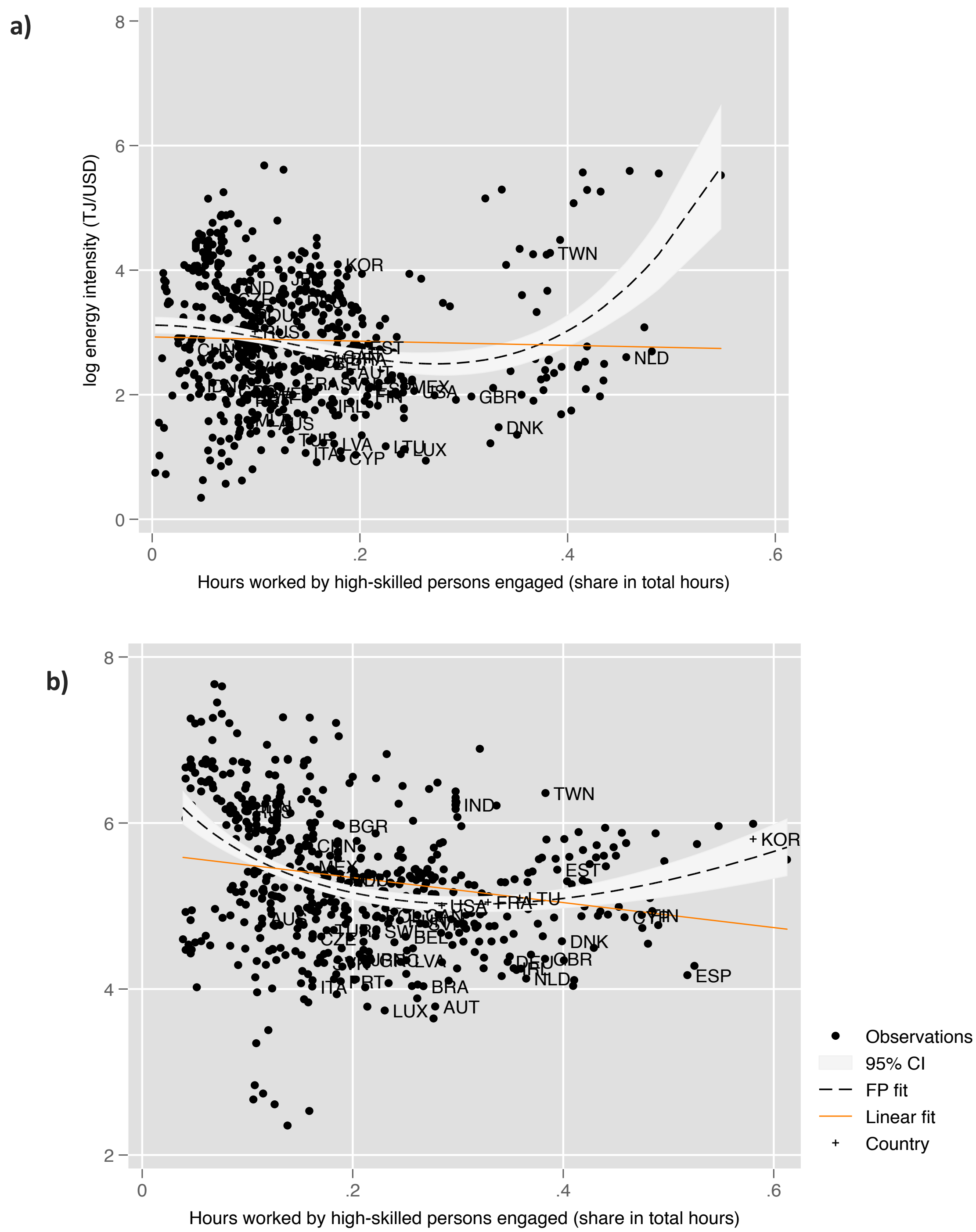

Figure 18. Relation between energy intensity and high-skilled persons employed in mining & quarrying (a) and electricity, gas & water supply (b).

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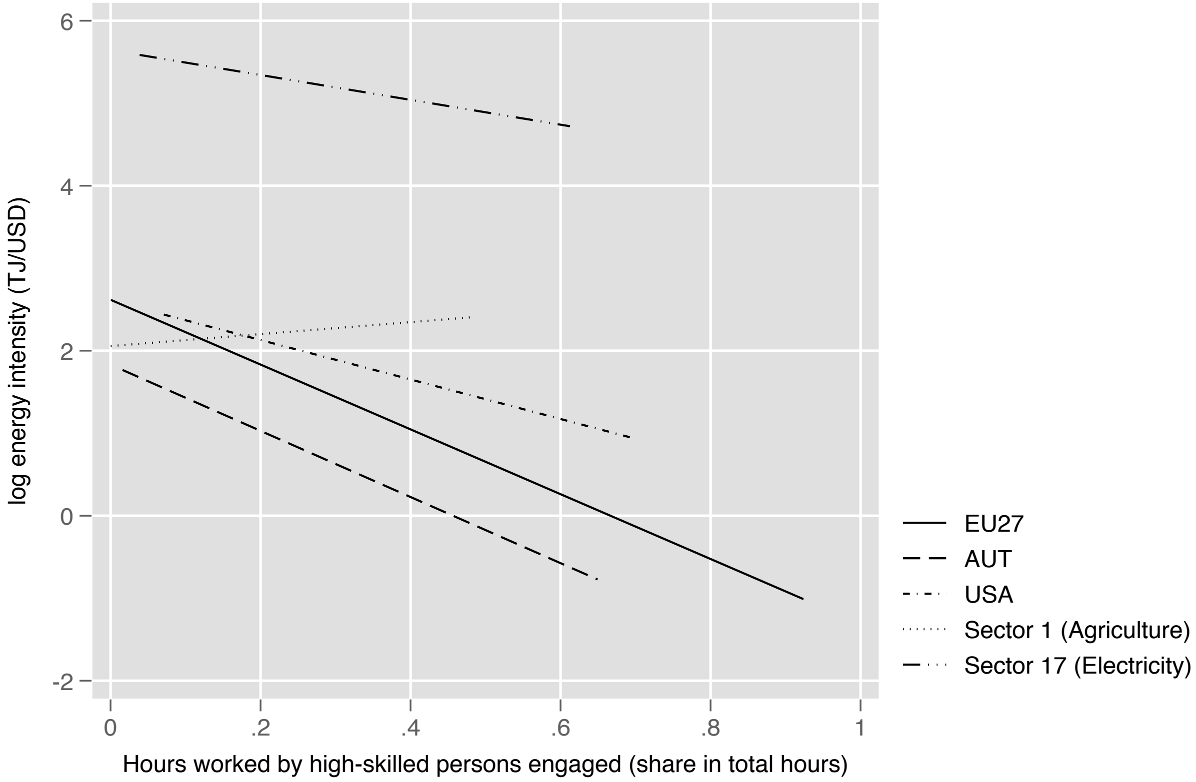

Figure 19. Linear relation between energy intensity and high-skilled labour across sectors and countries.

An important relationship concerns value added in relation to gross output of a sector. This relationship has a strong impact on energy intensities, as can be seen from Figure 20. The higher the value-added share of gross output (VA_GO), the lower the energy intensity of a sector. This is as hypothesized due to the fact that lower value-added shares imply longer processing chains within a sector, but would require further specific tests to be confirmed. This is not the focus of our analysis, however.

Another standard variable that influences energy intensities is the capital stock available in a sector per person employed (K_per_EMP). It is plausible to assume that a higher capital stock implies lower energy intensities. While higher capital stocks also imply more use of energy, the energy intensity reduces as the capital stock increases. This can be seen in Figure 21. A simple relation can illustrate the observation: A light-weight and energy-efficient car can still be less energy-efficient than a heavy-weight car, if the energy use increases less than proportionally with car weight. Energy intensities imply relations, and cannot inform us about absolute energy use scales.

Note that this relationship is not linear, especially for low levels of capital use. Nevertheless, different econometric specifications imply that a linear estimation is the most efficient fit.

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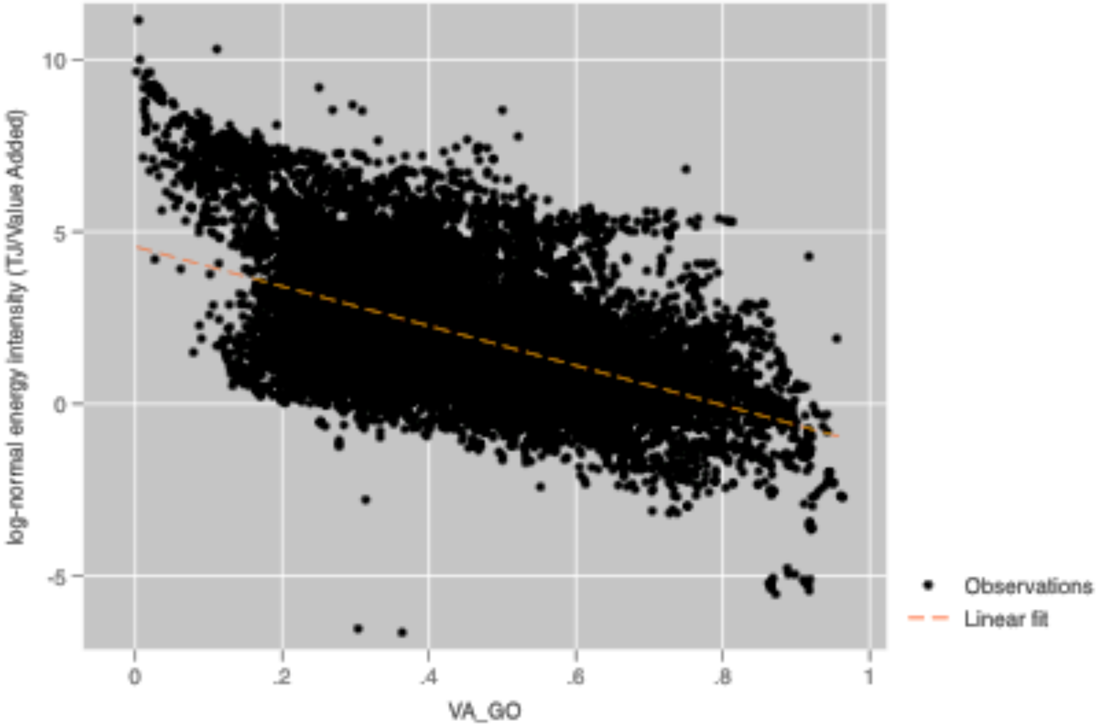

Figure 20. Energy intensity as a function of the relation between value added and gross output.

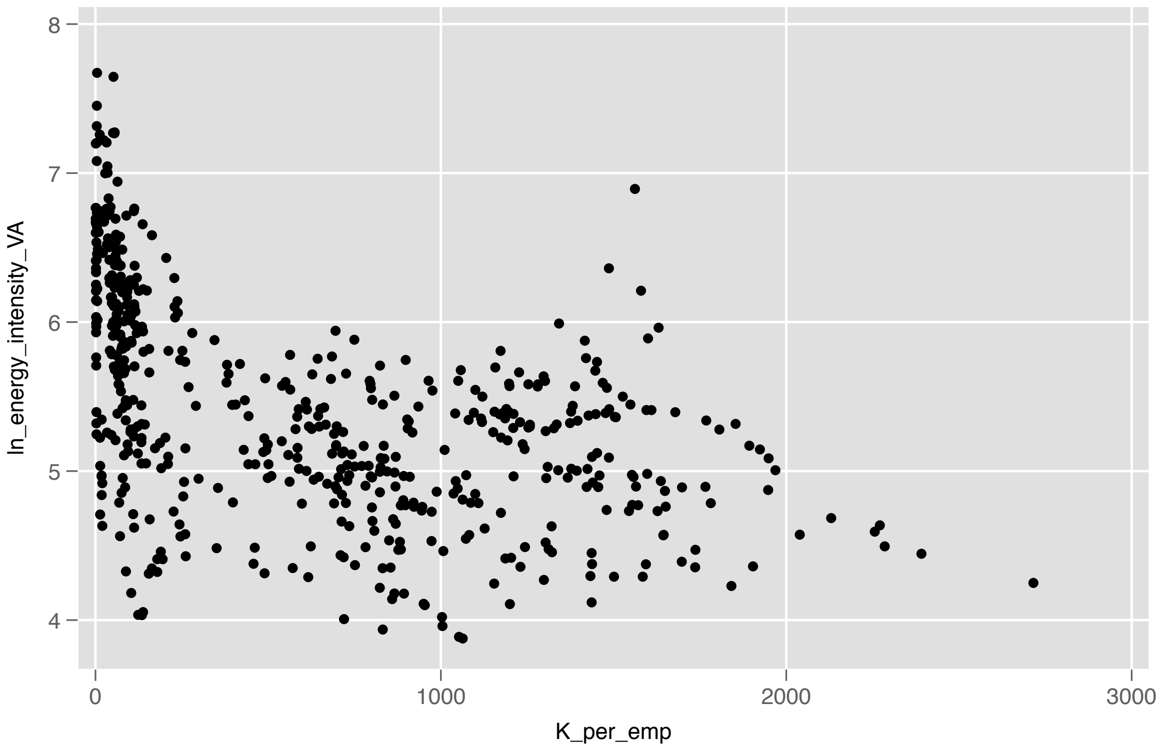

Figure 21. Energy intensity of the sector electricity & gas and water supply as a function of the capital stock per person.

Finally, while the capital stock reflects the stock variable of capital, we also need to account for the changes in capital stock, which are accounted by the variable Gross Fixed Capital Formation (GFCF). Figure 22 depicts this relationship with log-scaled GFCF. The results suggest that energy intensity is influenced by the changes in capital stock, although the reduction is relatively small. While new capital stock requires additional energy, the newly adopted capital is in general more energy-efficient than the older capital.

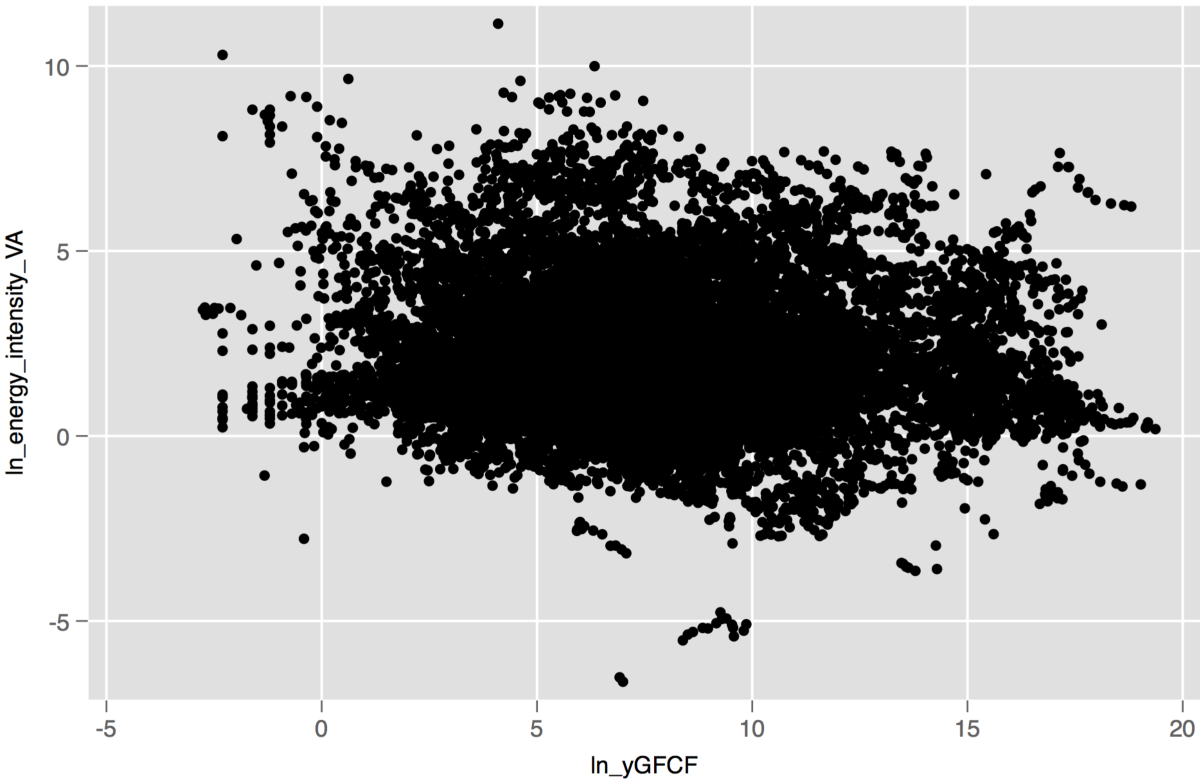

Figure 22. Energy intensity as a function of Gross Fixed Capital Formation.

