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Master of Science – Energy Engineering

Assessing Impact of Global Energy Transition: a World Trade Model Approach

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Contents

List of figures

List of tables

Sommario

Negli ultimi anni stiamo assistendo a una graduale transizione verso un sistema energetico a basse emissioni di carbonio. Con “Clean Energy Transition” si intende un graduale passaggio dal consumo di combustibili fossili ad un'elettrificazione degli usi finali, combinata con un maggiore sfruttamento delle fonti rinnovabili. In questo contesto, la modellazione energetica si è imposta come metodologia utile per la creazione e la sperimentazione di scenari futuri caratterizzati da un'elevata penetrazione rinnovabile.

In questo studio proponiamo un'analisi di fattibilità basata sulla reale disponibilità di risorse del Sustainable Development Scenario (SDS) elaborato dall'IEA per il 2040. Per affrontare la transizione energetica da una prospettiva olistica, abbiamo adottato il World Trade Model, un modello di ottimizzazione lineare ibrido appartenente alla categoria input-output basato sul vantaggio comparativo e soggetto alla limitazione di risorse. Questo approccio integrato ha permesso di coinvolgere la competitività delle risorse tra i settori produttivi, tenendo conto del fabbisogno di materiali. L'attenzione agli impatti ambientali è stata finalizzata a valutare le implicazioni su 5 diverse risorse naturali: emissioni di CO_2, esaurimento dei combustibili fossili, esaurimento dei metalli e dei minerali, utilizzo di suolo e consumo di acqua.

I risultati del modello mostrano benefici nella maggior parte dei suddetti indicatori, ad eccezione di un maggiore sfruttamento dei metalli e di occupazione di terreno. Nell’SDS, l'utilizzo del suolo relativo alla produzione di energia elettrica è quasi raddoppiato a causa del brusco aumento della capacità installata per quanto riguarda impattanti tecnologie come turbine eoliche e impianti a biomassa. Per ragioni analoghe, aumenterà anche l'estrazione di materie prime estrattive, in particolare per quanto riguarda i minerali non metallici e l'alluminio, che registreranno un significativo balzo rispettivamente del 50% e del 40%. Un risultato diverso si delinea per quanto riguarda le emissioni globali di CO_2, che si stima diminuiranno del 35%, e l'estrazione di combustibili fossili, per cui si prevede una riduzione soprattutto per quanto riguarda il petrolio greggio e il gas naturale. Nel corso della nostra analisi, ogni fabbisogno di risorse è stato confrontato con la disponibilità regionale al fine di individuare eventuali insufficienze critiche.

In conclusione, il nostro lavoro valuta che una transizione energetica come quella descritta dall'IEA nel loro Sustainable Development Scenario sarebbe un percorso praticabile anche per quanto riguarda lo sfruttamento delle risorse naturali.

Parole chiave: analisi input-output, World Trade Model, valutazione delle risorse, transizione energetica, valutazione d'impatto.

Abstract

In the recent years, we are witnessing to a gradual transition towards a low carbon energy system. For clean energy transition we mean a gradual shift from fossil fuel consumption to an electrification of final uses combined with an increased exploitation of renewable sources. In this context, energy modelling has come in the spotlight as a useful methodology for the creation and testing of future scenarios characterized by high renewable penetration.

In this study we propose a feasibility analysis based on real resources availability of the Sustainable Development Scenario (SDS) depicted by IEA for 2040. In order to approach energy transition from a holistic perspective, we adopted the World Trade Model, a hybrid linear optimization model based on comparative advantage and subjected to resource limitations belonging to input-output category. This integrated approach allowed to involve the competitiveness of resources among productive sectors and permitted an evaluation of material requirements. The focus on environmental impacts were aimed to assess the implications on 5 different natural resources: CO_2 emissions, fossil fuel depletion, metals and minerals depletion, land use and water consumption.

Model output evidences benefits in the majority of the abovementioned indicators, aside from an increased exploitation of metals and land occupation. In SDS, land use related to power generation nearly doubles due to the abrupt rising of installed capacity concerning impactful technologies as wind turbines and biomass plants. For similar reasons, also extractive commodities mining will increase, particularly regarding non-metallic minerals and alluminium which will witness a significant leap of 50% and 40% respectively. A different outcome is outlined for what concerns global CO_2 emissions, which are estimated to fall by 35%, and fossil fuel extraction, which is predicted to drop regarding mainly crude oil and natural gas. Along our analysis, each resource requirement has been compared with regional availability in order to identify possible critical shortages.

In conclusion, our work assesses that a clean energy transition as the one depicted by IEA in their Sustainable Development Scenario would be a practicable path also concerning natural resource exploitation.

Keywords: input-output analysis, World Trade Model, resource assessment, energy transition, impact evaluation.

1. Introduction

In the recent years, the transition to a cleaner energy system has been a pivotal topic both in public debates and in politics decision making. The pathway to achieve it is not straightforward and it is studded with international programmes, guidelines and targeted conferences.

This chapter aims primarily to give an outlook on the multiple themes and recent trends involved in this process and, in the second place, to introduce our main work objectives.

1.1 The complexity of a clean energy transition

For energy transition, by definition, international agencies mean a prominent change in the energy system. During the last decades, we are witnessing to a worldwide switch from a fossil fuels-based energy system to a renewable-oriented one. This process has specific and clear drivers and it is accountable for a wide variety of implications. The most evident cause on the surface of Governments deals about clean energy development is the will to mitigate climate change effects. In fact, the link between the increase of anthropogenic greenhouse gases (GHG) emissions and Earth temperature rising is now undeniable (IPCC, 2018).

Avoiding a simplistic tunnel vision, it is equally clear that the orientation of the global energy system is strictly related to geopolitics, and a transition in this field involves major investments. As stated by United Nations Environment Programme, over the 2010-2019 decade $2.7 trillion has been invested globally in new renewable energy capacity, with a yearly contribution that never fell below $250 billion for the last five years. In Figure 1 the top 20 investing countries over the last decade are reported; China earned the first place also for outward renewable energy capacity additions, mainly in Africa.

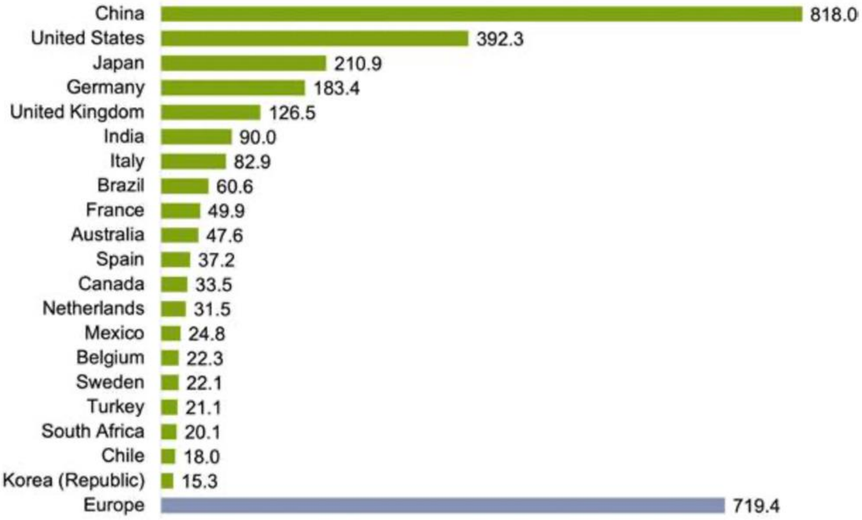


Figure 1 - Renewable energy capacity investment from 2010 to 2019, $BN; Source: UNEP, Frankfurt School-UNEP Centre, BloombergNEF

Focusing on 2019, nearly 78% of the net gigawatts of generating capacity added globally were in renewable sources, excluding large hydro (Frankfurt School-UNEP Centre/BNEF, 2020).

As introduced before, the increasing share of electricity generated by renewable sources brings with it several technical and socio-economic consequences. Concerning the first point, flexibility would become a critical feature for a power grid because of the difficulties to predict and dispatch sources like sun radiation and wind. These complications can lead to a future substantial reshape of electrical grids as they are known (Schmalensee, 2011). From a socio-economic perspective, the modular nature of photovoltaic modules and wind turbines enables smaller-scale decentralized power generation and allows consumers to become also producers. Spreading of renewable generation also plays a predominant role in the achievement of energy security, allowing countries dependent on the import of fossil fuels to develop their own internal capacity.

1.2 Impact of Covid-19 on clean energy transition

“If governments take advantage of the ever-falling price tag of renewables to put clean energy at the heart of Covid-19 economic recovery, they can take a big step towards a healthy natural world, which is the best insurance policy against global pandemics.” With this statement, Inger Andersen, the Executive Director of the UN Environment Programme, decides to open up the UNEP “Global Trends in Renewable Energy Investment 2020” report. This is only one of the multiple voices coming from energy related international organizations, trying to address and evaluate Covid-19 impact on energy transition (IRENA, 2020).

The International Energy Agency (IEA) estimates a decline of global energy investment in the current year of around a 20% - or almost $400 billion - compared to 2019 values. This capital spending cutback would be the largest on record and it would affect both fuel supply, power sector and energy efficiency.