These control variables help us to estimate the net effects of labour skills on energy intensities. We employ a country fixed-effects (FE) Ordinary Least Squares (OLS) panel regression to estimate our model. A panel regression analyses the effects of time-dependent and cross-sectional independent variables. The country fixed-effects control for the time-independent unobserved characteristics of each country. The following tables provide the model results (M1-M35) for each sector of WIOD (Tables 2-5). As can be seen from the standard errors in parentheses, the relationship is quite strong and statistically significant for almost all coefficients. "yH_HS" is the variable for the share of high-skilled labour. We found that the effects of Gross Fixed Capital Formation are stronger in a linear relation of GFCF per person employed in a sector. Only the best model specifications are reported

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here. The explanatory strength is considerable for explaining the within-country evolution of energy intensities, but the model can only explain the variance between countries for a number of sectors.

Table 2. FE panel regression for sectors M1-10.

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
VA_GO	-2.47 (0.41)	-3.84 (0.44)	-2.81 (0.51)	-2.47 (0.51)	-2.98 (0.44)	-2.27 (0.59)	-2.13 (0.52)	-5.50 (0.43)	-4.17 (0.44)	-4.40 (0.65)
yH_HS	-2.64 (0.72)	-0.82 (0.52)	-3.20 (0.49)	-2.72 (0.64)	-4.62 (0.70)	-1.08 (0.81)	-3.53 (0.53)	-10.54 (1.20)	-8.31 (0.69)	-3.32 (0.84)
yGFCF_P	-0.24 (0.03)	-0.43 (0.05)	-0.31 (0.03)	-0.33 (0.04)	-0.25 (0.04)	-0.20 (0.04)	-0.33 (0.03)	-0.33 (0.08)	-0.28 (0.03)	-0.21 (0.04)
K_per_emp	-1.97 (0.56)	-0.64 (0.11)	-6.32 (0.63)	-3.01 (1.02)	-0.17 (0.13)	-3.11 (0.98)	-2.23 (0.42)	-0.93 (0.16)	-1.19 (0.32)	-11.24 (1.08)
_cons	3.74 (0.23)	5.48 (0.25)	3.95 (0.15)	3.56 (0.19)	3.39 (0.15)	3.66 (0.22)	4.04 (0.22)	9.87 (0.21)	6.72 (0.19)	4.38 (0.26)
R^2 within	0.17	0.27	0.40	0.23	0.25	0.08	0.28	0.34	0.39	0.28
R^2 between	0.04	0.02	0.47	0.09	0.01	0.09	0.04	0.04	0.09	0.32

Table 3. FE panel regression for sectors M11-20.

	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20
VA_GO	-5.11 (0.61)	-1.50 (0.62)	0.32 (0.65)	-1.96 (0.43)	-1.14 (0.43)	-1.92 (0.69)	-2.42 (0.22)	-0.54 (0.62)	-4.29 (0.46)	-3.14 (0.39)
yH_HS	-6.91 (0.73)	-7.46 (0.75)	-6.63 (0.71)	-5.02 (0.78)	-4.90 (0.70)	-5.44 (0.92)	-2.72 (0.29)	-0.95 (0.80)	-3.30 (0.54)	-4.85 (0.51)
yGFCF_P	-0.39 (0.04)	-0.37 (0.04)	-0.38 (0.05)	-0.39 (0.05)	-0.17 (0.04)	-0.22 (0.05)	-0.32 (0.03)	-0.51 (0.04)	-0.16 (0.04)	-0.21 (0.04)
K_per_emp	-2.70 (0.46)	-5.74 (0.93)	-2.36 (0.79)	-1.81 (0.79)	-5.22 (0.73)	-1.17 (0.97)	-0.70 (0.08)	-25.69 (2.18)	-7.80 (1.08)	-11.04 (1.02)
_cons	6.64 (0.28)	5.15 (0.24)	2.39 (0.25)	2.70 (0.17)	2.81 (0.17)	3.05 (0.30)	7.53 (0.13)	2.49 (0.26)	4.12 (0.29)	3.62 (0.24)
R^2 within	0.34	0.37	0.29	0.25	0.24	0.12	0.42	0.31	0.26	0.40
R^2 between	0.20	0.18	0.07	0.06	0.22	0.03	0.17	0.07	0.04	0.05

The chosen model specification is especially strong for those sectors that are in general also energy-intensive. Food processing (M3), Rubber and plastics (M10), the electricity sector (M17) and inland transport (M23) stand out with high R^2 values, for both within and between country variances.

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Table 4. FE panel regression for sectors M21-30.

	M21	M22	M23	M24	M25	M26	M27	M28	M29	M30
VA_GO	-4.61 (0.32)	-4.13 (0.41)	-0.98 (0.37)	0.35 (1.37)	-5.84 (0.32)	-2.93 (0.33)	-1.90 (0.28)	-3.94 (0.31)	-0.66 (0.50)	-4.06 (0.45)
yH_HS	-2.85 (0.53)	-2.03 (0.57)	-0.71 (0.56)	-2.86 (3.43)	-5.25 (0.79)	-1.79 (0.59)	-4.69 (0.56)	-3.66 (0.26)	-2.24 (0.57)	-4.24 (0.35)
yGFCF_P	-0.30 (0.03)	-0.28 (0.03)	-0.36 (0.03)	-0.29 (0.21)	-0.46 (0.05)	-0.47 (0.04)	-0.27 (0.04)	-0.22 (0.04)	-0.21 (0.05)	-0.24 (0.04)
K_per_emp	-19.27 (1.85)	-18.17 (1.59)	-4.93 (0.47)	-1.78 (0.70)	-1.81 (0.28)	-3.98 (0.39)	-1.44 (0.27)	-3.56 (0.53)	-0.03 (0.01)	-3.18 (0.41)
_cons	4.78 (0.22)	4.19 (0.22)	3.99 (0.22)	4.66 (0.70)	7.47 (0.17)	3.89 (0.19)	2.82 (0.21)	3.79 (0.23)	0.91 (0.47)	4.58 (0.31)
R^2 within	0.43	0.36	0.31	0.02	0.47	0.42	0.25	0.45	0.08	0.36
R^2 between	0.24	0.27	0.22	0.02	0.40	0.11	0.03	0.04	0.28	0.07

Table 5. FE panel regression for sectors M31-34.

	M31	M32	M33	M34
VA_GO	-3.14 (0.34)	-1.35 (0.48)	-2.72 (0.35)	-0.10 (0.36)
yH_HS	-3.99 (0.29)	-2.49 (0.35)	-2.39 (0.35)	-3.84 (0.50)
yGFCF_P	-0.19 (0.04)	-0.20 (0.04)	-0.22 (0.04)	-0.13 (0.04)
K_per_emp	-2.52 (0.32)	-8.22 (1.26)	-10.99 (1.18)	-2.96 (0.86)
_cons	4.54 (0.23)	3.65 (0.43)	3.69 (0.24)	2.32 (0.22)
R^2 within	0.51	0.25	0.35	0.23
R^2 between	0.16	0.08	0.31	0.03

A comparison between the models also indicates where the magnitude of the labour skill coefficient ("yH_HS") is especially strong. Sector 8 (Coke, refined petroleum, and nuclear fuel) and Sector 9 (Chemicals and chemical products), (M8 and M9 respectively) stand out in this regard, as could be expected. Capital intensity per employed person ("K_per_emp") reduces energy intensity especially in the Sector 10 (Rubber and plastics) and Sector 20 (Wholesale trade and commission trade).

These findings have a fundamental policy implication: Education levels seem to correlate strongly with energy intensities of economic sectors, i.e. the higher skilled labour employed by a sector, the

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lower its energy intensity. This suggests that it is worth further investigating education as a means of reducing energy intensity. The biophysical rationale is that higher labour skills are required to employ technology that is less energy-intensive. The differences between sectors can guide policies to identify those sectors where the effects are strongest.

Obviously, correlation does not imply causality. It is likely that there are interaction effects between capital vintages and labour skills demanded. Only jointly can new capital and suitable labour reduce energy intensities. Further investigations would need to look at such multiplicative interaction effects with appropriate proxies for capital vintages.

In a next step, these models can be used to estimate future energy intensities under different scenarios concerning education and the development of high labour skills. This also enables us to calculate the minimally feasible energy intensities, given an optimal global distribution of high-skilled labour. Thereby, a tough but achievable goal for energy intensities on a global scale could be estimated. Unlike the physical optimum for energy intensities, which is derived for a technology by assuming optimal use, this analysis therefore provides us with an estimate of what is realistically feasible within the next decades on a global scale, albeit conservatively assuming current technologies. An illustration makes this point clear: The fuel use of a car can be measured with an optimal driving style, approaching the physical optimum, or alternatively with an average driving style observed in the streets. The estimated energy intensities with non-optimal use will remain significantly above the physically achievable optimum. Also, high-skilled labour will usually not utilize machinery optimally, as even automated control systems cannot account for all environmental conditions.

3.3.2. Critical aspects for the energy system transformation

3.3.2.1. Literature review

Many studies analysing the employment effects of a transition to a more sustainable, low-carbon or post-carbon economy have been carried out, especially in the context of the European Union (EU) (Acquaye et al., 2017; Calzadilla et al., 2014; de la Rúa and Lechón, 2016; Markandya et al., 2016; Ortega et al., 2015). At the same time, the financial crisis has triggered interest of economists in possible negative socioeconomic consequences of the post-carbon transition, including increasing unemployment and amplified inequality. Any such analysis needs to consider both environmental and socio-economic implications.

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Recently, many roadmaps to a low-carbon economy have been developed. The literature on the employment effects associated with a low-carbon transition and, especially, with renewable energy deployment is abundant as well (Markandya et al., 2016). We have searched through existing studies on employment effects of the renewable transition using input-output analysis. Other methods were not considered due to their incomparability with the input-output framework (and thus to our analysis), which, unlike other types of analysis takes into account direct as well as indirect effects (Ortega et al., 2015). The following combination of key words was used:

- Input-output – labour
- Input-output – job effects
- Input-output – employment
- Input-output – technological change
- Input-output – green jobs

From the results it was already obvious that many of the studies are concerned with the topic of the renewable transition, even though we did not explicitly mention the renewable energy transition in the keywords. To double-check the search, we did a second round with the following key words:

- Job effects – renewable transition
- Employment effects – renewable transition
- Job effects – low-carbon economy
- Employment effects – low-carbon economy

Out of the overall 34 studies found, most focus on the country level (de la Rúa and Lechón, 2016; Garrett-Peltier, 2017; Haerer and Pratson, 2015; Hienuki et al., 2015; Hondo and Moriizumi, 2017; Markaki et al., 2013; Nakano et al., 2017; Oliveira et al., 2013; Silalertruksa et al., 2012; Varela-Vázquez and Sánchez-Carreira, 2017) and on various renewable energy sources, and 5 deal with the EU (Acquaye et al., 2017; Calzadilla et al., 2014; de la Rúa and Lechón, 2016; Markandya et al., 2016; Ortega et al., 2015; Tarancón et al., 2017). Because of their methodology combining the input-output approach with EU climate goals, (Markandya et al., 2016; Ortega et al., 2015) are the most relevant sources of comparison with our study.

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Markandya et al. (2016) look at the past net employment impacts from the transformation of the EU energy sector including spill-over effects, by using a multi-regional input-output model and the World Input-Output Database. They show that the gradual increase in using renewable energy sources between 1995 and 2009 created 530,000 jobs in the EU (0.24% of total employment in 2009). One third of the jobs created in the EU were a consequence of spill-over effects (i.e. employment generated in one country due to the changes in another). In 21 out of the 27 member states the total effect on employment was positive. The main gainers were Poland, Germany, Hungary, Italy and Spain. The main losers in terms of total job creation (destruction) were Ireland, Lithuania, France and the Czech Republic, with most of the losses in the sector of Mining and Quarrying, respectively Coke, Refined Petroleum and Nuclear Fuel (Markandya et al., 2016). The losses due to the decline in the Mining and Quarrying sector were concentrated in Germany, Poland and the Czech Republic. However, in Germany the job losses in the fossil fuels industry were compensated by the job creation in the renewable energy industry.

Markandya et al. (2016) recommend to:

- Focus on the trans-boundary effects due to changes in trade flows derived from the transformation in the energy sector of a specific country. Especially relevant in an increasingly globalized world, in which the production inputs are internationally traded.
- Learn from the ex-post (confirmed) results of "post-carbon interventions ", rather than on the ex-ante (predicted) impacts of different policies. Do not make a high number of assumptions about the evolution of the economy.

Ortega et al. (2015) discuss the differences between importing and exporting countries, calculating the dynamic employment factors (considering technology learning effects) and trade effects. Their approach is applied to three renewable energy technologies: photovoltaics, wind on-shore and wind off-shore in the EU Member States in the 2008-2012 period.

One of the major recommendations by Ortega et al. (2015) is to consider carefully the learning curve. For example, learning curves imply that technological improvements together with economies of scale lead to cost reductions and can result in a reduction of jobs per unit produced or installed. (which is somewhat similar to the second recommendation on making assumptions about the evolution of the economy given by Markandya et al. (2016).

Ortega et al. (2015) and IRENA (2013) also mention three types of employment associated to renewable energy sources.

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- **Direct employment** – jobs being created in the renewable energy sector, without considering the employment created in the value chain of other manufacturing industries (e.g. manufacturing of wind turbines).

- **Indirect employment** – jobs generated in secondary sectors of activity, which are not directly related to the renewable energy sector while they provide inputs to its main activities (e.g., steel industry).

- **Induced employment** refers to the employment created in other sectors of activity, which are different to the main and secondary sectors associated to renewable energies and not linked with their value chain. The increase in the income of workers in sectors directly or indirectly related to renewable energies can lead to such employment depending on where that extra income is spent (e.g., jobs created in unrelated service sectors such as leisure).

Similarly, Calzadilla et al. (2014), studying the employment effects of PV, CSP, and wind energy in Middle East and North Africa countries (Egypt, Morocco, and Saudi Arabia) and European countries (Germany and Spain), also point out the importance of indirect job creation – both national and international – that results from the domestic and import demand of renewable energy sectors for equipment and intermediate goods (in IOA language, backward linkages and trade linkages).

The vast majority of studies (including non-IO ones) confirm that the renewable energy transition is about to bring more jobs than destroy. Ragwitz et al. (2009) suggest that policies supporting renewable sources of energy to meet the 20% target by 2020 would provide 410,000 additional jobs in the EU. Another study by Cambridge Econometrics ("Employment Effects of selected scenarios from the Energy roadmap 2050," 2013) estimates that the 2050 Road Map, which is also of our concern in this study, would result in an increase in employment ranging up to 1,5%. Similar results emerge from more local studies in Europe (Lehr et al., 2012; Markaki et al., 2013; Moreno and López, 2008). They find slightly higher employment in a scenario with more renewables and less fossil fuel energy than the base case.

Cai et al. (2014) call specifically for studying the distributional employment impacts of renewable and new energy (RNE) development on **gender and personnel structure**. The case study of the Chinese power sector in their paper says that RNE development will aggravate the gender inequality problem (RNE needs engineers, who are currently mostly men – therefore, if the demand trend would continue, the gap between men and women would become even bigger) and add to the level of mismatch between the structure of labour demand and supply, causing structural unemployment problems. The quantitative analysis in this report outlined here implies that from 2011 to 2020 the

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development of RNE will bring about 7 million employment gains, but only 81.8% of which can be realized due to the mismatch problem. The authors suggest providing suitable training and equal promotion opportunities for women, offering courses and vocational trainings to RNE-related majors, in order to reduce the structural unemployment problem and further speed up the development of RNE.

Among the non-IO studies, (Bernardo and D'Alessandro, 2016) evaluate the socioeconomic consequences in terms of job creation of the implementation of the EU 2050 Energy roadmap (European Commission, 2014) in Italy, with the assumption that the number of workers per unit of energy being constant. It is, however, plausible that the required units of labour change over time. The authors show that the effect on the overall level of unemployment depends on the elasticity of wages to the employment rate in the energy sector. If this elasticity is high (low) the effect of an increase in green job creation on the unemployment rate can be negative (positive). This elasticity can be interpreted as the bargaining power of the workers in the sector of renewable energy.

3.3.2.2. Direct and indirect labour demand of electricity production

We have conducted an analysis of the current direct versus indirect labour demand for the sector Electricity, Gas, Steam and Air-conditioning supply (Table 6). This was done in order to see how many jobs in the current Austrian economy (as a case study at the country level) is generated directly within the sector itself, and how many jobs are created indirectly, via demand for products from other sectors.

Roughly one half of the jobs is generated directly (27,099), while most of the indirectly created jobs are in the sectors such as Administrative and support service activities (4,035), Warehousing and support activities for transportation (2,529), Construction (2,371), Repair and installation of machinery and equipment (1,687), Financial service activities, except insurance and pension funding (1,678), Wholesale trade, except of motor vehicles and motorcycles (1,649), Legal and accounting services; activities of head offices; management consultancy activities (1,506), and Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services (1,491).