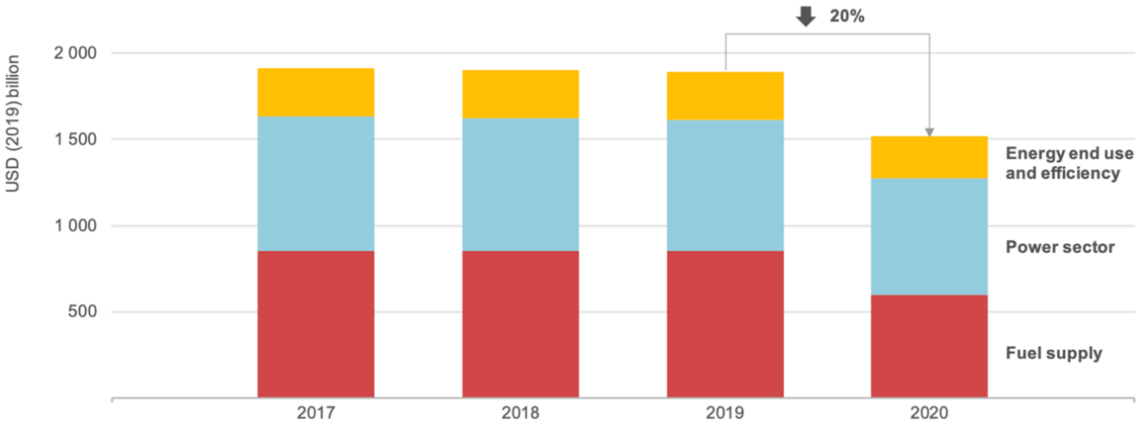


Figure 2 - Total global energy investment. Source: IEA, WEI2020

As depicted **Figure 2** fossil fuel supply experiments the largest variation with a drop of around 30%, meanwhile both power sector and energy end-use and efficiency suffer a 10% fall. Overall, China would undergo a decline in energy spending of only 12%, muted by the relatively early restart of industrial activity following strong lockdown measures in the first quarter of the year. On the other hand, United States would occur a larger fall in investment of over 25% because of its greater exposure to oil and gas, around half of all US energy investment is in fossil fuel supply. Europe's estimated decline is around 17%, with investments in electricity grids, wind and efficiency holding up better than distributed solar PV and oil and gas, which see steep falls (IEA, 2020b).

According to IEA, there is no cause for celebration about the immediate fall of CO_2 emissions due to major disruption of travel, trade and economic activity. Their analysis shows that 2020 could see an 8% drop in global energy-related CO_2 emissions and a global primary energy demand contraction of around 6%. The real challenge will be avoiding an emission rebound like the one experienced after the 2008 global financial crisis, taking on radical shifts in technology and consumer behavior. For this reason, the way that policy makers respond to the crisis today will determine the energy security and sustainability threats that the world will face tomorrow.

1.3 Decarbonizing energy sector

In order to enhance the clean energy transition process, a detailed examination of the energy sector is necessary. Many studies carried out by various energy agencies have tried to build guidelines for this transition, analysing the different technologies available nowadays. The Fondazione Eni Enrico Mattei (FEEM) one (SDSN & FEEM, 2019) and the International Renewable Energy Agency (IRENA) one (International Renewable Energy Agency (IRENA), 2018) are only two of the many available in literature.

In each part of the energy sector there are different possibilities to replace polluting technologies with cleaner ones. For this reason, it is essential to analyse their benefits and their limits, both from economic, technological and environmental point of view.

1.3.1 Power Sector

The power sector is obviously the easiest to act on, thanks to the wide choice of technologies available that represent valid alternatives to the fossil fuel power plants. Energy generation technologies can be divided into three main groups, according to their life cycle GHG emissions. This indicator is one of the most used for the calculation of energy generation impacts on human health because it computes global warming potential of an energy source through its life cycle assessment (LCA). This method tries to evaluate emissions, gCO2eq specific to kWh, deriving from the whole energy generation process: from material and fuel mining, through construction and operation, to waste management.

Fossil technologies without Carbon Capture and Storage (CCS) are the ones accountable for the highest specific emissions, due mainly to the direct CO_2 emissions coming from the fuel combustion, around 400-900 gCO_2eq/kWh. In contrast, nuclear and renewable technologies emissions are at least at one order of magnitude below, about 3-24 gCO_2eq /kWh, while the fossil technologies with CCS are in a middle range of 120-190 gCO_2eq /kWh (Treyer, Bauer, & Simons, 2014). In the calculation of life cycle GHG emissions, the upstream processes, as fuel exploration and mining, and the downstream ones, decommissioning and waste disposal, are taken into account. For traditional fossil fuel technologies, the emissions related to these parts of the life cycle account for about the 25% of the cumulative emissions, while, in technologies characterized by low direct emissions, they can represent up to the 90% (Weisser, 2007).

Among the wide variety of renewable alternatives, some are already competitive thanks to the decreasing costs trends of the last years, meanwhile others require a further technological research in order to be competitive in the market. For example, vertical axis wind turbines and c-Si PV modules have spread extensively during last years, thanks to enhancement of construction materials, consequent increased efficiency and a further reduction of costs, as a result of economies of scale, increased competitiveness, maturity of the sector and low cost production in China (IRENA, 2014; Kavlak, McNerney, & Trancik, 2018).

Concerning PV technologies, besides the common polycrystalline and monocrystalline silicon modules, a so called “second generation” is advancing quickly: thin-film modules present lower efficiencies but also lower costs compared to traditional modules. We can identify two types of photovoltaics systems: off-grid and grid-connected systems. The first ones have significant opportunity for application in unelectrified areas of developing countries, where mini-grid systems have become a reliable alternative for village electrification. In contrast centralized systems present different technical advantages as better performance, reduction of storage needs and dynamic behavior (Ellabban, Abu-Rub, & Blaabjerg, 2014). Photovoltaics is not the only way to harvest energy from the Sun: a completely different technology as Concentrating Solar Power (CSP) has also found its place in the energy market. CSP plants present a higher technical complexity and consequent superior costs but feature also a reliable energy storage method that enables dispatchability.

Wind turbines started to improve in the early ‘70s, but only in 1990 emerged as one of the most important clean energy sources. As for PV, also wind energy generation present a wide variety of types in the market. The most consolidated technology is the Vertical Axis one (VAWT) but also Horizontal Axis wind turbines (HAWT) are spreading thanks to their lower land use.

Wind turbines can be classified by:

- Typology: vertical axis (VAWT) or horizontal axis (HAWT);
- Plant location: onshore or offshore;

The major developments have been reached in onshore turbine, while offshore technology continue to be less mature and nowadays a not competitive option due to higher investment costs. Onshore VAWT is the most consolidated technology available, but current research is keen on the exploitation of the many positive aspects of offshore wind generation as higher and more constant wind availability, possibility to use larger wind turbines and consequent potential reduction of land use.

From 2009 to 2017, the levelized cost of electricity has fallen by 73% and 23% for solar photovoltaics and onshore wind respectively, while offshore generation presents a decrease in LCOE only from 2012. In recent years, PV and onshore wind projects are offered at 2-3 c$/kWh, prices sometimes below the costs of existing generation plants (Gielen et al., 2019).

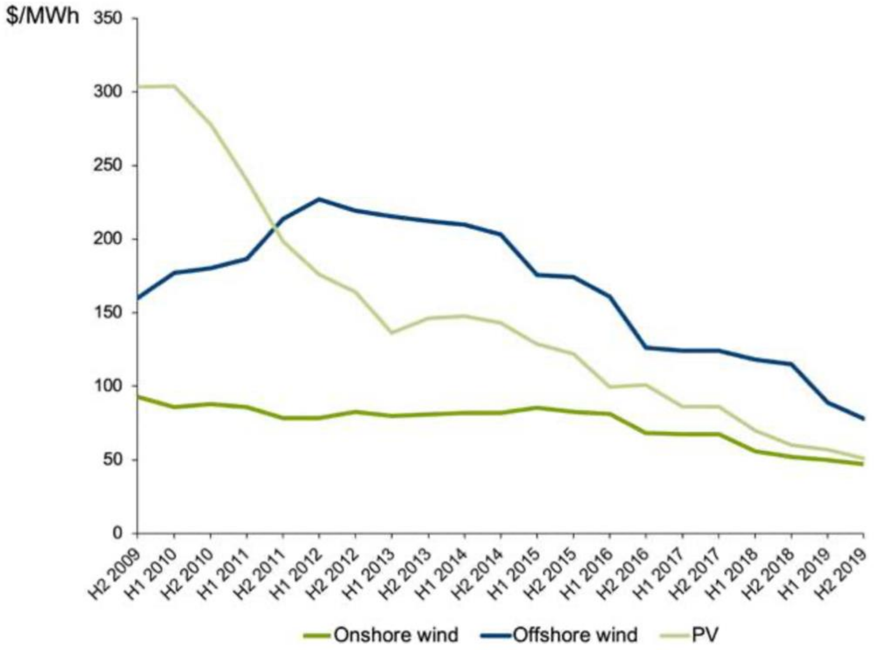


Figure 3 - LCOE trend, 2009 to 2019; Source: UNEP, Frankfurt School-UNEP Centre, BloombergNEF

Another natural exploitable source is biomass, considered CO_2 neutral according to EU despite conflicting opinions among experts (Brack, 2017). It can represent a good solution to limit the variability of the previous renewable sources because it can be used as feedstock to produce other liquid or gaseous fuels (biofuels) easy to store and transport. This versatility make biomass useful in an energy scenario with high shares of intermittent sources. In contrast to these benefits, some critical aspects still make this technology one of the most debated among experts. Biofuels high cost of transportation and collection, in addition to their low energy density, is the main one, followed by their high environmental impact on land, water and crops (Ellabban et al., 2014).

Hydropower completes this renewables outlook, representing one of the most exploited and consolidated sources having one of the highest conversion efficiencies (around 90%) thanks to the direct transformation of hydraulic energy to electricity. It is not possible to predict a large development since most of its potential has already been exploited. Although, there are some aspects on which further improvements are possible such as reducing environmental impacts, and developing more robust and cost-effective technological solutions (Ellabban et al., 2014).

Grid storage technologies will be increasingly important, considering also the gradual electrification of transports. Thanks to advances in research, storage costs are expected to decrease, making a scenario highly dependent on renewables competitive from an economic perspective. In particular the technologies that will bring more capacity on the market are the modular ones, such as Li-ion batteries. The experience in manufacturing (learning by doing) can be an important driver for the technical development of storage, as well as the R&D (learning by research) and the customer feedback (learning by use) (Schmidt, Hawkes, Gambhir, & Staffell, 2017).