This information can already give some guidance on which sectors might be affected by the transition and, therefore, also changes in input cost shares from other sectors to the sector Electricity, gas, steam and air conditioning supply. However, to know precisely which sectors will

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"lose" and which will "win" in terms of jobs creation/destruction thanks to the transition to the low-carbon economy, one has to know what are the exact shares of particular energy sources used for electricity production (fossil fuels, nuclear, hydro, wind, solar, biomass…) relative to the sector's total output. This is analysed in the next part, 6.2.c.3.

Table 6. Direct (sector Electricity, gas, steam and air-conditioning supply) and indirect (other sectors) labour demand of the sector Electricity, gas, steam and hot water supply (situation of 2014).

WIOD 2016 release sector	Changes in labour demand (Number of employees)
Electricity, gas, steam and air conditioning supply	27,099
Administrative and support service activities	4,035
Warehousing and support activities for transportation	2,529
Construction	2,371
Repair and installation of machinery and equipment	1,687
Financial service activities, except insurance and pension funding	1,678
Wholesale trade, except of motor vehicles and motorcycles	1,649
Legal and accounting activities; activities of head offices; management consultancy activities	1,506
Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services	1,491
Land transport and transport via pipelines	1,109
Mining and quarrying	938
Accommodation and food service activities	811
Retail trade, except of motor vehicles and motorcycles	636
Architectural and engineering activities; technical testing and analysis	592
Computer programming, consultancy and related activities; information service activities	498
Advertising and market research	430
Manufacture of electrical equipment	400
Education	390
Postal and courier activities	375
Wholesale and retail trade and repair of motor vehicles and motorcycles	366
Manufacture of machinery and equipment n.e.c.	356
Manufacture of fabricated metal products, except machinery and equipment	331
Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	327
Other service activities	304
Manufacture of other non-metallic mineral products	266
Public administration and defense; compulsory social security	263
Manufacture of basic metals	210
Real estate activities	181
Forestry and logging	179

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WIOD 2016 release sector	Changes in labour demand (Number of employees)
Telecommunications	162
Insurance, reinsurance and pension funding, except compulsory social security	150
Manufacture of food products, beverages and tobacco products	133
Activities auxiliary to financial services and insurance activities	130
Other professional, scientific and technical activities; veterinary activities	123
Publishing activities	112
Motion picture, video and television program production, sound recording and music publishing activities; programming and broadcasting activities	99
Printing and reproduction of recorded media	92
Air transport	76
Manufacture of rubber and plastic products	75
Manufacture of computer, electronic and optical products	66
Human health and social work activities	65
Manufacture of furniture; other manufacturing	63
Crop and animal production, hunting and related service activities	59
Water collection, treatment and supply	52
Manufacture of paper and paper products	45
Manufacture of chemicals and chemical products	30
Manufacture of basic pharmaceutical products and pharmaceutical preparations	22
Scientific research and development	19
Manufacture of motor vehicles, trailers and semi-trailers	18
Manufacture of textiles, wearing apparel and leather products	16
Manufacture of coke and refined petroleum products	12
Manufacture of other transport equipment	12
Water transport	1
Fishing and aquaculture	0
Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use	0

3.3.3. Social patterns helping to reach 2050 objectives

Wind onshore, solar PV, and biomass and waste are taken as sources of energy to replace fossil fuels because of their increasing importance in the energy mix and also promising competitiveness in comparison with conventional energy sources (REN21, 2017). Biomass and waste is included to partially compensate the base-load provided by conventional (fossil) sources of energy with stable supply to the grid.

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Electricity production is one of the largest sources of GHG (Greenhouse Gases) emissions from human activities from burning fossil fuels (together with heat and transportation) worldwide as well as in the European Union (IEA, 2018), which is why we focus on modelling changes in the sector of electricity production. However, if one would like to obtain a broader picture of the low-carbon economy, the next steps would be to focus on replacing fossil inputs in e.g. transportation or other sectors that are heavily dependent on fossil fuels.

Input-Output analysis with socioeconomic accounts (labour demand, full-time employees equivalent) are used to calculate the results. As a data source, WIOD 2016 release, combined with EXIOBASE v3 (with detailed sectors of electricity production) are used. WIOD 2016 sector „Electricity, gas, steam and air conditioning supply" is divided into 6 parts based on EXIOBASE v3 sectors:

- Electricity by hydro
- Electricity by wind
- Electricity by biomass and waste
- Electricity by solar PV
- Share of other RES and transmission + gas + steam and hot water supply
- Electricity by fossil fuels

For each part, shares (percentage of the total output of the aggregated WIOD sector) are calculated in case of each technical coefficient of the "Electricity, gas, steam and air conditioning supply"sector in the WIOD structure. Electricity by fossil fuels is then gradually replaced by wind, solar PV and biomass. Given that by 2050 the goal is to get rid of all fossil fuels, 50% is replaced in 2030 and the whole subsector of Electricity by fossil fuels is replaced by 2050).

The rest of the section is organised as follows: First, links to the MEDEAS model structure are explained. Second, the results (employment effects by WIOD sectors in general, and by skill levels and gender) are presented first for the zero GDP growth scenario, then for OLT (Optimum Level Transition) and for MLT (Mid-Level Transition) scenarios. The results are presented in Tables 7-18. The implications of the results are briefly discussed in the following section – Conclusion.

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3.3.3.1. Links to MEDEAS

GDP per capita evolution for different scenarios (OLT, MLT) in MEDEAS EU, as described in Deliverable 4.2 and in the "outputs" data document, is used as a basis for calculating the labour market effects. The OLT scenario is assumed to cover GDP developments for BAU+SCEN2, while what we refer to as MLT scenario covers GDP developments for SCEN3+SCEN4 from MEDEAS EU outputs data (Deliverable 4.2).

Apart from OLT and MLT scenarios with parameters taken from Deliverable 4.2, we also added another scenario for the IOA, assuming zero GDP growth, while keeping all other OLT and MLT parameters. The reason for this was to identify the differences in coefficient changes and labour demand stemming only from the energy mix change (shift from fossil fuels to using exclusively renewable energy), and not from the different GDP growth assumptions. We consider this helpful to derive the effects ceteris paribus, i.e. to isolate the effects of energy mix changes per se.

However, since, in MEDEAS, GDP is an endogenous variable, the exogenous GDP trend can be achieved only in the case that there are not constraints, limiting the GDP developments. It should be noted that the scenarios used to calculate the employment effects are not yet adjusted by the environmental constraints. Nevertheless, this is mostly the case of the OLT scenario, which assumes a 1.9% GDP growth over the whole period until 2050. MLT scenario fits better to the environmental limits, described in task 3.5 (by INSTM). MLT scenario used here assumed 0.7% annual GDP growth until 2030, and then 2.5% GDP decline until 2050. To compare the scenarios (and their complementarities) please see Deliverable 4.4 with a more detailed description.

One might object that the abrupt changes (in case of the MLT scenario) in the reference year of 2030 does not seem very realistic. Nevertheless, as we do not track changes in employment year by year, but we are rather interested in the aggregate effects *after* the transition takes place, we believe that this is not a problem for the calculations, as they are also focused on the aggregate effects first between 2014 and 2030, and then between 2030 and 2050.

The comparison between the Zero growth, OLT and MLT in the form described above is also interesting, since it gives (although rough) idea about the employment effects in case of a) unchanged GDP levels, b) GDP growth, c) GDP decline. Therefore, it gives general information what can be expected (at a case study of Austria as an example) at the country level if such transition takes place and if a certain development of GDP happens. The three trends (zero growth, growth

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and decline) can be then further multiplied, depending on the exact rates of growth/decline, but our calculations give an idea of the overall trends in employment structure that might be expected. The year 2014 is taken as the starting point since this is the year when the latest data from WIOD are reported.

For comparison, the following two paragraphs describe the relation of the OLT and MLT scenarios used here with the scenarios used by INSTM after imposing the environmental limits.

In case of OLT as implemented by INSTM, GDP is assumed to grow every year of 1.9% according to the average yearly rate of the last few years for Europe until 2020; then from 2020 to 2050, the yearly rate decrease of -1.0% is assumed (the *Green Degrowth 2020* scenario). OLT in our case is different from these rates, apart from the starting period until 2020. It assumes 1.9% GDP growth for the whole period until 2050.

In case of MLT as implemented by INSTM, GDP is assumed to grow every year of 1.9% according to the average yearly rate of the last few years for Europe until 2030 (respectively 2030 is the first year when the GDP growth stops); then the yearly decrease rate of -3% until 2050 is assumed (the *Green Degrowth 2030* scenario). This scenario fits in fact to our calculations better, as we assume 0.7% GDP growth until 2030 and then 2.5% GDP decline (annually) after 2030.

Figure 23 shows the MEDEAS socioeconomic module, which calculates the expected GDP per capita for the different scenarios (“Final GDP”). The “benchmark” Zero growth scenario is not linked to MEDEAS outputs and serves only for a comparison of the effects of the transition to the renewable energy itself and the effects of the changes in GDP. Its level of GDP is taken from WIOD data, 2016 release.

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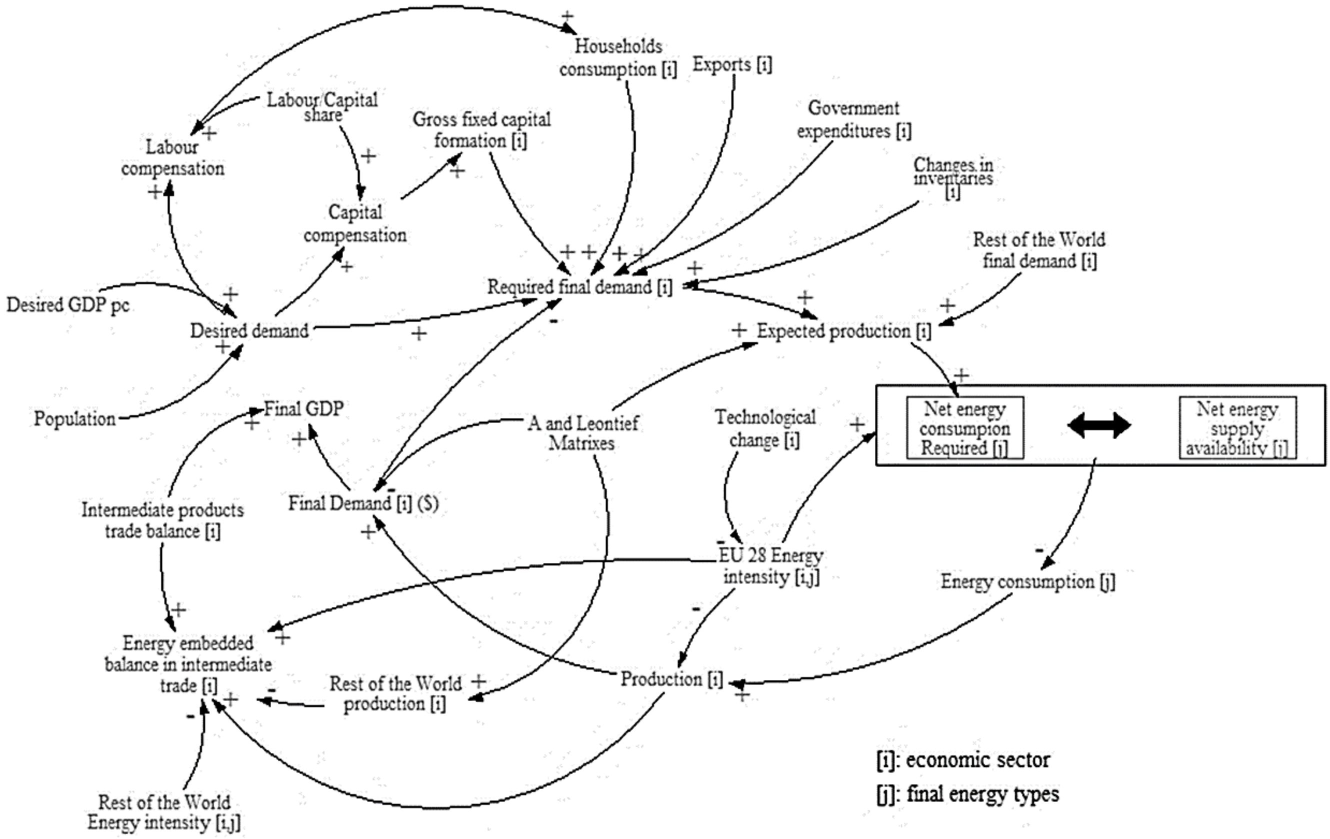

Figure 23. MEDEAS socioeconomic module.

3.3.3.2. Zero growth scenario

Zero growth scenario is used as a benchmark to differentiate between the effects of the transition to the renewable energy itself, and the effects of GDP growth or decline. Therefore, this scenario is not built upon the previous work in MEDEAS. It assumes the same level of GDP as in 2014, and shows what would be the employment impacts of the transition to the renewable energy without any other intervening effects.

The results below show the expected employment changes by WIOD sectors in case of zero GDP change between 2014, 2030 and 2050. These numbers give a rough idea on how would the transition itself affect the economy, without the effects caused by the GDP growth (or, vice versa, by the GDP decline). Table 7 shows the sectors where the biggest employment changes are likely to take place. Interestingly, apart from the sector Electricity, gas, steam and air conditioning supply itself, the biggest increase would happen in the sector Mining and quarrying (almost 1000 new jobs). This might be due to an increased need for inputs to the renewable energy construction and

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operation, such as need for silica or alumina or other metals necessary for construction of solar PV panels and wind turbines.

Table 7. Zero GDP growth scenario, selected sectors' employment changes

Labour demand (Number of employees)	2014	2030	2050
Forestry and logging	7,642	7,709	7,723
Mining and quarrying	7,695	8,486	8,581
Manufacture of coke and refined petroleum products	1,211	1,210	1,209
Manufacture of electrical equipment	42,148	42,288	42,301
Repair and installation of machinery and equipment	28,151	27,743	27,716
Electricity, gas, steam and air conditioning supply	27,099	28,509	28,626
Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services	21,873	21,227	21,179
Wholesale and retail trade and repair of motor vehicles and motorcycles	72,949	72,822	72,797
Wholesale trade, except of motor vehicles and motorcycles	193,918	193,466	193,359
Land transport and transport via pipelines	112,664	112,320	112,241
Air transport	7,375	7,395	7,397
Warehousing and support activities for transportation	52,604	51,702	51,551
Postal and courier activities	24,982	24,960	24,963
Computer programming, consultancy and related activities; information service activities	55,056	55,052	55,060

Source : WIOD 2016 release, EXIOBASE v3, own calculations

Further below, Table 8 describes the impacts of the “zero growth” transition scenario on different skill levels and gender. We can see that the impacts on the different groups are quite uniform. The lowest impact is on high-skilled labourers, albeit still perfectly comparable to the other groups. Males and females are affected equally.

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Table 8. Zero GDP growth scenario, total employment changes by skill level and gender

Labour demand (Number of employees)	2014	%2014-2030	2030	%2030-2050	2050	%2014-2050
Low-skilled	406,887	*-0.12%*	406,388	*-0.01%*	406,354	*-0.13%*
Medium-skilled	1,859,153	*-0.12%*	1,857,002	*-0.01%*	1,856,789	*-0.13%*
High-skilled	1,457,396	*-0.10%*	1,455,893	*-0.01%*	1,455,783	*-0.11%*
Male	1,934,285	*-0.11%*	1,932,136	*-0.01%*	1,931,944	*-0.12%*
Female	1,789,151	*-0.11%*	1,787,147	*-0.01%*	1,786,982	*-0.12%*

Source: WIOD 2016 release, EXIOBASE v3, own calculations

Table 8 summarizes the impacts of the “zero growth” transition. Again, it is clearly visible that the changes caused by the transition itself (without growth/decline of GDP effects) will be very minor, if any. The changes are in the range of hundreds, only exceptionally in thousands of full-time employees’ equivalents, even in the most affected sectors such as the Electricity, gas, steam and air conditioning supply sector or the Mining and Quarrying sector.

The reason for such developments in employment lies very likely in the similarities in the input cost shares structure for the renewable energy sources considered. The structure of employment generated by the Electricity, gas, steam and air conditioning supply sector now is not dramatically different from those generated by the same sector, if based on increasing share of renewable energy. This might be because of some common requirements necessary for all energy sources. AT the sectoral level, the differences are thus barely visible. The proposed next step would be to look at the product structure of inputs, which could give a more detailed idea of the changes in input requirements due to the transition.

3.3.3.2.1. 2014-2030 employment changes

Table 9 below show the expected labour demand changes between 2014 and 2030 for the benchmark Zero growth scenario. The biggest increase in this period is expected in the sectors 1) Electricity, gas, steam and air conditioning supply, 2) Mining and quarrying, and 3) Manufacture of electrical equipment. These three main “winners” are followed by Forestry and logging, which might increase its importance in terms of job creation due to the increased need for biomass (which is included in the modelled energy mix). Among the main “losers” is, interestingly, apart from administrative sectors, also Construction (-575 full-time job equivalents). Construction may lose its

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importance for the Electricity sector due to lower demand of the renewable energy sources in comparison with the fossil fuels-based energy sources.

Table 9. Zero GDP growth scenario employment changes (2014-2030) by WIOD sectors (Number of employees).

WIOD 2016 release sector	Change in labour demand (Number of employees)
Electricity, gas, steam and air conditioning supply	1,411
Mining and quarrying	791
Manufacture of electrical equipment	140
Forestry and logging	67
Public administration and defence; compulsory social security	63
Air transport	20
Human health and social work activities	1
Water collection, treatment and supply	0
Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use	0
Fishing and aquaculture	0
Water transport	0
Manufacture of coke and refined petroleum products	-1
Manufacture of motor vehicles, trailers and semi-trailers	-1
Manufacture of other transport equipment	-1
Manufacture of chemicals and chemical products	-2
Manufacture of basic pharmaceutical products and pharmaceutical preparations	-2
Scientific research and development	-3
Manufacture of furniture; other manufacturing	-4
Manufacture of textiles, wearing apparel and leather products	-4
Computer programming, consultancy and related activities; information service activities	-5
Manufacture of other non-metallic mineral products	-6
Manufacture of rubber and plastic products	-6
Manufacture of paper and paper products	-8
Telecommunications	-10
Publishing activities	-16
Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities	-18
Crop and animal production, hunting and related service activities	-20
Printing and reproduction of recorded media	-21
Postal and courier activities	-22
Other professional, scientific and technical activities; veterinary activities	-28
Manufacture of computer, electronic and optical products	-29
Activities auxiliary to financial services and insurance activities	-33
Manufacture of food products, beverages and tobacco products	-36

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WIOD 2016 release sector	Change in labour demand (Number of employees)
Insurance, reinsurance and pension funding, except compulsory social security	-38
Real estate activities	-38
Other service activities	-39
Manufacture of fabricated metal products, except machinery and equipment	-60
Architectural and engineering activities; technical testing and analysis	-65
Manufacture of basic metals	-70
Manufacture of machinery and equipment n.e.c.	-78
Advertising and market research	-100
Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	-112
Wholesale and retail trade and repair of motor vehicles and motorcycles	-127
Accommodation and food service activities	-137
Education	-138
Retail trade, except of motor vehicles and motorcycles	-212
Land transport and transport via pipelines	-344
Legal and accounting activities; activities of head offices; management consultancy activities	-347
Repair and installation of machinery and equipment	-408
Wholesale trade, except of motor vehicles and motorcycles	-453
Financial service activities, except insurance and pension funding	-532
Construction	-575
Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services	-646
Warehousing and support activities for transportation	-902
Administrative and support service activities	-949

Source: WIOD 2016 release, EXIOBASE v3, own calculations.

3.3.3.2.2. 2014-2050 employment changes

Table 10 below show the expected changes in labour demand until 2050 for the Zero growth benchmark scenario. The trend shown for the 2014-2030 period is further underlined, with the sector Electricity, gas, steam and air conditioning supply gaining more than 1500 full-time job equivalents; Mining and quarrying over 880 and Manufacture of electrical equipment over 150. In terms of job losses, the most threatened sector is Warehousing and support service activities for transportation, which might be connected to the weakened need for fossil fuels transport for electricity generation (note that also other transport sectors are expected to lose, or stay at the same levels, except for Air transport).

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Table 10. Zero GDP growth scenario employment changes (2014-2050) by WIOD sectors (Number of employees).

WIOD 2016 release sector	Change in labour demand (Number of employees)
Electricity, gas, steam and air conditioning supply	1,527
Mining and quarrying	887
Manufacture of electrical equipment	153
Forestry and logging	81
Public administration and defence; compulsory social security	75
Air transport	23
Computer programming, consultancy and related activities; information service activities	4
Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use	0
Fishing and aquaculture	0
Water transport	0
Water collection, treatment and supply	-1
Manufacture of other transport equipment	-2
Manufacture of coke and refined petroleum products	-2
Manufacture of motor vehicles, trailers and semi-trailers	-2
Human health and social work activities	-2
Manufacture of basic pharmaceutical products and pharmaceutical preparations	-3
Manufacture of chemicals and chemical products	-4
Scientific research and development	-4
Manufacture of textiles, wearing apparel and leather products	-5
Manufacture of furniture; other manufacturing	-7
Manufacture of rubber and plastic products	-8
Telecommunications	-8
Manufacture of paper and paper products	-9
Manufacture of other non-metallic mineral products	-10
Publishing activities	-16
Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities	-18
Postal and courier activities	-18
Crop and animal production, hunting and related service activities	-21
Printing and reproduction of recorded media	-23
Other professional, scientific and technical activities; veterinary activities	-29
Activities auxiliary to financial services and insurance activities	-34
Insurance, reinsurance and pension funding, except compulsory social security	-37
Manufacture of computer, electronic and optical products	-40
Real estate activities	-41
Manufacture of food products, beverages and tobacco products	-41

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WIOD 2016 release sector	Change in labour demand (Number of employees)
Other service activities	-45
Architectural and engineering activities; technical testing and analysis	-63
Manufacture of fabricated metal products, except machinery and equipment	-68
Manufacture of basic metals	-73
Manufacture of machinery and equipment n.e.c.	-83
Advertising and market research	-104
Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	-115
Accommodation and food service activities	-133
Education	-136
Wholesale and retail trade and repair of motor vehicles and motorcycles	-152
Retail trade, except of motor vehicles and motorcycles	-247
Legal and accounting activities; activities of head offices; management consultancy activities	-362
Land transport and transport via pipelines	-423
Repair and installation of machinery and equipment	-435
Financial service activities, except insurance and pension funding	-551
Wholesale trade, except of motor vehicles and motorcycles	-559
Construction	-591
Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services	-694
Administrative and support service activities	-988
Warehousing and support activities for transportation	-1,053

Source: WIOD 2016 release, EXIOBASE v3, own calculations.

3.3.3.3. OLT scenario

The results below show the expected employment changes by WIOD sectors for the Optimal transition level scenario between 2014, 2030 and 2050. This scenario assumes a 1.9% GDP growth over the whole period. Table 10 shows sectors with the biggest expected employment changes, induced by the low-carbon transition, as well as by the GDP growth. Similar to the "zero growth" scenario, the biggest absolute winner is the sector Electricity, gas, steam and air conditioning supply itself, followed by Mining and quarrying and Manufacture of electrical equipment. Again, the distributional effects (on skill levels and on gender) are more or less equally distributed, as can be seen in Table 11.

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Table 11. OLT scenario with 1.9% annual GDP growth, selected sectors' employment changes

Labour demand (Number of employees)	2014	2030	2050
Forestry and logging	7,642	10,060	13,259
Mining and quarrying	7,695	11,073	14,733
Manufacture of coke and refined petroleum products	1,211	1,579	2,075
Manufacture of electrical equipment	42,148	55,183	72,624
Repair and installation of machinery and equipment	28,151	36,203	47,583
Electricity, gas, steam and air conditioning supply	27,099	37,203	49,147
Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services	21,873	27,700	36,361
Wholesale and retail trade and repair of motor vehicles and motorcycles	72,949	95,028	124,981
Wholesale trade, except of motor vehicles and motorcycles	193,918	252,459	331,966
Land transport and transport via pipelines	112,664	146,569	192,699
Air transport	7,375	9,649	12,700
Warehousing and support activities for transportation	52,604	67,467	88,505
Postal and courier activities	24,982	32,571	42,858
Computer programming, consultancy and related activities; information service activities	55,056	71,838	94,530

Source: WIOD 2016 release, EXIOBASE v3, own calculations

The overall employment developments in the OLT scenario are shown below in Table 12. It can be seen that the employment growth gets even faster after 2030, probably due to the continued GDP growth. The most significant changes in the employment increase can be observed in sectors Computer programming, consultancy and related activities; information service activities, followed by other sectors where the link to the transition to the renewable energy itself is not very likely – therefore we assume that these effects are caused by the GDP growth itself. This is also why the "zero growth" scenario is very important, as it helps to distribute between the effects of the GDP growth and of the transition to the renewable sources in the Electricity sector.

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Table 12. OLT scenario with 1.9% annual GDP growth, total employment changes by skill level and gender

Labour demand (Number of employees)	2014	%2014-2030	2030	%2030-2050	2050	%2014-2050
Low-skilled	406,887	*30.33%*	530,306	*31.55%*	697,643	*71.46%*
Medium-skilled	1859,153	*30.34%*	2423,252	*31.55%*	3187,803	*71.47%*
High-skilled	1457,396	*30.36%*	1899,834	*31.56%*	2499,341	*71.49%*
Male	1934,285	*30.35%*	2521,296	*31.55%*	3316,832	*71.48%*
Female	1789,151	*30.35%*	2332,096	*31.55%*	3067,955	*71.48%*

Source: WIOD 2016 release, EXIOBASE v3, own calculations.

3.3.3.3.1. 2014-2030 employment changes

Table 13 shows the employment effects under OLT scenario until 2030. When we compare these figures with data for the "zero growth" scenario, we can observe that changes in some sectors are caused by the renewable transition rather than the GDP growth – such as Air transport, Forestry and logging and Mining and quarrying. Vice versa, job creation in sectors such as Construction or Human health and social work activities is induced rather by the GDP growth than the shift towards the renewable energy.

Table 13. OLT scenario with 1.9% annual GDP growth employment changes (2014-2030) by WIOD sectors (Number of employees).

WIOD 2016 release sector	Change in labour demand (Number of employees)
Human health and social work activities	120,962
Retail trade, except of motor vehicles and motorcycles	101,858
Construction	82,819
Public administration and defence; compulsory social security	77,027
Education	73,716
Accommodation and food service activities	73,106
Administrative and support service activities	64,020
Wholesale trade, except of motor vehicles and motorcycles	58,540
Other service activities	45,153
Land transport and transport via pipelines	33,905
Legal and accounting activities; activities of head offices; management consultancy activities	27,171
Manufacture of food products, beverages and tobacco products	24,347
Manufacture of machinery and equipment n.e.c.	24,317

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WIOD 2016 release sector	Change in labour demand (Number of employees)
Financial service activities, except insurance and pension funding	22,945
Manufacture of fabricated metal products, except machinery and equipment	22,434
Wholesale and retail trade and repair of motor vehicles and motorcycles	22,079
Computer programming, consultancy and related activities; information service activities	16,782
Warehousing and support activities for transportation	14,863
Architectural and engineering activities; technical testing and analysis	14,127
Real estate activities	13,112
Manufacture of electrical equipment	13,035
Manufacture of furniture; other manufacturing	12,761
Manufacture of basic metals	11,223
Electricity, gas, steam and air conditioning supply	10,104
Manufacture of other non-metallic mineral products	9,660
Manufacture of motor vehicles, trailers and semi-trailers	9,545
Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	9,405
Manufacture of rubber and plastic products	9,105
Insurance, reinsurance and pension funding, except compulsory social security	8,838
Repair and installation of machinery and equipment	8,052
Postal and courier activities	7,589
Manufacture of computer, electronic and optical products	6,794
Crop and animal production, hunting and related service activities	6,325
Advertising and market research	6,313
Manufacture of textiles, wearing apparel and leather products	5,828
Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services	5,827
Manufacture of chemicals and chemical products	5,476
Manufacture of paper and paper products	5,306
Telecommunications	4,817
Scientific research and development	4,479
Manufacture of basic pharmaceutical products and pharmaceutical preparations	4,435
Publishing activities	3,899
Activities auxiliary to financial services and insurance activities	3,802
Printing and reproduction of recorded media	3,507
Mining and quarrying	3,379
Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities	3,230
Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use	3,116

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WIOD 2016 release sector	Change in labour demand (Number of employees)
Other professional, scientific and technical activities; veterinary activities	2,644
Forestry and logging	2,418
Air transport	2,275
Manufacture of other transport equipment	2,066
Water collection, treatment and supply	861
Manufacture of coke and refined petroleum products	368
Water transport	140
Fishing and aquaculture	52

Source : WIOD 2016 release, EXIOBASE v3, own calculations

3.3.3.3.2. 2014-2050 employment changes

Employment changes until 2050 for the OLT scenario are shown below. The trend from the years 2014-2030 continues, with most of the employment changes caused by the GDP growth rather than the transition to the low-carbon energy sources in the Electricity, gas, steam and air conditioning supply sector, as is shown in Table 14.

Table 14. OLT scenario with 1.9% annual GDP growth employment changes (2014-2050) by WIOD sectors (Number of employees).

WIOD 2016 release sector	Change in labour demand (Number of employees)
Human health and social work activities	284,355
Retail trade, except of motor vehicles and motorcycles	239,679
Construction	195,444
Public administration and defence; compulsory social security	181,015
Education	173,483
Accommodation and food service activities	172,053
Administrative and support service activities	151,714
Wholesale trade, except of motor vehicles and motorcycles	138,048
Other service activities	106,192
Land transport and transport via pipelines	80,035
Legal and accounting activities; activities of head offices; management consultancy activities	64,318
Manufacture of food products, beverages and tobacco products	57,276
Manufacture of machinery and equipment n.e.c.	57,262
Financial service activities, except insurance and pension funding	54,624
Manufacture of fabricated metal products, except machinery and equipment	52,806
Wholesale and retail trade and repair of motor vehicles and motorcycles	52,032
Computer programming, consultancy and related activities; information service activities	39,474

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WIOD 2016 release sector	Change in labour demand (Number of employees)
Warehousing and support activities for transportation	35,900
Architectural and engineering activities; technical testing and analysis	33,303
Real estate activities	30,873
Manufacture of electrical equipment	30,476
Manufacture of furniture; other manufacturing	29,999
Manufacture of basic metals	26,473
Manufacture of other non-metallic mineral products	22,711
Manufacture of motor vehicles, trailers and semi-trailers	22,438
Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	22,257
Electricity, gas, steam and air conditioning supply	22,048
Manufacture of rubber and plastic products	21,410
Insurance, reinsurance and pension funding, except compulsory social security	20,830
Repair and installation of machinery and equipment	19,432
Postal and courier activities	17,876
Manufacture of computer, electronic and optical products	15,994
Advertising and market research	14,970
Crop and animal production, hunting and related service activities	14,895
Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services	14,488
Manufacture of textiles, wearing apparel and leather products	13,705
Manufacture of chemicals and chemical products	12,872
Manufacture of paper and paper products	12,482
Telecommunications	11,340
Scientific research and development	10,531
Manufacture of basic pharmaceutical products and pharmaceutical preparations	10,427
Publishing activities	9,188
Activities auxiliary to financial services and insurance activities	8,980
Printing and reproduction of recorded media	8,269
Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities	7,617
Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use	7,326
Mining and quarrying	7,038
Other professional, scientific and technical activities; veterinary activities	6,251
Forestry and logging	5,617
Air transport	5,325
Manufacture of other transport equipment	4,857
Water collection, treatment and supply	2,022
Manufacture of coke and refined petroleum products	864

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WIOD 2016 release sector	Change in labour demand (Number of employees)
Water transport	329
Fishing and aquaculture	122

Source: WIOD 2016 release, EXIOBASE v3, own calculations

3.3.3.4. MLT scenario

MLT scenario is characteristic with its gradual change after 2030, when the annual 0.7% GDP growth for the period 2014-2030 is replaced by annual 2.5% GDP decrease between 2030 and 2050. This shift is also reflected in the employment changes. The growth-induced job creation takes place between 2014 and 2030, whereas in the rest of the followed period (2030-2050), there is a decline in number of full-time job equivalents. Detailed figures can be found in Table 15 below. The distributional impacts on gender and skill levels are even more equally distributed than in the previous two cases ("zero growth" and OLT scenario), as shown in Table 16. The reasons for that are also similar to the two preceding cases – the employment changes induced by the shift to the renewable energies does not include a significant change in the distributional impacts.