The concept of Smart Energy System, that exposes the benefits of a cross-sectoral connection between the different actors in the energy sector, represents a good flexibility option in order to match demand and generation. Some flexibility options, such as demand side management (DSM), power-to-gas (P2G), power-to-heat (P2H) or vehicle-to-grid (V2G) could be interesting and would be significantly decrease the cost of the whole system (Henrik Lund, Østergaard, Connolly, & Mathiesen, 2017). This concept has been applied in a work on the European Union energy system, analysing the benefits of an integration of flexible solutions. 'Connolly et al' estimate that a 100% Renewable Energy System with a high penetration of flexible solutions compared with a business-as-usual (BAU) scenario will create about 10 million additional jobs only related to the EU energy sector. Without considering the indirect effect on other industries, it could avoid the dependence to bioenergy, limiting its share to sustainable levels. This benefits can be achieved with an overall investment up to 15% higher than a BAU scenario and would reach easily the 80% reduction on CO$_2$ emissions set as goal by European Union (Connolly, Lund, & Mathiesen, 2016).

1.3.2 Transport Sector

In 2017, transport globally accounted for 2794 Mtoe, about the 28% of Total Final Consumption (TFC) and its demand is predicted to increase with the population and economic growths. Almost 90% of the energy demand is still satisfied by traditional fossil fuels. The decarbonisation of this sector requires a multiplicity of solutions due to its complexity, especially in sea and air transports where emissions trend present the fastest rising rate. For road and railway transport, representing nearly 75% of the transport energy consumption, alternatives to conventional internal combustion engines (ICE) vehicles are electric and fuel-cell ones.

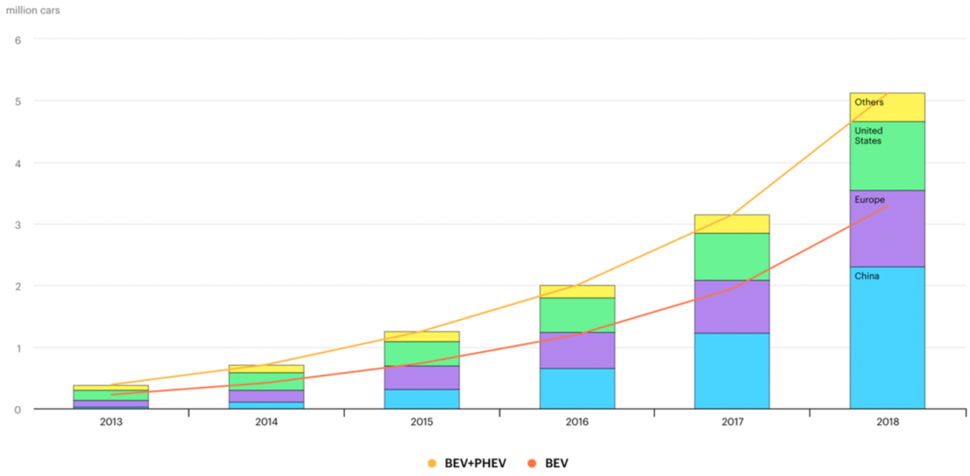


Figure 4 - Electric car stock by region and by technology; source: IEA

As shown in Figure 4, circulating electric vehicles fleet has grown in the last years and in 2018 was attested at about 7.2 million summing up Battery Electric Vehicles (BEV) and Plug-in Hybrid Electric Vehicles (PHEV). There is a long way to come if we analyse data from IRENA's Remap2050 that expect an increase up to 1 billion by 2050.

In order to decrease transport emissions, also hydrogen will play an important role as a green fuel. Besides its traditional steam reforming production process, H_2 production through electrolysis could develop taking advantage from the excess of renewable electricity and representing a flexibility solution to compensate the variability of the power sector (International Renewable Energy Agency (IRENA), 2018). The global Fuel Cell Electric Vehicle (FCEV) stock nearly doubled to 25210 units at the end of 2019, with 12350 new vehicles sold, more than doubling the 5 800 purchased in 2018. The adoption of fuel cell buses and trucks is spreading in China, making it the leader in global stock, and announced also in Europe and Japan.

1.3.3 Heating Sector

The last sector deserving an analysis concerns the heating and cooling energy demand. Heat is the largest energy end-use, reaching about a half of global final energy consumption and accounted for about 40% of energy related CO_2 emissions. About 50% of the heat production is used for industrial scopes, another 46% is used for buildings space and water heating while the remaining part is used to cook.

Heating sector is still dominated by fossil fuel technologies and old electric heating technologies like electric resistance heaters and water heaters, characterized by low efficiencies. However, a slow transition is started and gas boilers, which efficiencies are around 90/95%, have gradually replaced conventional coal and oil boilers, characterized by lower efficiencies and heavier environmental impact. Heat pumps or renewable technologies such as solar thermal systems represent only 10% of new sales of last years. The improvements of buildings and technologies efficiencies, combined to a fuel-shifting and a decarbonization of power sector, could bring to a reduction of the heating sector emissions of about 30% by 2030.

The most promising clean technology, looking specifically to building sector, is represented by heat pumps, which are about 5 times more efficient than common direct heating from combustion. In Europe, heat pumps sales increased by 25% in just two years, thanks to the reversibility of some models which permits the satisfaction of both heating and cooling demand. Although this increase in the heat pumps market, they meet only 5% of the global residential heating and cooling demand, showing that more efforts in the development of this technology are necessary.

While in residential sector electrification is increasing, different situation is the one related to industries, where, due to the high amount of heat demand, is not always possible to electrify final uses. For example, low-temperature heat from heat pumps can't always substitute high-temperature heat from gas boilers needed by some industrial processes. To overcome this problem, the best option is represented by a fuel-shifting, switching from traditional to biofuels or from coal to gas. (IEA, 2020a)

1.4 The environmental impact of decarbonisation

Given the variety of electricity generation sources available, it is clear that there is not a silver bullet but, depending on local conditions, there is a wide range of possibilities since every choice involves different environmental and economic implications. Energy sector origins a multiplicity of environmental impact. For this reason, an evaluation restricted only to emissions can be too simplistic and risks neglecting equally important effects such as water use and pollution, fossil and mineral depletion, land occupation and nuclear waste. Every technology affect in a different way each of the aspects mentioned above, it is therefore essential to study the availability of natural resources and choose the most appropriate technology in accordance with objectives of the study.

However, recent works show that, despite the significant impact of renewable power plants in use of land and mineral depletion, a transition to a low-carbon power system leads to benefits on most of the environmental aspects, in particular those related to human health (Hertwich et al., 2015; Luderer et al., 2019).

Nevertheless, decarbonization of energy sector has some aspects that should be taken into account and monitored. In the work by Kleijn on the metals requirements of renewable technologies three different configurations of energy system are studied: the actual one, the actual with the implementation of CCS technology and a high renewable one, taking as reference the IEA Blue Map one. This last scenario drastically changes the resources requirements of the power sector, shifting from fossil fuels (fossil depletion decreased by 90%) to mineral resources, with bulk material requirements (in particular iron, copper, aluminum and cement) increased four-fold compared to baseline levels. CCS for example increases substantially the demand for iron and nickel while biomass needs five time as much iron per kWh electricity produced than regular fossil fuel-based plants. Summing up, a switch to non-fossil electricity mix would result in an increase of the demand of nickel, uranium, silver, molybdenum, copper and aluminum (René Kleijn, van der Voet, Kramer, van Oers, & van der Giesen, 2011).

A deeper decarbonization of the energy sector would also lead to a further increase in material demand in other sectors. One of the most prominent will be the automotive one, due to the metals need for high tech parts like batteries, electric motors and fuel cells (Rene Kleijn & Van Der Voet, 2010). In fossil fuel power production, the materials requirement accounts for a small share in the total environmental impact (about 1% without CCS and 2% with CCS), while in renewable technologies this share greatly increases reaching 20-50%, showing that the materials requirement could be one of the limiting factors of this transition. Another aspect that has to be taken into account is the inevitable grid modification and extension, occurred during this decarbonization process (Williams et al., 2012) (Berrill, Arvesen, Scholz, Gils, & Hertwich, 2016).

Besides environmental repercussions, a phase out of the fossil fuel power plants could have also an impact on the employment rate. A deep analysis has to be carried out, assessing a comparison between the possible number of new jobs created by the renewable generation implementation and the ones lost related to the phased-out fossil fuel ones. Moreover, the construction of new renewable power plants could raise problems concerning landscape and its appearance, in specific areas. These effects may lead to lower acceptance levels and possible protests (Liebe & Dobers, 2019).

Since all of these energy sources have different benefits and drawbacks, it is crucial to evaluate direct and indirect impacts from the environmental and economic point of view. In last years, modelling of energy scenarios has become an increasingly used tool, adopted for its versatility and reliability on the previsions of renewable energy transition outcomes.

1.5 Thesis Objectives

Along this work, the focus has been concentrated on three main objectives.

The first one has involved the analysis of energy modelling state of the art, to find research gaps and possible dark spots. A deep literature review about high renewable penetration scenarios led to a creation of an extensive taxonomy, cataloguing each scenario on the base of its different features. Our focus has been on highlighting pros and cons of different configurations and main assumptions, in order to evaluate limits and lacks of existent energy models outputs.

Once completed this time-demanding task, the second pursue has been simulating actual good and services production through a reliable model. Implementing this model, our specific needs led us to maintain a global perspective, with a specific focus on electricity generation. In order to reach this ambitious goal, we also carried out a global resource assessment, improving the model adopted to better represent the reality.

The third and final objective has been the evaluation of economic and environmental impacts of a clean energy transition, testing the model previously calibrated. This aim has been corroborated by a feasibility analysis based on real resources availability and followed an integrated approach to involve the competitiveness of resources among different productive sectors.

Hereafter we will illustrate the process and results of our high renewable penetration energy scenarios literature review.

2. Literature review

In this chapter, a review of a multiplicity of high renewable penetration scenarios is presented. We will put in evidence the major characteristics and the different scopes of each scenario, underlying the fundamental assumptions taken in their building phase. Moreover, we will detect scenarios criticalities and we will try to find possible solutions to overcome them.