Table 15. MLT scenario with 0.7% annual GDP growth and then annual 2.5 GDP decrease, selected sectors' employment changes

Labour demand (Number of employees)	2014	2030	2050
Forestry and logging	20,830	23,211	13,009
Mining and quarrying	170	190	107
Manufacture of coke and refined petroleum products	11,592	12,906	7,232
Manufacture of electrical equipment	22,406	24,959	13,983
Repair and installation of machinery and equipment	41,866	46,692	26,169
Electricity, gas, steam and air conditioning supply	28,151	30,944	17,327
Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services	2,823	3,149	1,764
Wholesale and retail trade and repair of motor vehicles and motorcycles	274,063	305,043	170,969
Wholesale trade, except of motor vehicles and motorcycles	72,949	81,225	45,511
Land transport and transport via pipelines	334,947	373,358	209,248
Air transport	461	513	288
Warehousing and support activities for transportation	7,375	8,248	4,625

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Labour demand (Number of employees)	2014	2030	2050
Postal and courier activities	52,604	57,667	32,229
Computer programming, consultancy and related activities; information service activities	15,840	17,657	9,898

Source: WIOD 2016 release, EXIOBASE v3, own calculations

Table 16. MLT scenario with 0.7% annual GDP growth and then annual 2.5 GDP decrease, total employment changes by skill level and gender

Labour demand (Number of employees)	2014	%2014-2030	2030	%2030-2050	2050	%2014-2050
Low-skilled	406,887	*11.40%*	453,277	*-43.95%*	697,643	*-37.56%*
Medium-skilled	1,859,153	*11.41%*	2,071,264	*-43.96%*	3,187,803	*-37.56%*
High-skilled	1,457,396	*11.42%*	1,623,875	*-43.95%*	2,499,341	*-37.55%*
Male	1,934,285	*11.41%*	2,155,068	*-43.95%*	3,316,832	*-37.56%*
Female	1,789,151	*11.41%*	1,993,349	*-43.95%*	3,067,955	*-37.56%*

Source : WIOD 2016 release, EXIOBASE v3, own calculations

In the detailed, sectoral level, it is also possible to track changes induced by the renewable energy sources' deployment versus changes induced by the GDP change itself – sectors such as Mining and quarrying or Forestry and logging is much less affected by the GDP decline after 2030.

3.3.3.4.1. 2014-2030 employment changes

The expected changes until 2030 are very similar to those in the OLT scenario – see the ranking in Table 17. Sectors Human health and social work activities, Retail trade and Construction are the main "winners", although their increase is caused by the GDP growth itself – unlike the sectors Mining and quarrying or Forestry and logging, and partially also the Electricity sector (where the job creation takes place partly because of the GDP growth and partly because of the transition to the renewable energy sources).

Table 17. MLT scenario with 0.7% annual GDP growth (period 2014-2030) employment changes (2014-2030) by WIOD sectors (Number of employees).

WIOD 2016 release sector	Change in labour demand (Number of employees)
Human health and social work activities	45,771
Retail trade, except of motor vehicles and motorcycles	38,411
Construction	30,981
Public administration and defence; compulsory social security	29,185
Education	27,808

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WIOD 2016 release sector	Change in labour demand (Number of employees)
Accommodation and food service activities	27,577
Administrative and support service activities	23,635
Wholesale trade, except of motor vehicles and motorcycles	21,869
Other service activities	17,061
Land transport and transport via pipelines	12,615
Legal and accounting activities; activities of head offices; management consultancy activities	10,065
Manufacture of food products, beverages and tobacco products	9,190
Manufacture of machinery and equipment n.e.c.	9,153
Manufacture of fabricated metal products, except machinery and equipment	8,452
Financial service activities, except insurance and pension funding	8,352
Wholesale and retail trade and repair of motor vehicles and motorcycles	8,276
Computer programming, consultancy and related activities; information service activities	6,347
Architectural and engineering activities; technical testing and analysis	5,305
Warehousing and support activities for transportation	5,063
Manufacture of electrical equipment	5,019
Real estate activities	4,938
Manufacture of furniture; other manufacturing	4,826
Electricity, gas, steam and air conditioning supply	4,700
Manufacture of basic metals	4,203
Manufacture of other non-metallic mineral products	3,652
Manufacture of motor vehicles, trailers and semi-trailers	3,611
Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	3,489
Manufacture of rubber and plastic products	3,441
Insurance, reinsurance and pension funding, except compulsory social security	3,321
Postal and courier activities	2,858
Repair and installation of machinery and equipment	2,793
Manufacture of computer, electronic and optical products	2,553
Crop and animal production, hunting and related service activities	2,381
Advertising and market research	2,327
Manufacture of textiles, wearing apparel and leather products	2,202
Manufacture of chemicals and chemical products	2,071
Manufacture of paper and paper products	2,003
Telecommunications	1,817
Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services	1,803
Mining and quarrying	1,770
Scientific research and development	1,693

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WIOD 2016 release sector	Change in labour demand (Number of employees)
Manufacture of basic pharmaceutical products and pharmaceutical preparations	1,677
Publishing activities	1,466
Activities auxiliary to financial services and insurance activities	1,418
Printing and reproduction of recorded media	1,314
Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities	1,211
Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use	1,179
Other professional, scientific and technical activities; veterinary activities	983
Forestry and logging	957
Air transport	873
Manufacture of other transport equipment	781
Water collection, treatment and supply	326
Manufacture of coke and refined petroleum products	138
Water transport	53
Fishing and aquaculture	20

Source: WIOD 2016 release, EXIOBASE v3, own calculations

3.3.3.4.2. 2014-2050 employment changes

Unlike in the OLT scenario, MLT scenario expects job losses due to the GDP decline (either because of unplanned "recession", or due to planned "degrowth") between 2030 and 2050 – see Table 18 below. Therefore, we can observe that the main "winners" from the previous part (2014-2030 employment changes) are now among the main losers, in the same order. Similarly, the sectors which were growing (in terms of job creation) mainly due to the renewable energy transition, are not losing the jobs too much (such as Mining and quarrying or Forestry and logging, again). The renewable energy deployment makes these sectors less vulnerable to the GDP decline (or more stable in general – not too affected by the growth/recession itself).

Table 18. MLT scenario with 2.5% annual GDP decrease (period 2030-2050) employment changes (2014-2050) by WIOD sectors (Number of employees).

WIOD 2016 release sector	Change in labour demand (Number of employees)
Fishing and aquaculture	-64
Water transport	-173
Manufacture of coke and refined petroleum products	-455
Water collection, treatment and supply	-1,058
Mining and quarrying	-2,330

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WIOD 2016 release sector	Change in labour demand (Number of employees)
Manufacture of other transport equipment	-2,543
Air transport	-2,750
Forestry and logging	-2,814
Other professional, scientific and technical activities; veterinary activities	-3,314
Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use	-3,831
Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities	-4,011
Printing and reproduction of recorded media	-4,359
Activities auxiliary to financial services and insurance activities	-4,747
Publishing activities	-4,829
Manufacture of basic pharmaceutical products and pharmaceutical preparations	-5,457
Scientific research and development	-5,512
Telecommunications	-5,942
Manufacture of paper and paper products	-6,541
Manufacture of chemicals and chemical products	-6,736
Manufacture of textiles, wearing apparel and leather products	-7,174
Crop and animal production, hunting and related service activities	-7,821
Advertising and market research	-7,986
Manufacture of computer, electronic and optical products	-8,423
Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services	-8,632
Electricity, gas, steam and air conditioning supply	-9,202
Postal and courier activities	-9,375
Repair and installation of machinery and equipment	-10,824
Insurance, reinsurance and pension funding, except compulsory social security	-10,948
Manufacture of rubber and plastic products	-11,207
Manufacture of motor vehicles, trailers and semi-trailers	-11,736
Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	-11,813
Manufacture of other non-metallic mineral products	-11,890
Manufacture of basic metals	-13,953
Manufacture of furniture; other manufacturing	-15,696
Manufacture of electrical equipment	-15,702
Real estate activities	-16,205
Architectural and engineering activities; technical testing and analysis	-17,509
Warehousing and support activities for transportation	-20,376
Computer programming, consultancy and related activities; information service activities	-20,633
Wholesale and retail trade and repair of motor vehicles and motorcycles	-27,438

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WIOD 2016 release sector	Change in labour demand (Number of employees)
Manufacture of fabricated metal products, except machinery and equipment	-27,715
Financial service activities, except insurance and pension funding	-29,401
Manufacture of food products, beverages and tobacco products	-30,011
Manufacture of machinery and equipment n.e.c.	-30,067
Legal and accounting activities; activities of head offices; management consultancy activities	-34,182
Land transport and transport via pipelines	-42,493
Other service activities	-55,594
Wholesale trade, except of motor vehicles and motorcycles	-73,034
Administrative and support service activities	-80,833
Accommodation and food service activities	-90,166
Education	-90,919
Public administration and defence; compulsory social security	**-94,536**
Construction	**-103,094**
Retail trade, except of motor vehicles and motorcycles	**-125,699**
Human health and social work activities	**-148,688**

Source: WIOD 2016 release, EXIOBASE v3, own calculations

3.3.4. Brief conclusions on social costs of transition

The findings from section 3.3.1 (Task 6.2.c.1) have a fundamental policy implication: Sectors with higher educated people produce more output (in monetary terms) with less energy. The differences between sectors can guide policies to identify those sectors where the effects are strongest. The presented models can be used to estimate future energy intensities under different scenarios concerning education and the development of high-skilled labour. This analysis provides us with an estimate of what is feasible within the next decades on a global scale, while assuming only current technologies.

Concerning the results (Table 19) of the section 3.3.3 (Task 6.2.c.3), from the results of the Zero GDP growth scenario it is clear that the transition to the low-carbon economy (taking into account the assumptions that were described in the Methodology section) will not generate new jobs, and will per se mean a very slight decrease in labour demand (in total by 0,12%, from 3,723,436 to 3,718,926 until 2050). The results therefore have to be interpreted with caution – such a small change can be also caused due to data errors.

Whereas zero GDP growth in our analysis suggests job levels being approximately equal or slightly decreasing, assuming a certain level of GDP growth is translated into the creation of jobs by the

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model. The situation applies for both OLT and MLT. In case of OLT, the transition would mean a 30.35% increase in jobs between 2014 and 2030 (from 3,723,436 to 4,853,392). In case of MLT, the transition would bring a 11.41% increase in jobs between 2014 and 2030 (from 3,723,436 to 4,148,417). After the GDP growth stops in the MLT scenario, job creation stops as well. Therefore, between 2030 and 2050, MLT would mean a 43.95% decrease in jobs, from 4,853,392 in 2030 to 2,324,995 in 2050; whereas OLT with assuming continued economic growth would mean yet another increase by 31,55% (from 4,853,392 to 6,384,787).

Table 19. Aggregate changes in employment (comparison between Zero GDP growth, OLT and MLT scenarios for 2014-2030 and 2030-2050 periods (Number of employees, rounded to thousands)

Scenario	Change in labour demand 2014-2030 (Number of employees)	% change in labour demand 2014-2030	Change in labour demand 2030-2050 (Number of employees)	% change in labour demand 2030-2050	Change in labour demand 2014-2050 (Number of employees)	% change in labour demand 2014-2050
Zero growth	-4,150	-0.11%	-360	-0.01%	-4,500	-0.12%
OLT	1,130,000	30.35%	1,531,000	31.55%	2,661,000	71.48%
MLT	425,000	11.41%	-1,823,000	-43.95%	-1,398,000	-37.56%

Source: WIOD 2016 release, EXIOBASE v3, own calculations

Moreover, further GDP growth has also negative impacts on the environment and GHG emissions in particular (Arto and Dietzenbacher, 2014). Work-sharing, economic localization (to prevent job losses and to boost job creation at a regional level) and using different indicators to show the quality of life than GDP could help the transition.

Among the sectors with the most significant potential job losses are *(1) Construction*, *(2) Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services*, *(3) Administrative and support service activities*, and *(4) Warehousing and support activities for transportation*. On the contrary, sectors *(1) Electricity, gas, steam and air conditioning supply*, *(2) Mining and quarrying*, *(3) Manufacture of electrical equipment*, and *(4) Forestry and logging* can expect higher employment levels induced by the gradual switch from fossil fuels in electricity production.

The distributional effects of the gradual replacement of fossil fuels in electricity production are rather small (1% in total maximum). This may be due to the fact that the structure of employment in all the subsectors considered (electricity by hydro, wind, biomass and waste, solar PV, rest of the RES and of the WIOD D35 sector, as well as electricity by fossil fuels) has very similar employment structures by skill levels and by gender. However, as the analysis is done at the country level, the

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results may reflect a country-specific situation, and more general conclusions would have to be derived from an aggregate study either country-by-country or for the whole EU.

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3.4. Economic costs of transition

Given that electricity sector will play a key role in the low-carbon transition, in this project we analysed the cost structure of producing electricity from different energy sources, including fossil fuels, wind, hydro, solar, and other renewable energies. EXIOBASE version 3 database published the global multi-regional input-output tables and extension factors (e.g. labour compensation, consumption of fixed capital, demand for low, medium and high skill labours etc.) from 1995 to 2011 (Stadler et al., 2018). EXIOBASE 3 MRIO tables include 14 electricity sectors with detailed fossil fuel based and renewable electricity sectors. To estimate the economic cost of the low-carbon transition, one of the biggest challenges is to estimate the future input-output tables that represent the future energy mix and economic structure due to the change in energy mix. Here, we first construct the input-output table for the EU as a whole to be consistent with the MEDEAS EU model through aggregating the EU countries MRIO tables from the EXIOBASE3. And then, we estimated the future EU input-output table using the output from the MEDEAS model on the economic outputs and electricity output by detailed energy sources for 2030 and 2050.

In this section, we analyse the key socio-economic indices and variables and illustrate the allocation of financial and material resources in different electricity sectors by presenting the economic input of materials, employment, capital and other primary factors to produce one unit of electricity production. In addition, we estimate the total economic cost of switching fossil fuels to renewables by 2030 and 2050 under two future scenarios, the Business-as-usual (BAU) scenario and the green growth scenario using the estimated future EU IO tables.

3.4.1 Socio-Economic indices and variables

Many indices and variables are important for assessing the economic cost of transition to low-carbon society in the EU, including labour compensation by skill level, consumption of fixed capital, and total value added. Figure 33 shows the total added-value (both direct and indirect) associated with electricity production in the EU. From the Figure 24 we can see a rapid increase in total value added by 115% during 1995-2008. However, the increase in the total value added associated with electricity production was only 5% after the recession from 2009 to 2015. From the Figure 24 we can also see that although there was a significant change in total added-value, the changes in labour compensation and consumption of fixed capital were fairly small, meaning that the change in total added-value is largely due to the change in other value-added categories, such as Operating surplus. Labour compensation, in fact, has decreased after recession by 16%, while consumption of fixed capital (capital depreciation) slightly increased by 5% in 6 years (less than 1% per year).

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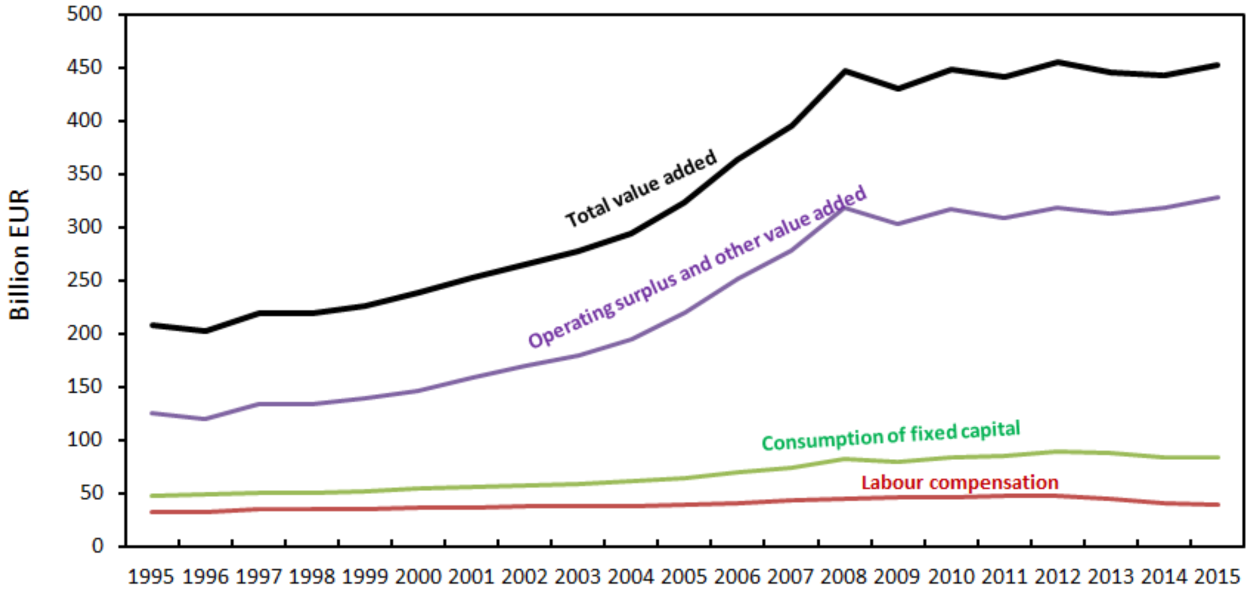

Figure 24. Total added-value associated with electricity production in the EU.

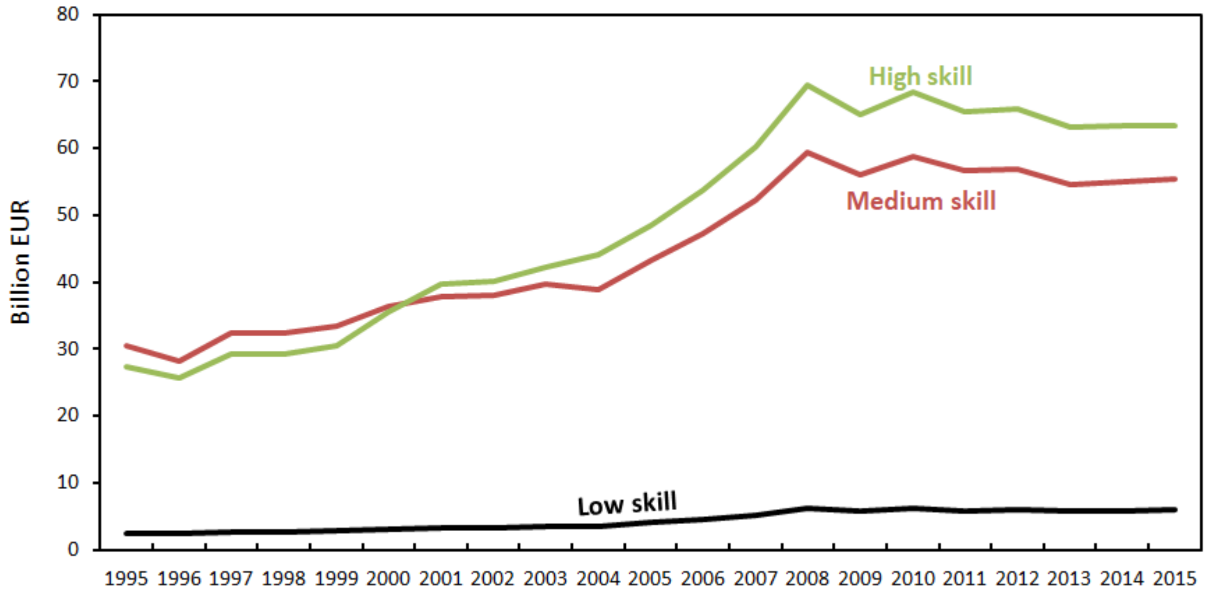

Figure 25. Total labour compensation associated with electricity production in the EU.

The IO tables in EXIOBASE include three employment categories (i.e. low skill, medium skill and high skill). From Figure25, we can see that the labour compensation of medium and high skilled labours significantly increased before the recession in 2009, and then lightly decreased after the recession. However, the total compensation for low skilled labour was very stable after the recession.

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3.4.2 Allocation of financial and material resources

Added-value per unit of electricity production is one of the most important economic indicators for assessing the economic impact of changing in electricity production. Here, we compare added-value per unit of electricity generation between fossil fuels and renewable energies as energy sources. Figure 26 shows that, in general, generating one unit of electricity from renewable energy may create significantly more added-value than the generation of one unit of electricity from coal which is the main energy source that need to be replaced for low-carbon transition. For example, hydroelectricity generates 34% more added-value than coal for producing the same amount of electricity output. The number becomes higher to 67% and 150%, when we compare wind and solar energy with coal. However, we also found that Natural gas is more competitive than hydro and wind, in terms of generating value added, but it is slightly uncompetitive compared with solar PV.

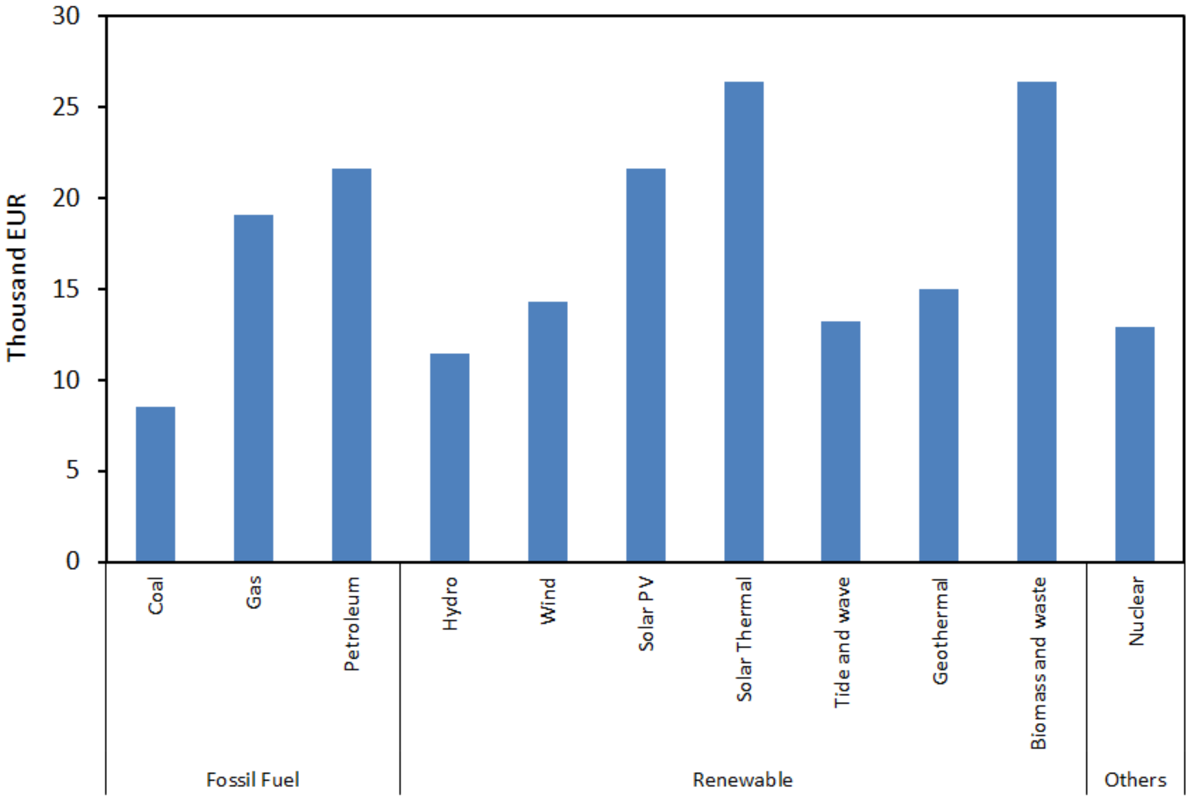

Figure 26. Added-value per unit of electricity production (thousand EUR/TJ).

Although total value added is very important for assessing economic impact as a whole, impact on labour compensation is important for social acceptance of the low-carbon energy transition. From Figure27, we can see that most of renewable energy is less favourable than the fossil fuels, in terms

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of labour compensation per unit of electricity generation. We also observe that renewable energy requires higher input for medium and high skilled labour, compared with fossil fuel-based electricity generation, but in general, electricity sector requires more medium and high skilled labour.

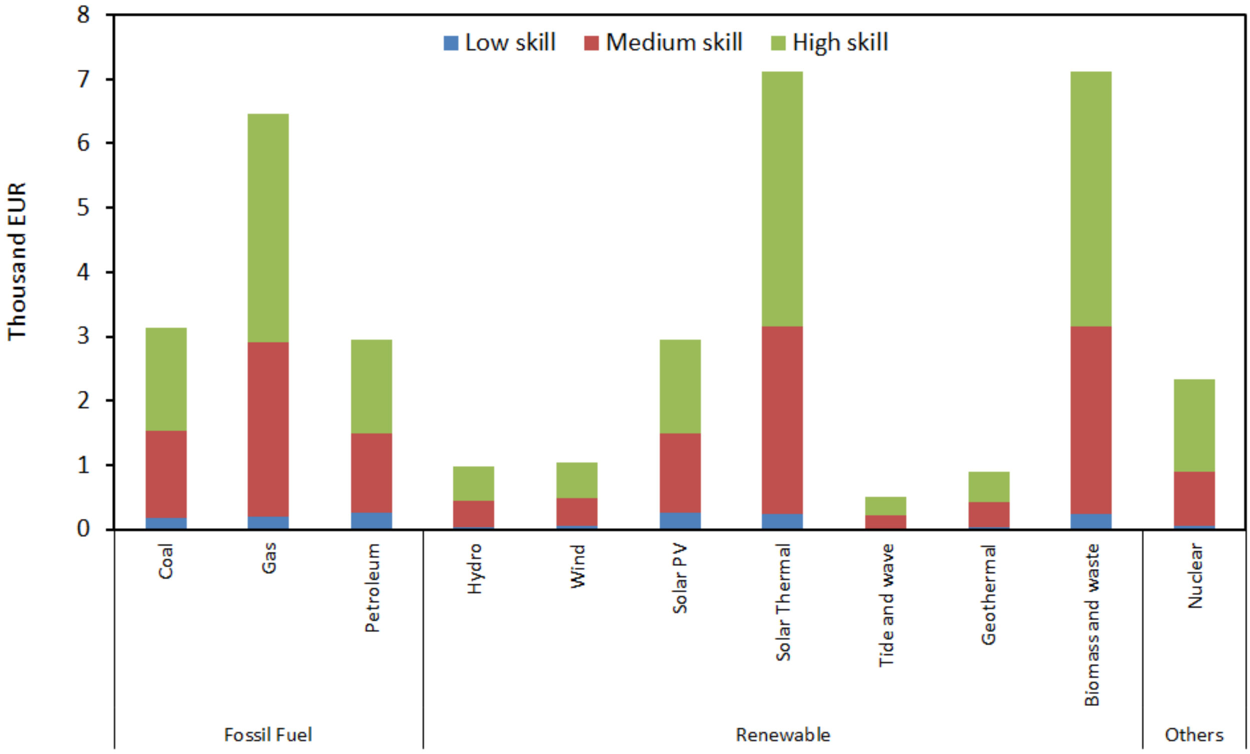

Figure 27. Labour compensation per unit of electricity production (Thousand EUR/TJ).

In contrast with the labour compensation, Figure 28 shows that renewable energy requires more capital input per unit of electricity production, for instance, the capital input per unit electricity output for hydro and wind is 4 times of the input for coal and 2 times of the input for natural gas. This is not very surprising because it has been broadly recognized that renewable energy production is more capital intensive.

Figure 29 shows that fossil fuel-based electricity production is much more material intensive than the production from renewable energy. From the figure, we can see that material input (intermediate products) for one-unit electricity generation from coal is about 3 times of the materials input for hydro, wind and solar PV. The material input for natural gas-based electricity is more than 6 times of the input for renewable energy. Therefore, transition to renewable energy can not only reduce carbon emissions but also decrease material consumption and associated environmental impacts.

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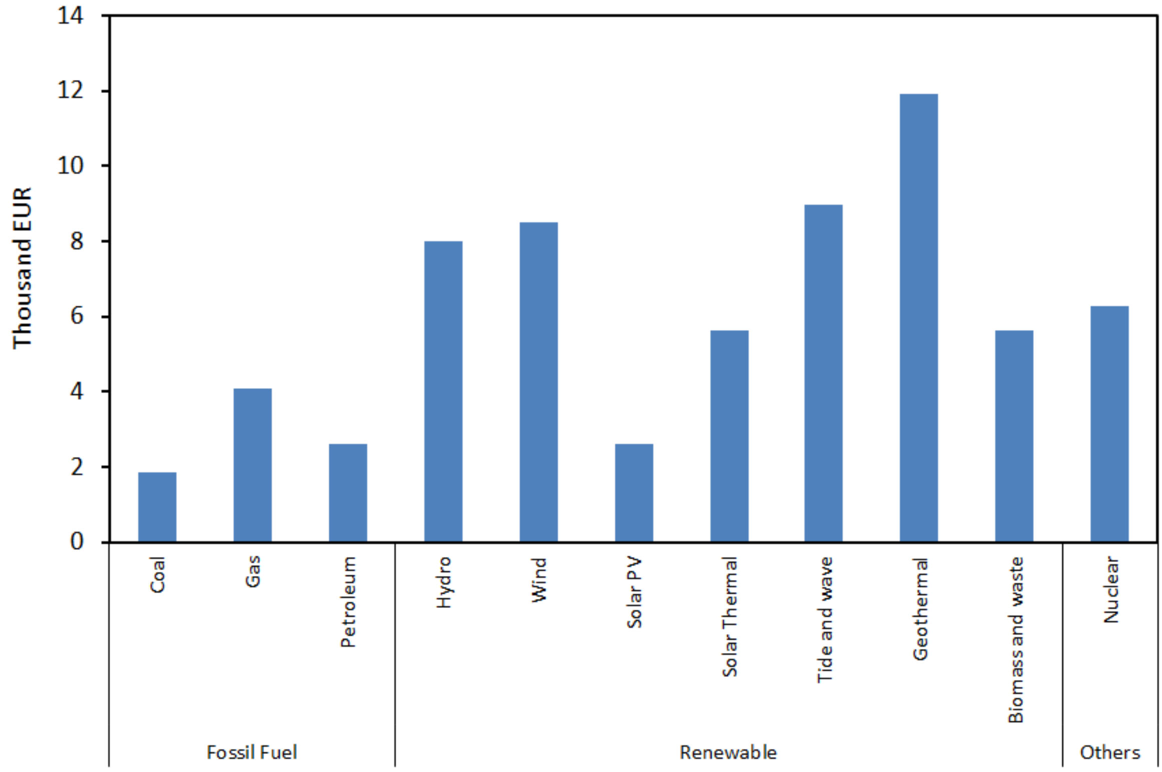

Figure 28. Consumption of fixed capital per unit of electricity production (Thousand EUR/TJ).

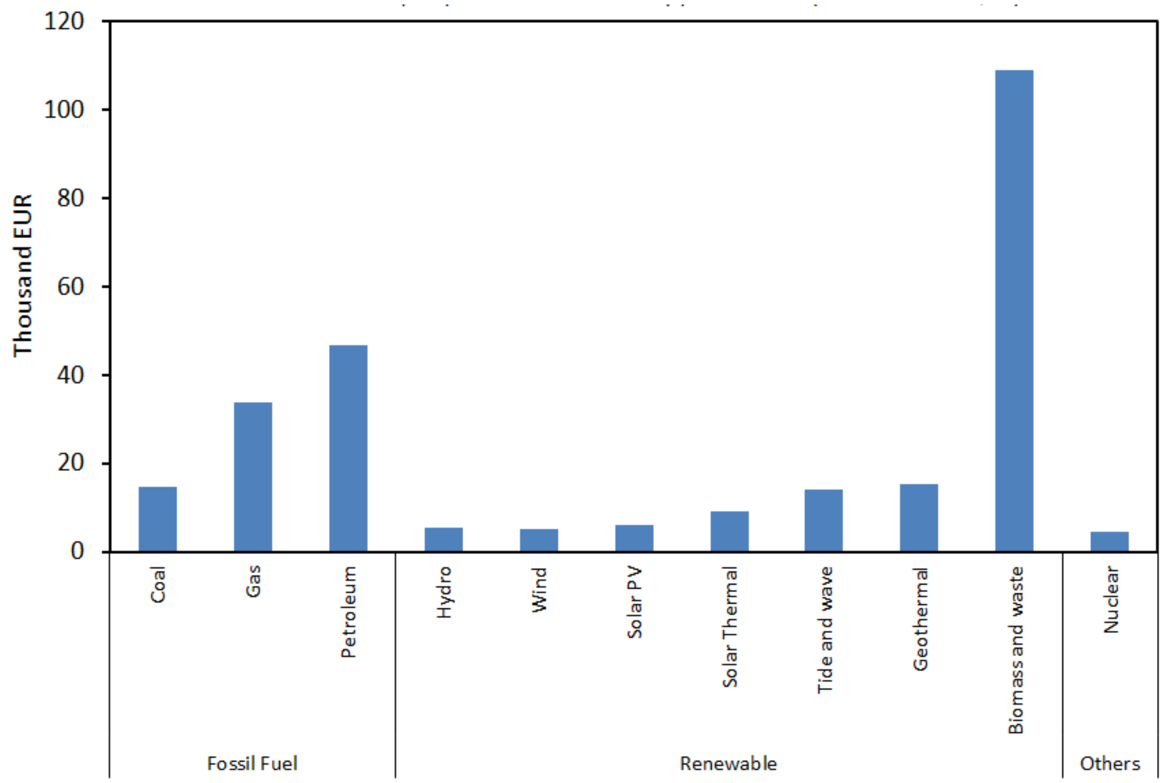

Figure 29. Cost of material input to produce one unit of electricity output by energy sources (Thousand EUR/TJ).

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3.4.3 Economic cost under BAU scenario

In the MEDEAS project, many scenarios have been set to explore the impacts of low-carbon transition pathways. Here, we simulate the economic cost under two scenarios, the business-as-usual (BAU) scenario and the green growth scenario. In addition, we select two time points, 2030 and 2050, for our analysis.

Figure 30 shows the total added-value associated with electricity production under BAU scenarios for 2014, 2030 and 2050. From the figure we can see that nuclear energy will be largely replace by wind energy for electricity generation, while the share from other energy sources have only small changes by 2030. Also, electricity production will keep increase by 2030 which leads to an overall increase in total added-value associated with electricity production by 31%. The total added-value will be increased by 160% by 2050, because of the overall production increase in wind, solar PV as well as fossil fuels, including coal and natural gas.