2.1 Taxonomy of high penetration renewable scenarios

To have a clear overlook about the existent background we have reviewed 46 future energy scenarios. Doing this, we composed a classification based on:

- Geography
- Analytical Approach
- Time Resolution
- Path
- Model Type
- Technology Detail (Power, transport, heating and cooling)
- Main assumptions
- Results
- Limitations

A reduced taxonomy can be found in the Appendix A.

During our analysis, we wanted to know how the feasibility of a nearly 100% Renewable Scenario is assessed and which factors, as electric grid or environmental and economic impacts, have been considered.

Authors use different criteria to establish the feasibility of a low carbon energy system, from a simple demand satisfaction with different time resolutions to an examination of the necessary resources. Modelling future energy scenarios are an important tool for the development of energy policies. Since each scenario is different from another according to scope, assumptions and parameters, an high grade of transparency regarding technical and economic assumptions is required (Child, Koskinen, Linnanen, & Breyer, 2018).

In the last years, multiple studies on 100% Renewable Energy Sources (RES) systems have been carried out, presenting different approaches and assumptions, which can lead to different solutions.

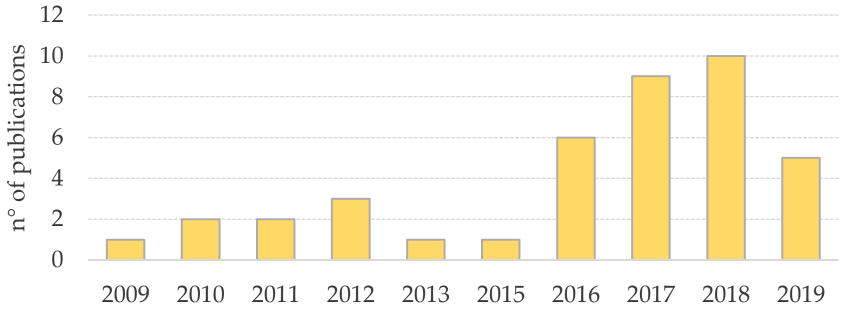


Figure 5 - Timeline of the reviewed scenarios; source: own elaboration

In the work by Hansen et al. on the status on 100% RE system studies, we can find a report on the level achieved by the scenarios in actual literature, some predictions about this tool and a brief classification on geography considered, the sector included and the publication journal (Hansen, Breyer, & Lund, 2019). Most of these studies conclude that a shift to 100% low-carbon energy systems is technically feasible, keeping some uncertainties about the economic practicability, while others find that is both technically and economically feasible. Some papers, despite pondering a shift to low-carbon system necessary, believe that it cannot be implemented in the near future and at the current level of technology (Heard, Brook, Wigley, & Bradshaw, 2017) (T. W. Brown et al., 2018).

Our objective is to catalogue the scenarios present in literature trying to highlight the limits and assumptions that have determined the results. In order to construct a clear mind map, we classified them in different categories, which can represent some limits or peculiarity of the scenarios modelled.

2.2 Geography of the scenarios

The first distinctive feature of these scenarios is the geographical area considered. The area included in the analysis is a central characteristic of every energy scenario; from this trait, different limits or strengths can be outlined. Defining a classification, three geographical levels can be drawn: regional, multiregional and global.

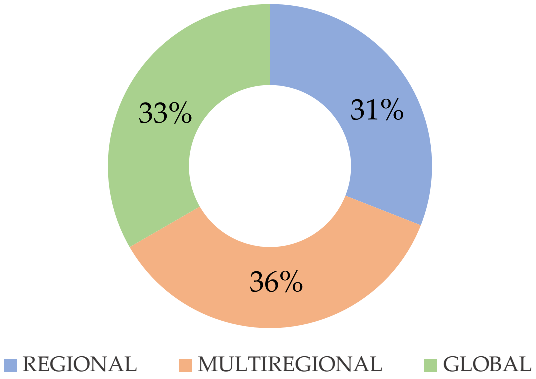


Figure 6 - Geography classification of the scenarios; source: own elaboration

2.2.1 Regional level

The regional scenarios correspond to about the 30% of the total cases overviewed. These have the limitation of being hardly replicable in other parts of the world, due to local conditions that influence the technological choices made during the modelling phase. There are, for example, regions where wind power is more exploitable, others with large water availability or solar irradiation: these characteristics can be decisive in choosing the optimal technologic mix. In addition to this, it should be considered that each region has a different history of its own energy sector, with more established technologies than others that are still unused.

Mason et al., in a study on the feasibility of a 100% renewable system in New Zealand, whose current energy system is already heavily dependent on hydropower, use the high quantity of natural water reserves as storage to overcome renewable variability. The study evaluates the practicability of a system dominated by hydropower (53-60%). The result is strongly affected by the conformation of New Zealand and by its current energy system which present a share of fossil fuel power generation of 32%, well below the mean share in other countries of Asia & Pacific area (70%) (Mason, Page, & Williamson, 2010). This configuration cannot be replicable straightforwardly, in other zones alternative solutions can be implemented to compensate renewable sources variability. Another regional study has been developed by Williams et al. on the electrification and decarbonization of California, where low demand, if compared to the entire USA's one, can ease the transition process (Williams et al., 2012). Another limit of a regional scenario is the impossibility to show detailed trade system among countries, considering the topic region as an isolated part of the world, a situation totally different from the actual one. To include this possibility in the analysis, a multiregional configuration can be adopted.

2.2.2 Multiregional level

A multiregional perspective makes viable the study of an optimal level of interconnection between regions. In literature, multiple studies explain the different interconnection options among energy systems. Some experts prefer a decentralized view, while others opt for a strong connection and a high centralized system focused on import and export.

Lilliestam and Hangar, in a study at European level, try to describe the two different configurations, highlighting their limits and benefits. Their report illustrates two different energy system visions outlined by Desertec and Eurosolar. The first identifies an optimal solution in the import of large quantities of solar energy from deserts to speed up the decarbonization process. On the other hand, Eurosolar underlines the concept of energy autonomy and therefore pushes for a rapid decentralization process of the energy system through an increase of renewable penetration. Both the options are cheaper than actual system and improve energy security, but the Desertec's vision has the peculiarity of being able to start a process of sustainable development of the Middle East & North Africa (MENA) countries, reinforcing also the cooperation among these and Europe (Lilliestam & Hanger, 2016). A third vision is presented by Battaglini, who tries to combine the benefits of the two options to compensate their limits, producing a SuperSmart Grid vision (Battaglini, Lilliestam, Haas, & Patt, 2009).

In a study on the European energy sector, Child has elaborated two scenarios: in the first regions are independent from an energy point of view, while in the second they are interconnected with high transmission lines and cables. The review of this analysis shows how the second configuration leads to lower costs and faster decarbonization (Child, Kemfert, Bogdanov, & Breyer, 2019). Moreover, Tröndle et al. evaluate different possible configurations for Europe. The work highlights that, despite a high interconnected energy system has typically lower costs, the technological requirements of this energy system could create problems on physical appearance and land use. A possible solution is a trade-off among these two designs, in order to obtain lower costs and a higher social acceptance (Tröndle, Lilliestam, Marelli, & Pfenninger, 2020).

Similar studies have been carried out in Sub-Saharan Africa (SSA) and Asia. Concerning SSA, Barasa et al. simulate a high renewable scenario with different mixes of technologies and interconnection. The levelized cost of electricity (LCOE) results show that the installation of high voltage direct current (HVDC) transmission lines leads to a significant reduction of electricity cost of the entire system (Barasa, Bogdanov, Oyewo, & Breyer, 2018). In Asian continent, three different scenarios have been set up on the basis of HVDC level in grid connections. The results illustrate a decrease from 66.7 €/MWh in a decentralized scenario to 63.5 €/MWh for a centralized grid connected scenario (Gulagi, Bogdanov, & Breyer, 2017). These outcomes highlight even more one of regional scenarios limits: the impossibility to consider a trade system based on import and export.

Almost 36% of the reviewed cases have been developed at a multiregional level, the majority involves European continent while a smaller share refers to Africa and Americas. All these analyses assure that a high renewable penetration energy system is possible, even without affecting greatly the LCOE. In conclusion, low details are given about the amount of the investments required in this energy transition (Berrill et al., 2016; Heide et al., 2010; Zappa, Junginger, & van den Broek, 2019), (T. Brown, Schlachtberger, Kies, Schramm, & Greiner, 2018), (H. Lund & Mathiesen, 2009), (Schlachtberger, Brown, Schramm, & Greiner, 2017) (De Barbosa, Bogdanov, Vainikka, & Breyer, 2017) (Taliotis et al., 2016) (Aghahosseini, Bogdanov, Barbosa, & Breyer, 2019).

2.2.3 Global Level

The residual 30% of the reviewed scenarios have a global perspective, enabling a better representation of trades among countries and the possibility to satisfy demands using different technologies according to the specific characteristic of each territory involved. The feasibility of a high renewable penetration energy system is typically controlled ensuring the satisfaction of the demand, assuming high level of interconnection among countries and high level of storage. The common conclusion is that a high renewable system by 2050 is possible. These studies agree on the future centrality of PV modules and onshore wind turbines, typically accounting for more than 60/70% of energy production. Moreover, this percentage tends to rise considering only the power generation sector. This is usually justified by the decreasing LCOE trend coupled with a reducing environmental impact of PV modules and wind turbines.

Among global scenarios, the two developed by Jacobson et al. have been the most ambitious in current literature. In these works, authors use a bottom-up simulation model with LOADMATCH hourly resolution combined with GATOR-GCMOM weather provision tool in order to provide wind and solar time series. These works peculiarity consists in the satisfaction of the demand only through wind, water and sunlight (WWS) resources. Results suggest that "low-cost solutions can be obtained with either (a) CSP with storage, batteries, and thermal energy storage; (b) CSP with storage, additional hydropower turbines, and no batteries or heat pumps; (c) CSP with storage, batteries, and heat pumps but no thermal energy storage or additional hydropower turbines; or (d) combinations of the above" without substantial cost differences among these configuration (Jacobson et al., 2019; Jacobson, Delucchi, Cameron, & Mathiesen, 2018).