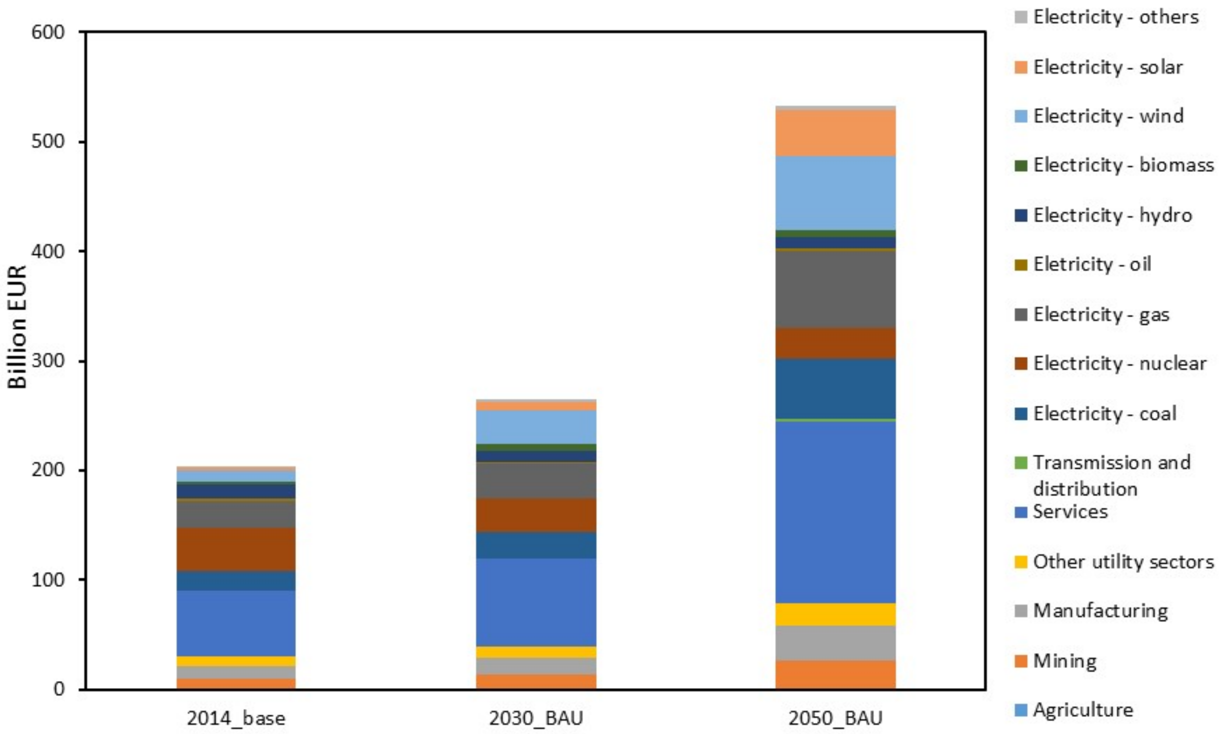

Figure 30. Total Impact of electricity sector transition on value added under baseline and BAU scenarios.

When look at both direct and indirect impacts of change in electricity production (Figure 31), we found that more than 60% of the labour compensation driven by electricity production occurred in

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the upstream supply chain, such as services, manufacturing goods and mining, which are the critical inputs for electricity production. Under the BAU scenario, labour compensation will increase by 30% and 160% by 2030 and 2050, respectively. The large increase by 2050 is mainly due to the increase in total electricity production. The impact from the change in energy mix is relatively small when taking both direct and indirect (supply chain) impact into account.

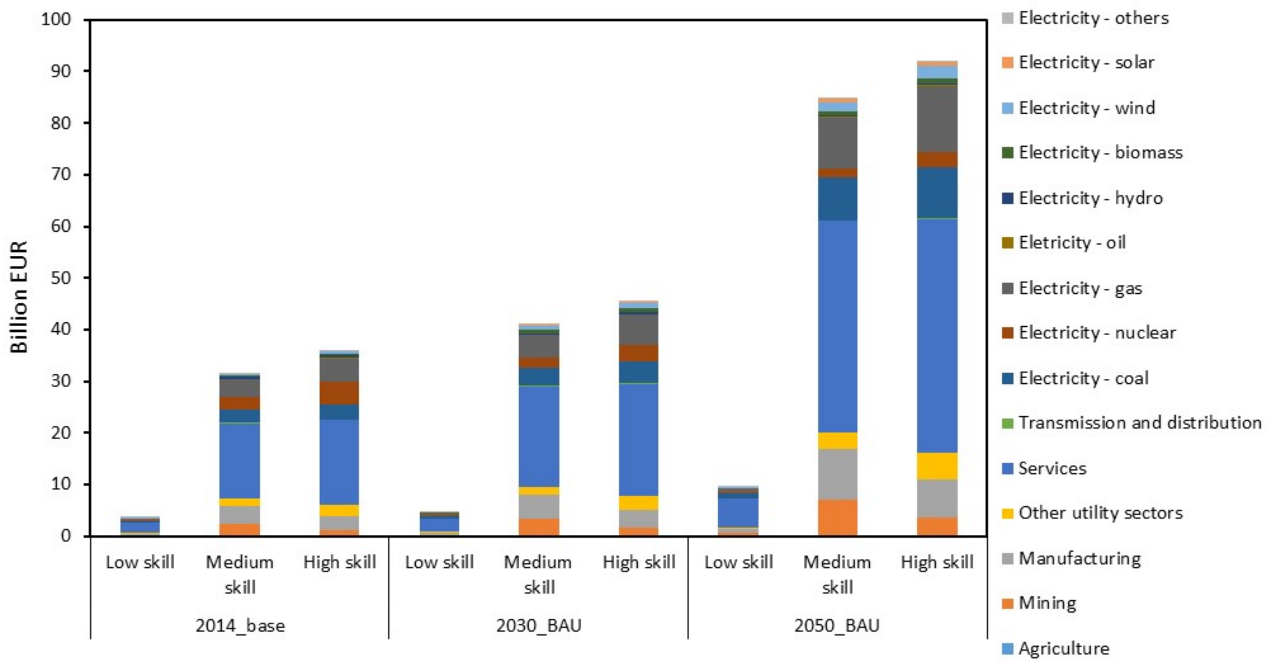

Figure 31. Total Impact of electricity sector transition on labour compensation under baseline and BAU scenarios.

However, capital input driven by electricity production is largely occurred within the electricity production sector. For example, capital input in electricity sector accounted for about 80% of the total capital input (both direct and indirect). From Figure32, we can see that the increase in electricity production also lead to great increase in capital: 31% and 160% by 2030 and 2050, respectively.

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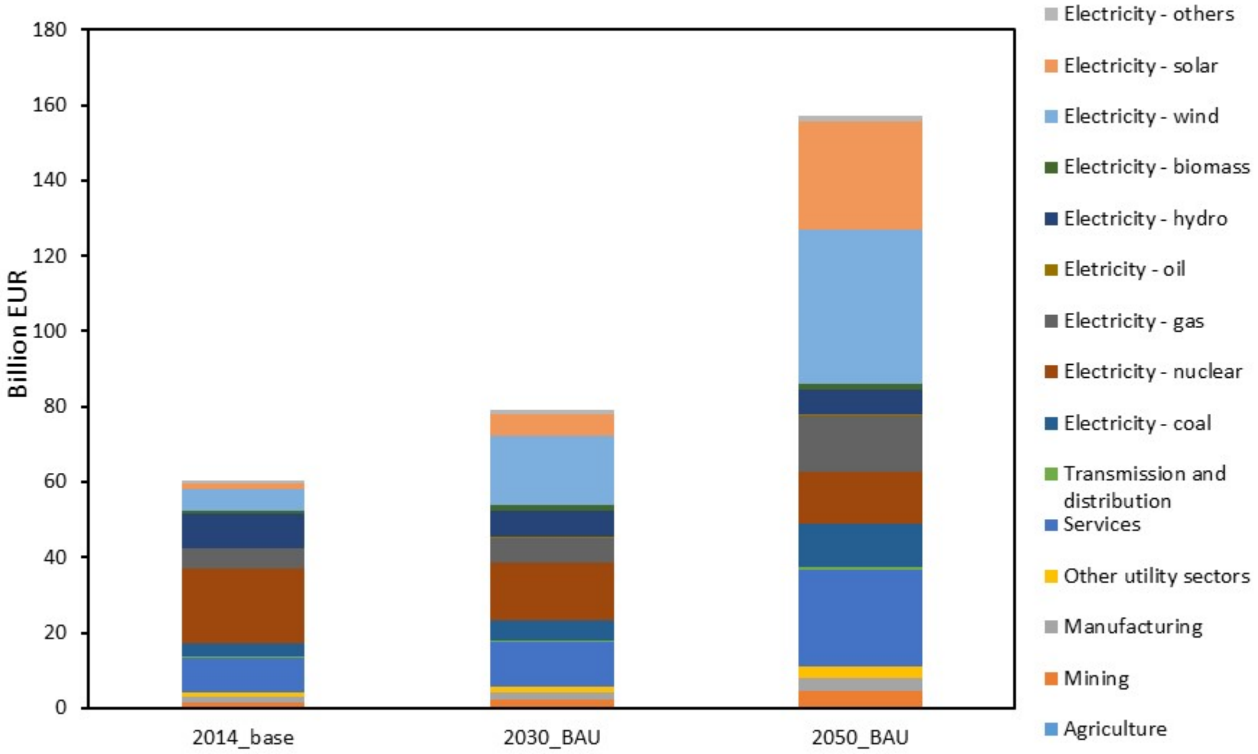

Figure 32. Total Impact of electricity sector transition on fixed capital under baseline and BAU scenarios.

3.4.4 Economic cost under Green growth scenario

The total economic cost might be huge under the green growth scenario, when we consider both direct and supply chain effects. Figure 33 shows the change in total value added due to the change in electricity production. From the figure we can see that the total value added associated with electricity production will slightly decrease by 10% by 2030. From 2014 to 2030, wind and solar PV started to replace coal and natural gas. In addition, nuclear also decreased by 32%. The decrease in the total value added is much dramatic by 43% from 2030 to 2050.

The decrease in labour compensation will be more serious than the total value added under the green growth scenario given that renewable energy production in the EU is less labour intensive than other energy sources, such as coal and natural gas. Under green growth scenario, labour compensation decreases by 27% from 2014 to 2030 and further decreased by 55% from 2030 to 2050 (Figure 34).

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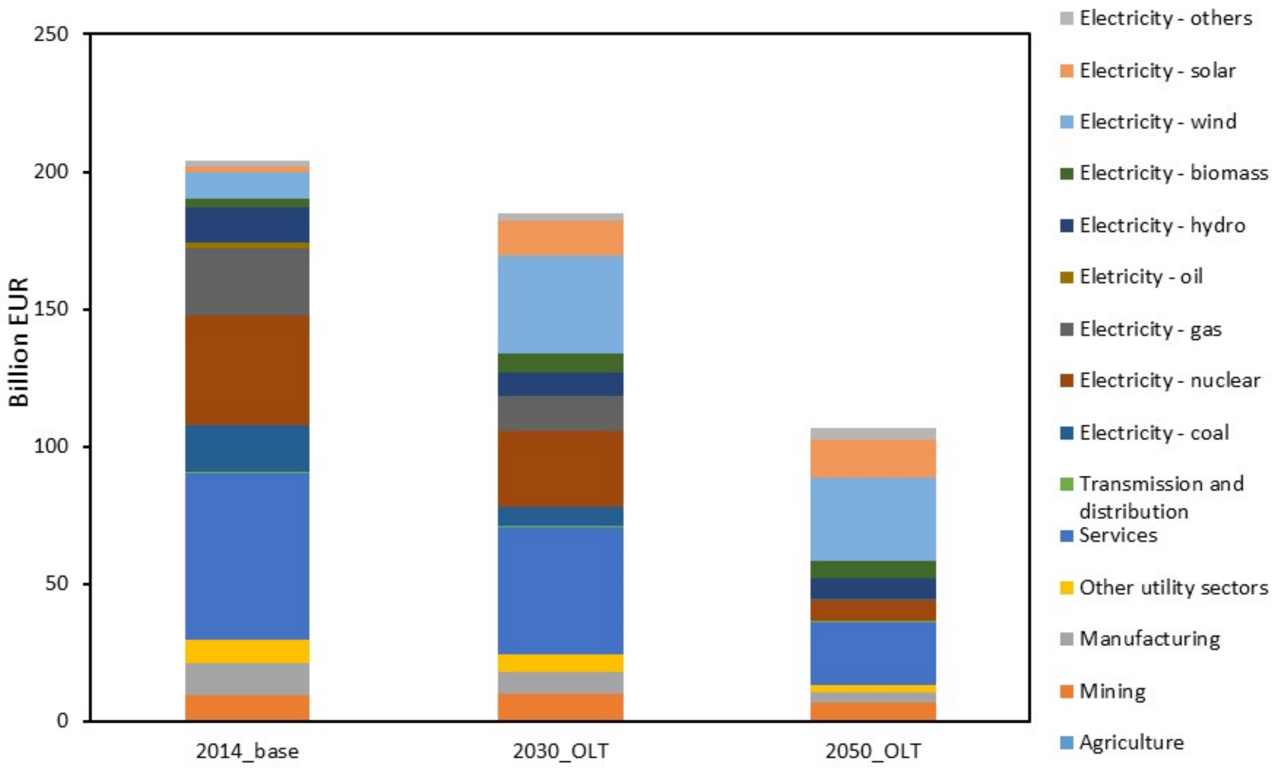

Figure 33. Total Impact of electricity sector transition on value added under baseline and OLT scenarios.

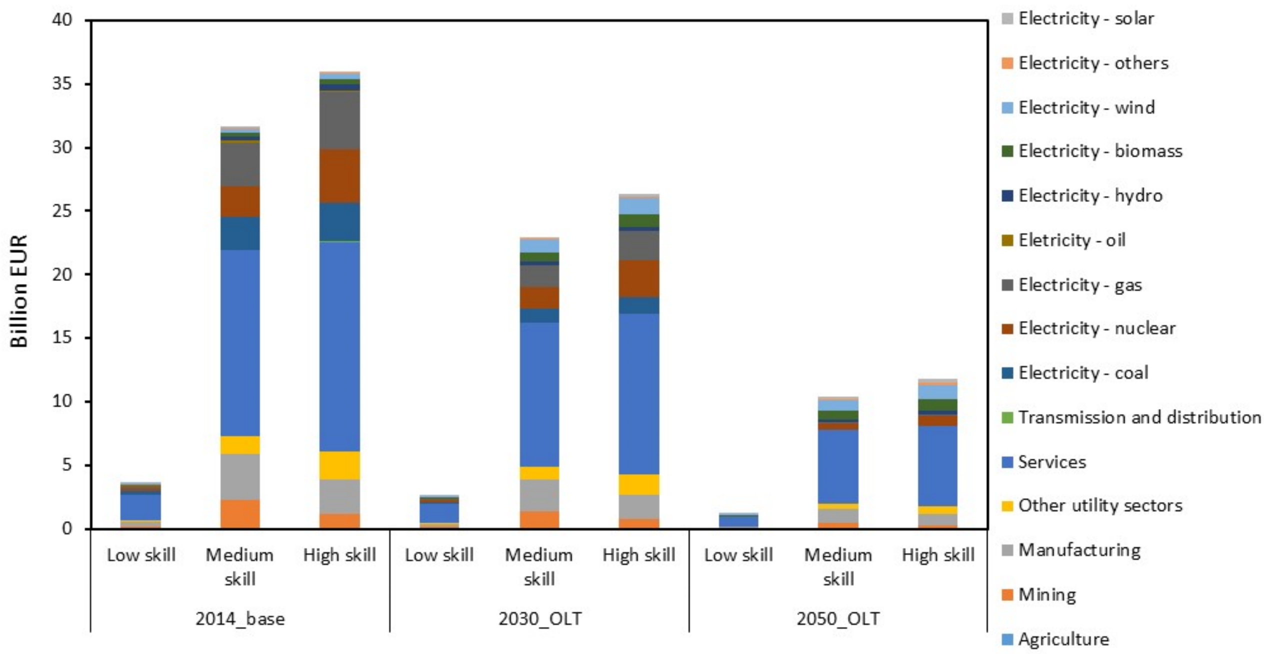

Figure 34. Total Impact of electricity sector transition on labour compensation under baseline and OLT scenarios.

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When look at the capital input under the OLT (green growth) scenario (Figure 35), we found that in fact the capital input will increase by 11% from 2014 to 2030 because the increase in renewable energy production overcome the negative effects from the reduction in fossil fuel based electricity production. However, this trend reversed and the total capital input decrease by 33% from 2030 to 2050 because of the big reduction in total electricity production.

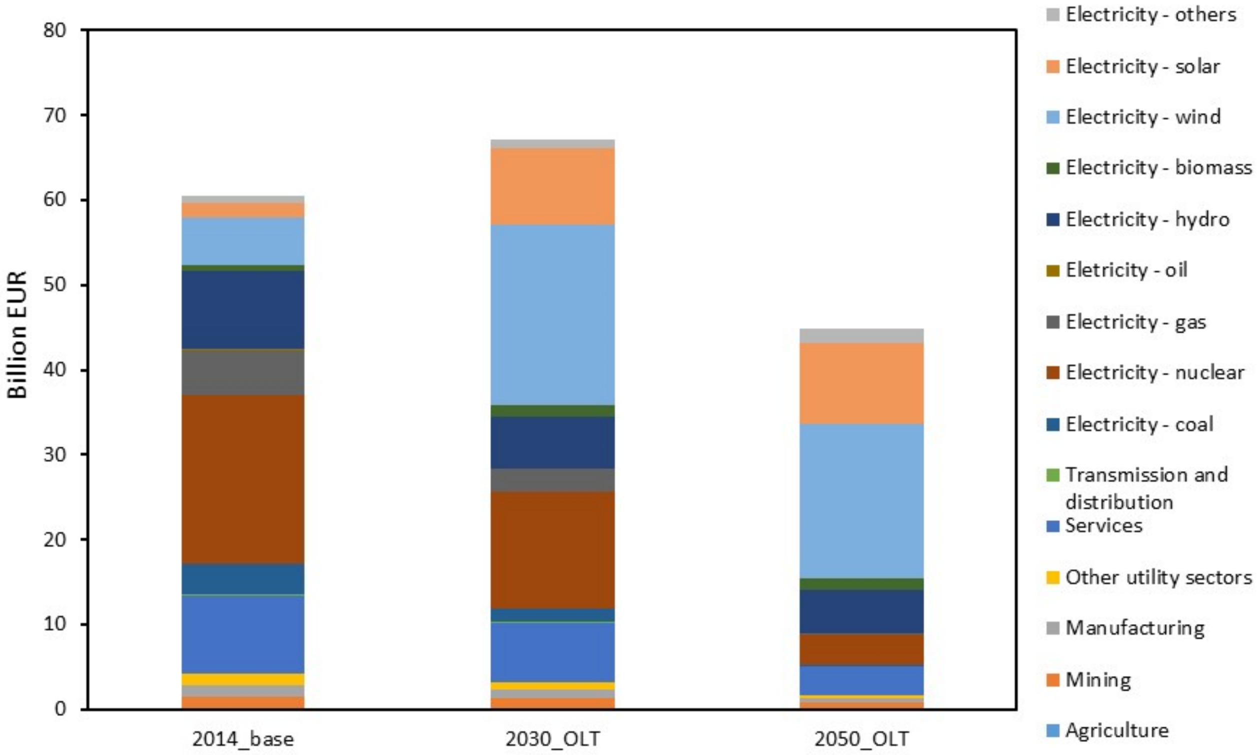

Figure 35. Total Impact of electricity sector transition on fixed capital under baseline and OLT scenarios.

3.4.5 Brief conclusions on economic costs of transition

As shown in the previous sections summarized in Table 20, we found that total value added from electricity sectors became flat after the 2009 global economic recession. In the assessment of economic cost of transition, we found that renewable energy-based electricity production may generation more value added per unit of electricity than coal power, which also indicates that the cost of one-unit electricity production from renewable energy is higher than coal power. The higher cost per unit electricity from renewable energy is mainly due to the higher capital input to produce one unit of electricity output. Our results suggest that to make the renewable energy more

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competitive in the market it is crucial to have climate policies to support this transition such as imposing carbon tax on domestic and imported products in all EU countries.

Our scenario simulation results showed an increase in total value added from electricity sector as a whole under the BAU scenario, in particular there will be a big growth in total value added from 2030 to 2050 largely due to the growth in electricity generation to fuel the economic growth without requirement for low carbon transition in energy mix in electricity sector. However, our green scenario (OLT) result showed a slightly decrease in total value added associated with electricity production by 2030 but a big decrease by 2050. The large decrease in total value added is mainly due to the big reduction in total electricity generation. However, when we zoomed into the impact of low carbon transition, we found that fixed capital input increased by 2030, but this increase is overwhelmed by the decrease in labour compensation and operation surplus, thus leads to a negative impact on the total value-added generation. However, by 2050 all value-added sectors (i.e. labour compensation, fixed capital input, operational surplus) have significant decrease due to the decrease in total electricity production from the higher electricity price as renewable energy-based electricity has a higher cost than fossil fuels-based electricity. This result again reflects that transition to low carbon society is expensive and requires strong policy support.

Table 20. Total value added associated with electricity production under baseline, BAU and OLT scenarios (billion Euros = 10^9 Euros).

	2014	2030		2050	
	Baseline	BAU	OLT	BAU	OLT
Agriculture	0	0	0	1	0
Mining	9	14	9	26	7
Manufacturing	12	15	8	32	4
Other utility sectors	9	10	6	20	3
Services	60	79	46	167	23
Transmission and distribution	1	1	1	2	0
Electricity - coal	17	24	7	55	0
Electricity - nuclear	40	31	27	28	7
Electricity - gas	25	32	13	70	1
Electricity - oil	2	2	0	4	0
Electricity - hydro	13	10	9	9	7
Electricity - biomass	3	6	7	7	7
Electricity - wind	9	30	35	68	30
Electricity - solar	2	9	13	42	14
Electricity - others	2	3	4	2	4

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4. Conclusions

The objective of the MEDEAS project is to provide simulation tools that facilitate the design of energy policies in the European Union to achieve a transition to a low-carbon economy. Task 6.2 analyses the costs of the energy transition from different perspectives, taking into account energetic, raw material, and social costs, and showing different scenarios.

In particular, subtask 6.2a is devoted to energy costs for transition. Since energy needs energy to be produced, the key concept used here is Energy Return On Investment (EROI), quantifying energy invested per unit of energy produced. Thus, the dynamic evolution of the EROI has been simulated for three 2060 scenarios (system EROI) and the EROI of the different RES technologies used for electricity generation: wind onshore, wind offshore, Solar Photovoltaic (PV) and Solar Concentrated Power (CSP). The EROIst of the system decreases while the EROIst of the individual RES variable technologies increases due to the fact that the EROI of the latter is lower than the current EROI of the full system, and their share increases over time in the simulated scenarios. The decrease in the EROI of the system has implications for the rest of the system: in order to satisfy the same level of final net energy consumption, the system needs to process more energy and materials. It has been modelled by an overdemand function. Overdemand and energy intensity increases 6 to 70 %, and about 6 to 40 %, respectively, depending on the scenario chosen.

Subtask 6.2b illustrates the raw materials needed for energy transition. The most affected technologies would be some solar PV technologies (tellurium, indium, silver, manganese), solar CSP (silver, manganese) and Li batteries (lithium, manganese). Also, transition to alternative technologies will intensify global copper demand. Furthermore, a sensitivity analysis has been performed considering the rest of the economy, so that the risk results worsen: by the end of the period, the cumulated demand is higher than the current estimated level of reserves for 11 minerals in at least one of the considered scenarios: indium, tellurium, gallium, cadmium, tin, chromium, silver, lithium, lead, zinc and manganese. Three more minerals would require at least ½ of the current reserves: molybdenum, copper and nickel. By the end of the period, the cumulated demand is higher than the current estimated level of resources for 2 minerals in at least one of the considered scenarios: tellurium and indium. Three more minerals would require at least ½ of the current resources: silver, molybdenum and manganese.

Subtask 6.2c focuses specifically on the socially necessary adaptations of the energy system transformation. Unemployment rates, consumption patterns and collaborative versus competitive behaviours are critical aspects that are considered to evaluate the societal influence of the transition

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towards a 2050 framework. Associated with these social indicators, behavioural social patterns helping to reach the objectives of 2050 are explored. A possible pattern of societal changes is analysed as bottom up as well as top-down. This means, from small groups and self-organising patterns to policy makers (bottom up) or from policy-makers to citizens and small groups (top down). This aspect is explored introducing the selected social behaviour in the MEDEAS nested model approach.

Subtask 6.2d tries to understand the economic costs of the energy transition to a low-carbon society by considering the changes in the added-value for two scenarios: the BAU and Green Growth, and according to three factors: total electricity production, labour compensation and capital input. The BAU scenario shows that the added-value associated with electricity production will increase 31 % in 2030, and 160 % by 2050, with similar growths for the labour compensation, and fixed capital. Instead, the Green growth scenario presents decreases of 10 % and 43 % in the added-value of electricity production for 2030 and 2050, respectively. Thus, the labour compensation will also decrease 27 % and 55 %, and the capital input will initially increase by 11 % and finally decrease by 33 % from 2030 and 2050, as a consequence of the reduction in total electricity production.

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Appendix A: Cumulated extraction of materials including the whole economy

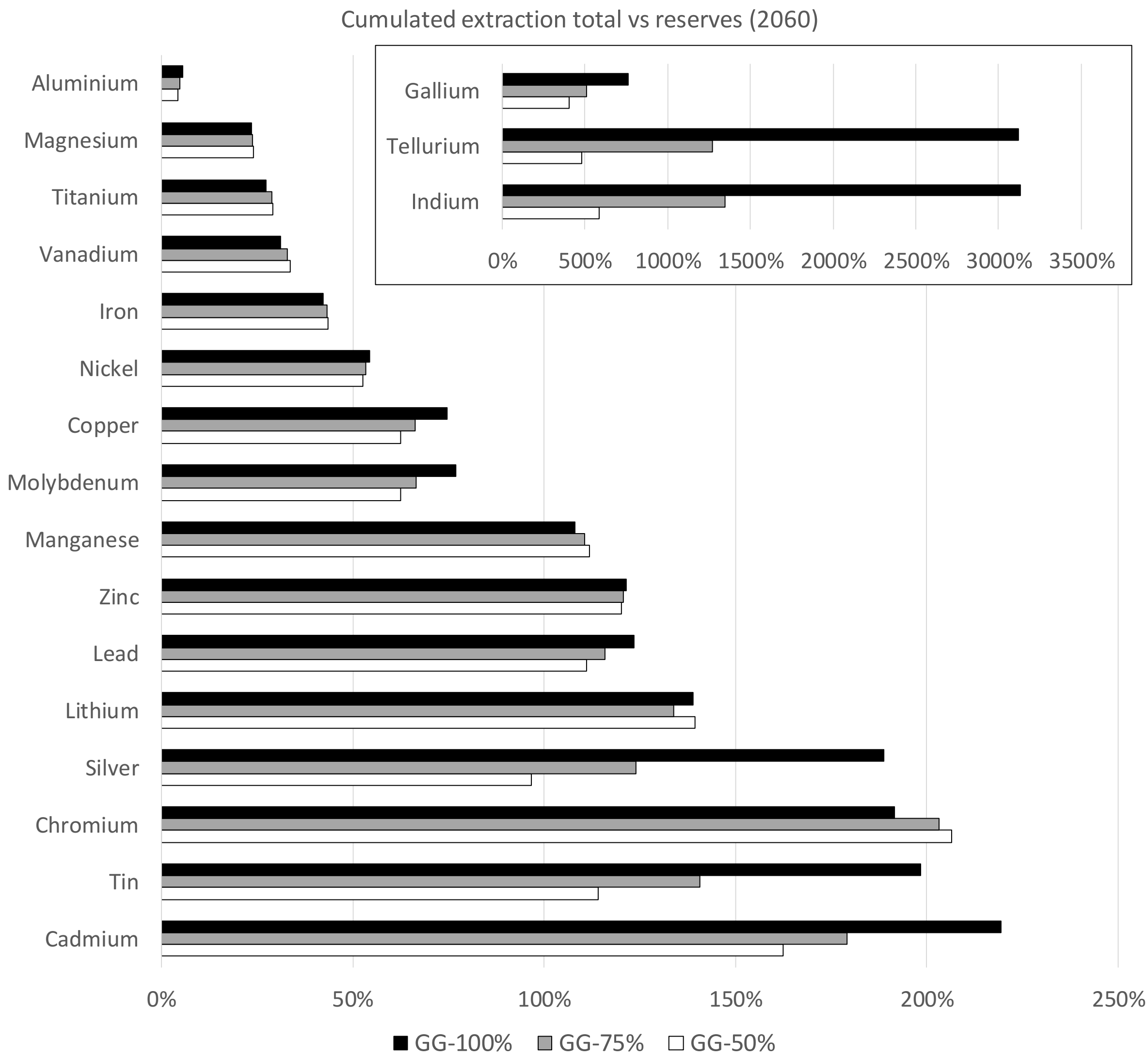

Figure A1: Cumulated extraction (2015-2060) of minerals for the total system vs current reserves for the three scenarios GG-20%, GG-50% and GG-100%.

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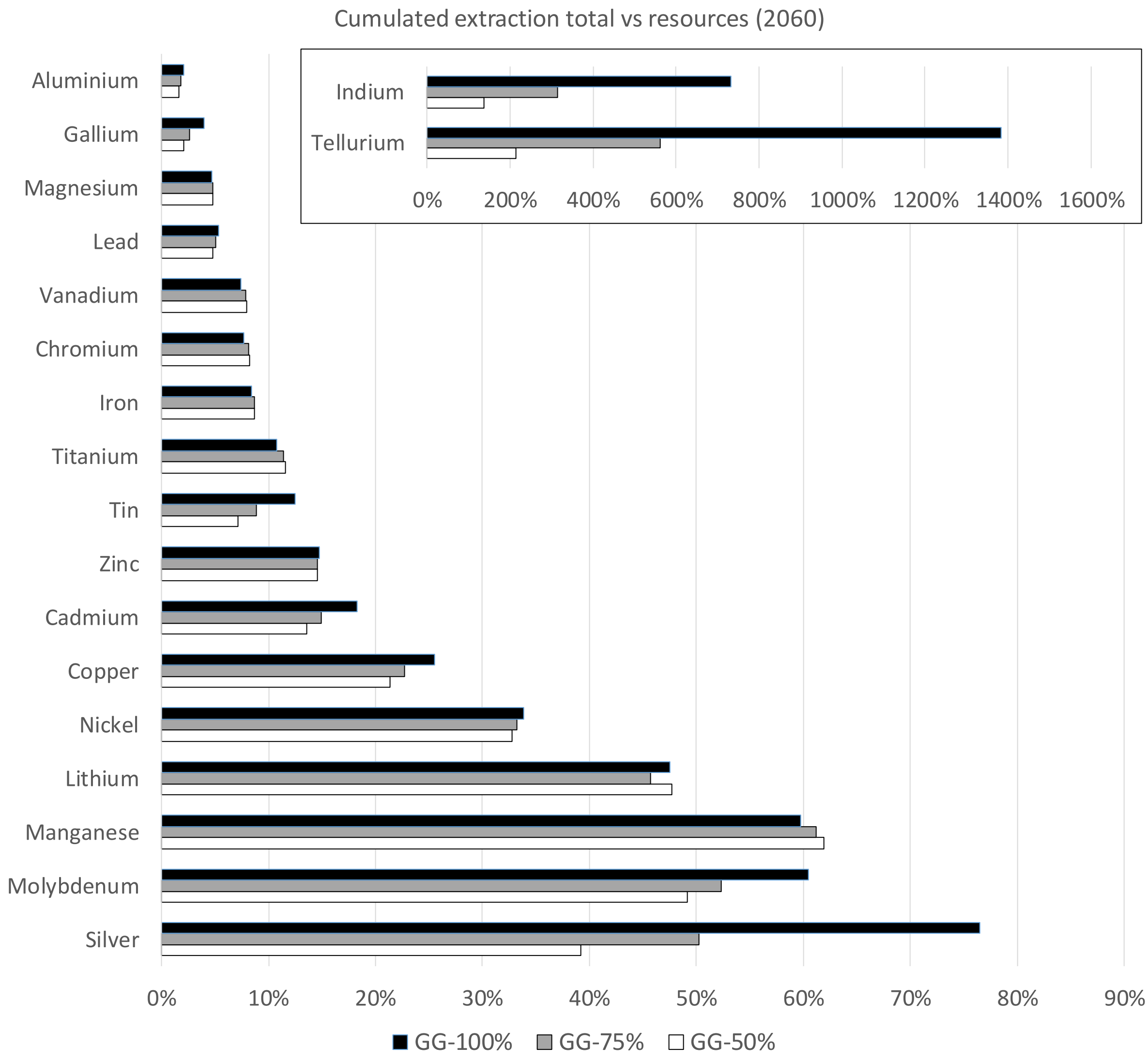

Figure A2: Cumulated extraction (2015-2060) of minerals for the total system vs current resources for the three scenarios GG-20%, GG-50% and GG-100%.

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