Global scenarios are not immune to limits and deficiencies, even the aforementioned reports lack in transparency. The model limits are never mentioned and, in addition, also cost assumptions are never clearly described. In Pursiheimo et al., the authors do not clarify time resolution of the adopted model (TIMES-VTT, a bottom-up optimization model) and express doubts about this aspect, admitting that a greater level of detail would have been necessary (Pursiheimo, Holttinen, & Koljonen, 2019). Teske et al. rely heavily on unripe technologies and assume steep increases in major energy technologies yields (Teske, Pregger, Simon, & Naegler, 2018). Bogdanov et al., in their study on the global power sector, designate PV as the main power source, responsible of about 70% of electricity generation. However, to overcome this high solar penetration, a considerable increase in storage technologies is expected (Bogdanov et al., 2019). In conclusion, among global scenarios, we can also find reports published by the main energy agencies such as British Petroleum (BP p.l.c., 2019), Greenpeace (Teske, 2015), IIASA (IIASA, 2013) and IEA, whose Sustainable Development Scenario will be later examined.

2.3 Energy Sector Detail

Besides the previous geographical classification, energy scenarios can be also categorized through another key driver: the energy sector and technological detail considered.

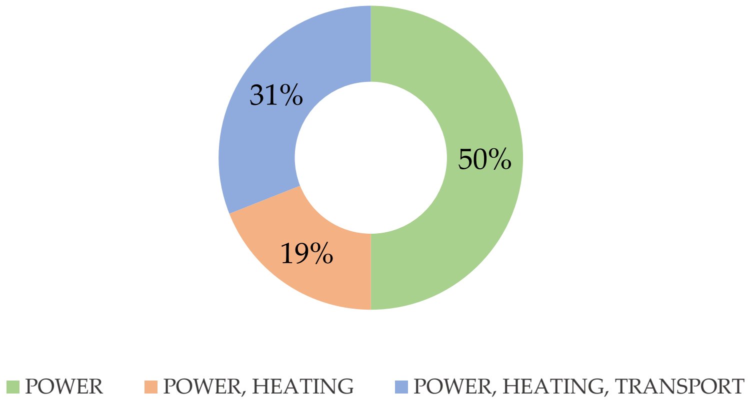


Figure 7 - Sections of the energy system considered in the reviewed scenarios; source: own elaboration

Almost one third of the studies acts on the whole energy sector: power, heating and transport. This approach is the most complete and typically allows to obtain better results thanks to the connections between the different actors of the energy system. As introduced before, some flexibility option such as demand side management (DSM), power-to-gas (P2G), power-to-heat (P2H) or vehicle-to-grid (V2G) could significantly decrease the cost of the whole system if integrated in the energy system to form a "Smart Energy System" (Henrik Lund et al., 2017). The benefits of a cross-sectoral integration of the different players in the energy system are highlighted in several studies. Brown et al. show as in Europe a higher level of synergies among different entities and a developed transmission structure can reduce total system costs by 37% compared to a scenario without these features. This can lead to a 95% drop in emissions but only marginally more expenses than today's energy system. This result is obtained with a bottom-up model (PyPSA-Eur-Sec-30) with an hourly resolution and representing European countries as 30 regions, each one identified by a node. Every node has its own demand and it is connected with the other nodes through the transmission grid. This high aggregation level, which does not allow to represent properly local conditions, represent one of the major limits of this scenario, still one of the most transparent and detailed in literature (T. Brown et al., 2018).

Connolly et al., using the bottom-up model EnergyPLAN, estimate that a 100% Renewable Energy System corroborated by flexible solutions could limit bioenergy to a sustainable consumption. This benefits can be achieved with an overall cost only 10/15% higher than a business-as-usual scenario, but reaching easily the 80% reduction on CO_2 emissions set as goal by European Union (Connolly et al., 2016). These two scenarios exploit the multiregional feature to incorporate the cross-sectorial integration to a high level of interconnection among energy systems.

A different approach is used in Child et al. pursuing the modelling of an energy scenario for Aland Island, one of the coldest regions in Finland. Here, the regional limited perspective, as explained before, make impossible the option of a trade system integration. In the work, authors assess the benefits that an energy system with a large penetration of V2G technology could bring, reducing at the same time both the costs and problems related to variability of renewable technologies (Child, Nordling, & Breyer, 2018).

The integration of all the energy actors also affects the power mix resulting in a model. Löffler et al. in their global scenario show the different configurations of the energy mix between the whole system and the portions taken individually. Analyzing only power generation, results display an 80% of PV and onshore/offshore wind, confirming the trend presented by other global studies. The situation is quite different considering the whole sector, where the percentage drops to about 55% due to the extensive use of biomass in heating and transport sectors. By 2050, heat demand will be satisfied for 60% by biomass and 20% by hydrogen and electricity respectively (Löffler et al., 2017). As a drawback, the inclusion of these sectors leads to a higher difficulty in the modelling phase. In fact, the few alternatives available for these sectors need a high level of technologic detail, such as flexibility options. Moreover, industrial processes requiring high temperatures, still have some uncertainties about the replacement of fossil fuels.

2.4 Model Adopted

Another peculiar characteristic defining reviewed scenarios is the model adopted. This specific feature discerns differences among each case study in terms of general or specific purpose of the model, analytical or mathematical approach, time horizon or data requirements.

2.4.1 Time Resolution

Feasibility of a clean energy transition is often studied through the satisfaction of the demand. In these cases, it is important to evaluate the time-resolution of the model, in other words the size of the time steps used in variables calculations. This aspect is even more important in a high renewable scenario modelling, where the variability of sources make often difficult the perfect overlap between demand and supply. Renewable energy generation presents high fluctuations and for this reason the provision of energy despite depending on external influences like weather is one of the major challenges when considering renewable sources.

The most common approach consists in using an hourly resolution, perceived by many studies as a suitable timescale to accurately predict fluctuations in supply and demand. Mason et al. is the most virtuous study from this point of view, with a half-hourly resolution which allows to ensure the satisfaction of the demand with low level of uncertainty (Mason et al., 2010).

The second approach, less frequent and less precise, involves the period subdivision in time-slices able to reflect short-term variations in supply and demand. For example, Löffler et al. divide one year in 6 time-slices, each one with different load demand, to simulate different seasons and daytimes and the concomitant fluctuation of renewable energy production. This resolution is very risky, given the high variability of renewable sources. (Löffler et al., 2017).

Oliveira & Antunes, adopting a model based on multiregional and multisectoral Input-Output (IO), cannot count on an optimal time resolution. These IO tables provide a picture of the production of a region, a country or the whole world in a determined year, similar concept than using a yearly time-resolution. As in the previous case, this level of detail is not enough to properly predict the satisfaction of the demand.

2.4.2 Simulation vs Optimization & Overnight vs Transition

Other noteworthy distinctive features among the multiple models adopted in the reviewed studies refers to the methodology used to find a solution and the path of the shock.

Concerning the first aspect we can distinguish two type of models: optimization and simulation. The first type is the most used in the reviewed scenarios and is typically used to optimize energy investment or energy cost. The outcome reaches the best solution, given variables and specific constraints. On the other hand, simulation models are descriptive representations aiming at the reproduction of a simplified system operation.

Jacobson et al. in their work utilize a simulation model to study different configurations and compare them from an economic point of view (Jacobson et al., 2018). Child & Breyer, through a simulation model, study the change in the Finnish energy system implementing variations on the installed capacity of biomass and nuclear power. They try different designs with different penetration of these two critical technologies. The result of this analysis suggests that costs decrease as the biomass penetration increases, which is therefore identified as a possible backbone of Finland's future energy mix, thanks to the benefits explained in the introduction. The opposite trend is instead observed as the percentage of nuclear power increases, which leads to higher costs and doubts about social acceptance and waste disposal (Child & Breyer, 2016). A similar study is carried out by Hansen et al. in Germany. This research group adopt the same model of the Finnish case: EnergyPLAN, a bottom-up simulation model with hourly time resolution. The peculiarity of this work is that the authors use a step by step methodology to evaluate the impact of each measure rather than their impact simultaneously. It consists of electrifying German energy sectors one by one, creating and analyzing different options. The outcome shows that the biomass availability could be the bottleneck of a 100% renewable transition. In fact, its large use, especially in transport or heating sectors, could exceed the threshold given by actual availability (Hansen, Mathiesen, & Skov, 2019).

As concerned the shock path, we can distinguish two options. The first case is an overnight shock, an immediate radical change in the energy sector. With this approach it is possible to compare the current situation with the final one, neglecting the evolution of the energy system during this process. For example, fossil fuels required from renewable technologies production processes and emissions of these processes can be underestimated. This criticality can be overcome with a transition model.

Bogdanov et al., in their global scenario, try to evaluate the entire transition process to a high renewable penetration energy system. The work shows as biomass and biogas are very valuable resources through the whole transition period. During the first steps of transition, biomass and biogas are used for baseload electricity generation, whereas later, as the growing RES share requires an increased system flexibility, biomass capacities start to play a regulatory role, and biogas is converted to biomethane and stored in gas storage. In the final energy mix, these two sources account only for a combined 10%. With this approach, it is possible to recognize the important role that these two particular technologies could have, an outcome impossible to detect with an overnight model. (Bogdanov et al., 2019).

2.4.3 Top-Down vs Bottom-Up

The last feature considered as watershed is the analytical approach applied by the models. Methodologies can be categorized in top-down and bottom-up, according to the classification provided by Herbst et al. (Herbst, Toro, Reitze, & Jochem, 2012).

Many articles try to detail these two model types, although a clear definition is not provided. Generally, we can associate the top-down models with macroeconomic models with a multi-sectorial approach while bottom-ups with models characterized by a high technological detail and a single sector view.

Nicole van Beeck, in her work "Classification of Energy Models", defines the first "Economic Paradigm" while the second "Engineering Paradigm" or "Engineering Approach". Economy sees technology as a set of inputs such as capital, labor or energy that can be transformed into useful outputs, in order to optimize market efficiency. Engineering studies, on the other hand, neglect market behaviors. They describe the techniques, the performances, and the direct costs of all technological options in order to identify improvement possibilities (Van Beeck, 1999).

The top-down energy models, as the Input-Output Analysis (IOA), show the effects of a change in the energy sector from an economic perspective on the entire economy. They show, for example, the implications that this change has to other sector, like the manufacture and services ones. TO reach this objective, top-down models use aggregated data to examine interactions between different sectors and to examine the overall macro-economic performance of the economy.

Oliveira & Antunes adopt this approach to build a high renewable penetration scenario for Portugal. They use a multi-objective linear programming (MOLP) based on IOA to assess economy-energy-environment (E3) interactions. In this way they can depict the whole economic and environmental impact caused by a transition to a low carbon energy system. As a drawback, neglecting transport and heating sectors makes this type of analysis partial and incomplete. Moreover, the environmental impact is assessed only through CO_2 emissions, without a deeper analysis on the exploitation of natural resources (Oliveira & Antunes, 2011).

On the other side, bottom-up models, as EnergyPLAN or PyPSA-Eur-Sec-30, usually use highly disaggregated data to precisely describe energy end-uses and technological options, maintaining a restricted focus only on energy sector and not enlarging it to external effects. Most of the scenarios analyzed are created utilizing this approach in order to take advantage of the high technological detail on efficiencies and costs. This framework leads, however, to a poor analysis of natural resources availability for the construction and maintenance of the new energy system, neglecting also their competitiveness among different productive sectors. A further deficiency regards the economic impact that a clean energy transition would have at national or global level on the entire productive sectors, often reduced to a simplistic prevision of the Levelized Cost of Electricity (LCOE). Only in recent years, researchers have been recognized that these two models' types, rather than being in antithesis, are complementary to each other. Therefore, there has been an increase in hybrid models to try to overcome the limits of both types previously described by exploiting their potential. In this category we can include the work by Rocco et al., that consists in a soft-linking bottom-up energy model with top-down input-output model to obtain both a detailed energy system and an overview of the shock consequences on the others economic sectors. This scenario concerns the Egyptian national system in 2040, assuming the reaching of about 70% renewable penetration that would lead to a decrease in energy-related emissions. However, despite this drop, emissions will continue to increase due to non-decarbonized sectors, showing that to achieve satisfactory results more cooperation among sectors is needed (M. V. Rocco, Rady, & Colombo, 2018). Heinrichs et al. also try to link the two types of models to analyze the phase-out of coal-fired power plants in Germany and reach a similar conclusion: a coal phase-out can contribute to CO_2 reduction, but it is not sufficient to achieve the political goals (Heinrichs et al., 2017).

Often, these integrations are used to better evaluate the economic and environmental impact of the transition process, as we will see later in the next section.

2.5 Environmental Impact Analysis

A crucial aspect that concerns the transition to a cleaner energy system is its environmental impact. As mentioned above, radical changes in global energy mixes can result in different implications. Their assessment, linked with a feasibility analysis, accounts as a fundamental aspect of future energy scenarios modelling.

A multiplicity of indicators concerning environmental impacts can be considered:

- GHG emissions
- Metals and minerals depletion
- Water consumption
- Land use
- Water pollution

In the majority of the reviewed scenarios, the environmental impact of the transition is restricted to the estimation of CO_2 emissions, neglecting other natural resource indicators, possibly critical for high renewable penetration scenarios feasibility. An example is presented by Hansen et al. in

Germany, where the quantity of biomass required by the whole energy system can become a critical resource if its penetration increases above a determined threshold (Hansen, Mathiesen, et al., 2019).

Despite representing a limited share on the total scenarios reviewed, some studies embody a wider variety of transition impact indicators.

Berril et al. show how their work affects five different indicators: climate change, freshwater eutrophication and ecotoxicity, particulate matter formation, land occupation and mineral resource depletion. This study evaluates how the transition could lead to significant benefits in the majority of the identified indicators, except for land occupation and mineral resource depletion. A possible improvement could consist in a deeper disaggregation detail in "mineral depletion", in order to identify the possible critical materials. Another model limit lies in the power-bounded perspective that tend to forecast a lower share of biomass technology in the energy mix, one of the most impactful on land use (Berrill et al., 2016). Luderer et al. try to evaluate environmental impacts on global scale combining an integrated assessment modelling (IAM) with a life cycle assessment (LCA) approach. Through the creation of four 2050 energy scenarios, the study shows that a highly renewable scenario would lead to a significant decrease of energy sector impact, especially in aspects related to human health, which ultimately induces a 60% lower mortality (Luderer et al., 2019).

Even Hertwich et al. evaluate impacts of global clean energy transition discovering that it can reduce environmental effects of electricity production, especially in GHG emissions, freshwater ecotoxicity, eutrophication, and particulate-matter exposure. The pollution caused by material requirements of these technologies is smaller compared to the direct emissions of fossil fuel power plants. Bulk material requirements appear manageable but not negligible compared to the current production rates, in exception of copper which supply may be a concern (Hertwich et al., 2015).

As stated in the beginning of this chapter, this energy transition feasibility has to take into account the availability of required natural resources and materials. The increase in some indicators, as found in these studies for metal extraction, should be compared with real data of available quantity to avoid the emergence of possible bottlenecks. Moreover, there is another aspect neglected in the case studies reviewed: the competitiveness of resources. In fact, all the required natural inputs of energy generation can be contended also by other productive processes. The evaluation of an energy transition feasibility focusing only on this specific sector risks becoming too simplistic and can lead to underestimate the actual needed resources.

2.6 Literature review conclusion and thesis development

During this literature review, we examined 46 high renewable penetration scenarios classifying them in different categories.

In conclusion, we can assess a lack of detailed low carbon transition feasibility analysis based on natural resources availability. Some studies try to evaluate the environmental impact of a renewable energy system, but their analysis results incomplete and partial. Most of the studies focus their evaluation only on CO_2 emissions or on aggregated environmental indicators, while a more disaggregated level is necessary. No global studies present a detailed comparison between the materials requirement and the availability threshold. Moreover, no scenarios include the competitiveness of the resources and persist to focus only on energy generation.

To overcome these shortcomings, we will carry out a feasibility and environmental impact analysis of the Sustainable Development Scenario (SDS), a high renewable scenario elaborated by IEA. To do this we will use the World Trade Model (WTM), a hybrid optimization model with an overnight path, belonging to the chain of input-output models and based on comparative advantage. In the first part, our focus is addressed on model improvement in order to recreate a reliable representation of the reality. After this phase the work aims to evaluate the environmental impact of a clean energy transition on five different indicators: CO_2 emissions, fossil fuels depletion, metals and minerals depletion, land use, water consumption. Along the model development, a feasibility analysis will be carried out following real resources availability and pursuing an integrated approach in order to involve resource competitiveness among different sectors.

3. Methodology

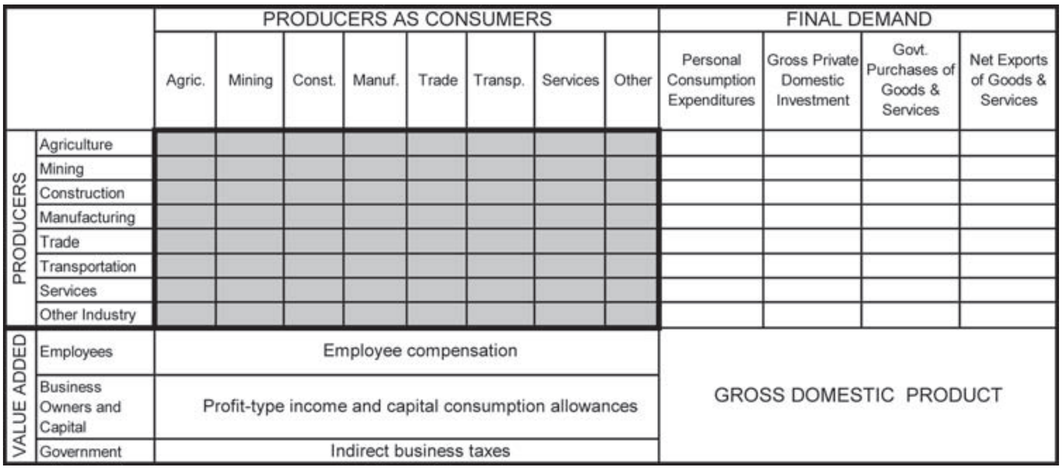
This chapter aims to provide a complete description of the methodology adopted in this work. Starting from the concept of top-down model and Input-Output Analysis, we will explain World Trade Model through its main equations, potentialities and limits. Furthermore, we will present the construction of the scenarios involved in our study by enlightening the assumptions taken during modeling phase.

3.1 Input-Output models

The Input-Output Analysis (IOA) takes roots from the logical framework of Wassily Leontief economic theory which earned him the 1973 Nobel Prize in economic sciences (Leontief, 1974). IOA describes the whole economy as the interconnection of different sectors, showing the total flow of goods and services among them.

These data are contained in an interindustry transaction table that provides a static photograph of the world in a determined year and can have a regional or multiregional perspective. This crucial modularity makes IOA suitable either for specific and bounded studies or global and wide evaluations.

In **Figure 8** is shown an example of an input-output table.



		PRODUCERS AS CONSUMERS								FINAL DEMAND			
		Agric.	Mining	Const.	Manuf.	Trade	Transp.	Services	Other	Personal Consumption Expenditures	Gross Private Domestic Investment	Govt. Purchases of Goods & Services	Net Exports of Goods & Services
PRODUCERS	Agriculture	▨	▨	▨	▨	▨	▨	▨	▨				
	Mining	▨	▨	▨	▨	▨	▨	▨	▨				
	Construction	▨	▨	▨	▨	▨	▨	▨	▨				
	Manufacturing	▨	▨	▨	▨	▨	▨	▨	▨				
	Trade	▨	▨	▨	▨	▨	▨	▨	▨				
	Transportation	▨	▨	▨	▨	▨	▨	▨	▨				
	Services	▨	▨	▨	▨	▨	▨	▨	▨				
	Other Industry	▨	▨	▨	▨	▨	▨	▨	▨				
VALUE ADDED	Employees	Employee compensation								GROSS DOMESTIC PRODUCT			
	Business Owners and Capital	Profit-type income and capital consumption allowances											
	Government	Indirect business taxes											

Figure 8 - Input-Output table, source: Miller and Blair

In the dark grey portion, the flows of goods among sectors are listed, while in final demand are represented the sales of specific output of each sector to final markets. The additional rows, labelled Value Added, account for other (non-industrial) inputs to production, such as labor and imports (R. Miller & Blair, n.d.). As illustrated in Figure 9, IOA can be depicted through a simplified scheme consisting of n production processes. These blocks are interconnected with each other and with the external environment through a multiplicity of flows. In particular, r_i represents input resources required while x represents each sector output, subdivided in a vector f_i that exits the system to meet external demand, another becoming an input for another block and the last one that recirculates in the same process.

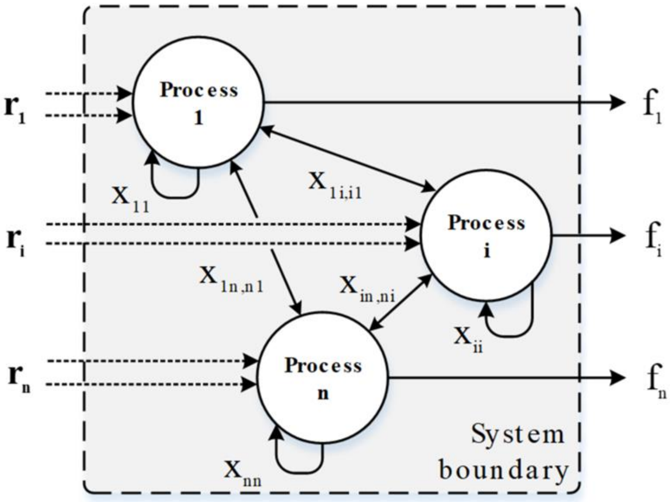


Figure 9 - Graphical representation of IOA applied on a system of n sectors

The main equation of IOA, also known as *Leontief input-output model,* is:

$$\boldsymbol{x} = (\boldsymbol{I} - \boldsymbol{A})^{-\boldsymbol{1}}\boldsymbol{y} \tag{1}$$

Where:

- x (n x 1) is the production vector;
- I (n x n) is the identity matrix;
- Z (n x n) is the endogenous transaction matrix, it contains the flows of goods between sectors;
- A (n x n) is the technical coefficient matrix, it is the ratio between the transaction matrix and the diagonalized production vector;
- y (n x 1) is the final demand vector;
- L (n x n) is the Leontief inverse matrix and represent the quantity of ith product needed by the jth sector to produce one unit of its product.

The elements of Leontief inverse matrix represent the embodied amount of each product required to produce one unit of product of each sector. Being a top-down model the IOA is useful for the impact assessment of each sector on various natural and economic resources, either in input, such as land use, or in output, such as GHG emissions.

This aspect of the model can be represented by the set of equations:

$$\boldsymbol{R} = \boldsymbol{F} \cdot \hat{\boldsymbol{x}} \tag{2}$$

$$\boldsymbol{e} = [(\boldsymbol{I} - \boldsymbol{A})^{-\boldsymbol{1}})]^{\boldsymbol{T}}\boldsymbol{F}^{\boldsymbol{T}} = (\boldsymbol{F}\boldsymbol{L})^{\boldsymbol{T}} \tag{3}$$

$$\boldsymbol{E} = \hat{\boldsymbol{y}}\, \boldsymbol{e} = \hat{\boldsymbol{y}}\, (\boldsymbol{FL})^{\boldsymbol{T}} \boldsymbol{x} \tag{4}$$

- **R** (k x n) is the exogenous resources matrix and represent the quantity of resources extracted from the environment by the jth sector;
- **F** (k x n) is the factor coefficients matrix; kth direct exogenous transaction caused by the production of one unit by the jth sector;
- **e** (k x n) is the specific resource matrix;
- **E** (k x n) is the total embodied resource matrix, representing the distribution of resources among final demand product.

This model is able to represents the direct resources consumption, R matrix, but also the indirect ones. E matrix accounts, in addition to direct consumption, also the indirect one linked to other sectors and necessary to complete the production of specific sector. This impact is commonly called 'footprint'. It is important to point out that these two matrices actually provide the same total information, simply calculated differently. If we sum the different voices, we will get ETOT = RTOT, which represent the impact of overall system. Some assumptions are required to properly apply the Leontief model (M. V. Rocco, Golinucci, Ronco, & Colombo, 2020) (R. E. Miller & Blair, 2009):

- Process characterization. Every productive process must produce one single kind of product, measured with one specific unit. However, any production process may receive as input any resource or product from any other sector.
- Technical coefficients. Technical coefficients are constant values, this means that technology do not change in a specific time slice. So, if the output of a specific process will change, the input requirements will change in a proportional way.
- Exogenous resource elasticity. The Leontief model is known as a demand driven model and assumes an infinite supply of resources. As we will show later this assumption can be redefined by the introduction of factor endowments.
- Aggregation of processes. IOA requires a certain grade of aggregation to represents the whole economy on a large scale.

3.1.1 Input-Output Database

Data gathering represents one of the core tasks in IOA field. Along the last decades, several databases were developed, progressively more detailed thanks to the increasing availability of data worldwide. Within them, we focused on the subcategory of Environmental Extended Global Multiregional Input-Output (EE GMRIO) Databases. Our analysis adopts data from EXIOBASE3 (Stadler et al., 2018); in particular its monetary version referred to 2011, the latest year depicted. EXIOBASE3 include 44 countries and 5 Rest of the World (RoW) regions that close the world balance (RoW Asia & Pacific, RoW America, RoW Europe, RoW Africa and RoW Middle East). Moreover, it comprehends 200 products and 163 different industries in accordance to the classification provided by NACE2 (Statistical Classification of Economic Activities in the European Community) (European Commission, 2008). One of the main objectives of EXIOBASE is to grant a high level of detail for what concerns sustainability environmental analysis; for this reason, a wide section of resource accounts has been developed. This matrix comprehends multiple sections: 9 Value Added factors, 14 Employment factors, 423 Emissions factors, 20 Land Use factors, 444 Material factors, 194 Water factors (Stadler et al., 2018).

EXIOBASE, from its earliest release, takes place within European Union projects such as EXIOPOL, CREEA and DESIRE and therefore tends to align with international recognized accounting rules. This purpose represents one of the most complex and delicate parts concerning the compilation of a MRIO Database. For instance, the definition of boundaries among economic activities is arbitrary and, a fortiori, it is within a global value chain context. Monetary Input-Output Tables (MIOT) provide a standardized approach by presenting endogenous transaction matrix, final demand and total production vectors in monetary units.

A proper handling of the database has been performed both to make it compatible with World Trade Model and to set the field for the analysis of our case study.

3.2 World Trade Model

The World Trade Model (WTM) is a linear input-output optimization program developed by Faye Duchin and governed by comparative advantage that minimizes global factor use satisfying final demand and respecting resource limitations (Duchin, Levine, & Strømman, 2016).

In WTM the production occurs in the least-cost region until the depletion of a required resource. In Table 1 all the elements of the model are listed, and a brief description is provided.

	Symbol	**Dimensions**	**Description**
	m		Number of regions
	n		Number of sectors
	k		Number of factors of productions
	i,j		Indices for regions $i,j = 1 \dots m$
Exogenous variables	$\mathbf{A}$	$(nm \times nm)$	Matrix of technical coefficients
	$\mathbf{F}$	$(k \times nm)$	Matrix of factor input
	$\mathbf{y}$	$(nm \times 1)$	Vector of final demand
	$\mathbf{p}$	$(k \times m)$	Matrix of factor costs
	$\mathbf{f}$	$(k \times m)$	Matrix of factor endowments
Endogenous variables	$\mathbf{x}$	$(nm \times 1)$	Vector of production
	$\mathbf{ex}$	$(nm \times m)$	Matrix of import and export
	$\mathbf{p}$	$(nm \times 1)$	Vector of goods price index
	$\mathbf{r}$	$(km \times 1)$	Vector of factor scarcity rents

Table 1 - Exogenous and endogenous variables for WTM

There are two objective functions in this model, representing one the primal model while the other the dual one. The primal model, known as Quantity Model, is based on the minimization of the global factor use.

$$\boldsymbol{Min(Z) = \sum_{i} \pi^{T} F_{i} x_{i}} \tag{5}$$

$$\boldsymbol{x_i + \sum_{j \neq i} ex_{ji} \geq A_i x_i + y_i + \sum_{j \neq i} ex_{ij}.} \qquad \forall \boldsymbol{i} \tag{6}$$

$$\boldsymbol{F_i x_i \leq f_i} \qquad \forall \boldsymbol{ix} \tag{7}$$

$$\boldsymbol{x_i \geq 0} \qquad \forall \boldsymbol{i} \tag{8}$$

- **ex**ji (n x 1) represents the export from region *j* to region *i;*
- **y**i (n x 1) is the final demand, so the quantity of output requested by final users of region *i;*

The objective function works under three constraints. The first secures the total domestic supply, so the sum between production and imports must cover the sum of the final demand, exports and intermediate demand. The second constraint requires that each country's factor use not exceed the available quantity. The third one states that production cannot be negative.

Analyzing the dual model, also called the Price Model, the objective function maximizes the total value of final demand net of scarcity rent.

$$\boldsymbol{Max(W) = \sum_{i} y_i^T pi - \sum_{i} f_i^T ri} \tag{9}$$

$$\boldsymbol{pi - A_i^T pi \leq F_i^T (\pi i + ri)} \qquad \forall \boldsymbol{i} \tag{10}$$

$$\boldsymbol{pi \geq 0} \qquad \forall \boldsymbol{i} \tag{11}$$

- **p**i (n x 1) is the price of goods and services vector;
- **r**i (*n x 1*) is the scarcity rent of a specific factor;

Maximization is subjected to two constraints. The first one is necessary to ensure that the price of an asset does not exceed the cost internally, while the second ensures the non-negativity of prices.

3.3 Model Calibration

The aim of this chapter is the description of the logical process behind the practical transposition of WTM equations previously illustrated, in order to reach a realistic baseline case. A large portion of our work has been focused on the selection of the proper level of spatial aggregation and economic detail. Besides this, also the choice of which productive factors include and analyze in our study has been crucial.

3.3.1 Database and model preparation

In order to fit MIOT with WTM, the two main components which we had to reshape were the A matrix of technical coefficients and the y vector of final demand. For the first one, all the submatrices A had to be summed down the column jth. After this operation, the resultant matrix Aw contains the requirement of outputs from all the other sectors independently on where outputs are produced. Through this calculation we get to matrix $\mathbf{A}j$ of total direct inputs per unit of each output for the jth region:

$$\sum_i \mathbf{A}_{ij} = \mathbf{A}_j \ \forall j \tag{12}$$

This operation can be repeatable for the final demand that is provided unpacked, making explicit demand satisfied by import. So, also for y:

$$\sum_i \mathbf{y}_{ij} = \mathbf{y}_j \ \forall j \tag{13}$$

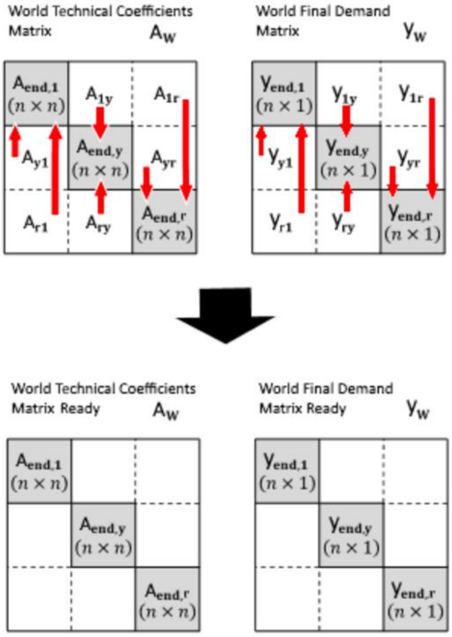


Figure 10 - Database preparation

At this point of the analysis, we had to set the level of aggregation of three different features of the model: regions, sectors and factors of production.

In regard to regions and sectors we relied to pymrio, an already existent input-output dedicated python library, and more specifically to its proper function aggregation.py. Otherwise, we achieved the aggregation of factors through the function pandas.py, suitable to work with Excel files. This part of the python code can be consulted in the Annex B, where we report the complete code used in this work. In the following chapters we will deepen the logical process underlining our aggregation choices.

3.3.2 Regional aggregation

As introduced before, EXIOBASE contains data for 49 regions. The majority of them are concentrated in the European area, where data were easier to collect thanks to the higher availability of national and international data sources. Starting from this number of countries and assembled Rest of the World regions, we had to take a decision about the level of spatial aggregation present in our study. Our choice has been driven by a trade-off between the desire of a deep detail level and the necessity to reach a clear and sharp results representation and interpretation. Furthermore, we tried to follow the same regional aggregation applicated by IEA in their World Energy Outlook. The result converged in a 4 regions world, nearly overlapping a continental division among Europe, America, Asia & Pacific and Africa. In fact, our analysis aims to embark in a global approach to the energy production sector.

Table 2 summarizes the regional aggregation.

Exiobase Regions		Aggregated Regions
Austria	Lithuania	Europe
Belgium	Luxembourg	
Bulgaria	Latvia	
Cyprus	Malta	
Czech Republic	Netherlands	
Germany	Poland	
Denmark	Portugal	
Estonia	Romania	
Spain	Sweden	
Finland	Slovenia	
France	Slovakia	
Greece	United Kingdom	
Croatia	Russia	
Hungary	Switzerland	
Ireland	Norway	
Italy	RoW Europe	
USA	Mexico	America
Canada	RoW America	
Brazil		
Japan	Turkey	Asia & Pacific
China	Taiwan	
South Korea	Indonesia	
India	RoW Asia and Pacific	
Australia	RoW Middle East	
South Africa	RoW Africa	Africa

Table 2 - Regional Aggregation in WTM model

3.3.3 Sectoral aggregation

The second database feature that we had to handle were the sectorial specification. As we stated before, EXIOBASE divides each economy in 163 sectors. In order to put the focus on energy area we implemented a sectorial aggregation that leads us to only 25 sectors. The logic underlying our choice was based on the idea of the conservation of a high detail on electric generation section of the economy and a lower specification on other sectors. We kept 9 sectors of electricity production differentiated among generation sources, a sector that represent transmission and distribution of electricity and 15 sectors which depict all the others production activities of each economy. One of the main drivers leading our choices was the will to aggregate economic sectors with similar needs of input resources, in order to highlight and expose the major dynamics existent in an economy for what concerns resource competitiveness. Our framework has been as much as coherent with the one proposed by International Standard Industrial Classification of Economic Activities presented in their report ISIC.rev4 (UNSD, 2015).

The aggregated sectors are shown in Table 3.

Sector Name	ISIC Code
Agriculture, Farming and Fishing	ISIC.A-B
Extraction of fossil fuels	ISIC.C
Mining of metals	ISIC.C
Quarrying	ISIC.C
Manufacturing	ISIC.D
Chemical Industry	ISIC.D
Manufacture of coke oven products	ISIC.D
Petroleum Refinery	ISIC.D
Material Processing	ISIC.D
Construction	ISIC.F
Production of electricity by coal	ISIC.E
Production of electricity by gas	ISIC.E
Production of electricity by nuclear	ISIC.E
Production of electricity by hydro	ISIC.E
Production of electricity by wind	ISIC.E
Production of electricity by petroleum and other oil derivatives	ISIC.E
Production of electricity by biomass and waste	ISIC.E
Production of electricity by solar photovoltaic	ISIC.E
Production of electricity nec	ISIC.E
Electricity Transmission and Distribution	ISIC.E
Services and Finance	ISIC.G-H-J-K-L
Manufacture of gas	ISIC.E
Transport	ISIC.I
Biogas Production	ISIC.M-N-O
Waste Management	ISIC.M-N-O

Table 3 - Sectorial aggregation of WTM model

3.3.4 Factor Inputs choices

As we mentioned in chapter 2, World Trade Model calculates the optimal solution in terms of global use of factor inputs. Therefore, one of the central tasks of our work has been the detailed examination of the environmental extension matrices of factor inputs featured in EXIOBASE3. Specifically, R (k x mn) that is the exogenous resource matrix that shows the quantity of exogenous resources extracted from the environment by the jth sector and needed for its production activities and F (k x mn) that represent the direct factor requirements specific to one unit of jth sector's output. The latter, displaying coefficients, is useful to investigate the interconnections among natural resources and productive sectors, while the previous one helps to explore the real quantities of resources needed for the extensive output of each sector.

For the sake of clearness, in the following table we summarize in macro-categories the 1104 resources displayed in these two matrices.

Macro-category	Unit of Measure	Number of Factors
Value Added	M.EUR	9
Employment	1000p	7
Employment hours	M.hr	7
Emissions	kg	423
Land Use	km2	20
Energy	TJ	4
Extraction Used	kt	217
Extraction Unused	kt	223
Water Consumption	Mm3	116
Water Withdrawal	Mm3	78

Table 4 - Macro-categories of 1104 EXIOBASE factors

The selection of which factors were crucial to be monitored throughout our analysis was driven by two different reasons. The first one is represented by our will to explore how key resources are distributed among productive activities, especially in electric generation field. The second one is centered on the necessity of a detailed assessment of factor endowments: resources maximum amounts exploitable by each region. This has represented one of the most time-demanding tasks, but it is essential in the context of modelling energy scenarios with World Trade Model. This theme will be expanded in the next chapters.

Different types of factors were taken into account in order to detect a complete spectrum of direct and crosswise effects of decarbonization in electricity sector.

Before setting reasonable endowments above the selected factors, we endured a literature review about the resource accounting rules adopted by EXIOBASE. The principal accounting report which this database follows is the System of National Accounts 2008 (Commission of the European Communities, International Monetary Fund, Organisation for Economic Cooperation and Development, 2008). From that report on, several frameworks developed and refine resource accounting; System of Environmental-Economic Accounting (SEEA) was pivotal among them. EXIOBASE takes into account all these backgrounds and operate within European Commission FP7 project, the root for further branches like CREEA and DESIRE. Here we report a brief list of the selected factors, the detailed one is available in Appendix D.

- Taxes & Wages: section of Value-Added concerning the amount of net taxes (taxes minus subsidies) plus factors concerning compensation of employees, wages, salaries and employers' social contribution.
- Consumption of fixed capital: remaining part of Value-Added; accounts for consumption of fixed capital, rents on land, royalties on resources and remaining net operating surplus. During the analysis of the R matrix, data validation of the previous two factors through measures of countries GDP were carried out.
- Employment: number of people employed in each economy. EXIOBASE gives this data divided by gender and skill level.
- CO_2 Emissions: emissions of carbon dioxide through combustion released in air.
- Land Use: aggregation of 20 factors covering several different land categories.
- Fossil Fuels Extraction: amount of coal, crude oil and natural gas extracted from the ground.
- Bauxite and Aluminium Ores: amount of bauxite containing aluminium extracted from existent mines.
- Copper Ores: amount of gross ores containing copper and concentrates extracted from existent mines.
- Iron Ores: amount of gross ores containing iron extracted.
- Non-Metallic Mineral Ores: amount of valuable minerals extracted in each region.
- Water Consumption: quantity of green and blue water consumed by every sector of each economy.

As mentioned before, for each of the previous production factors we conduct an analysis to assess the realistic maximum quantity available for each region of the world. For the sake of clarity, we summarize the results in the table below.

Factor Input Name	Unit of Measure	Type of Factor	Type of Factor Endowment	Factor Endowment Value	Data Sources
Taxes & Wages	M.EUR	Priced	Not Bounded	-	WorldBank; Eurostat
Operating Surplus	M.EUR	Priced	Regional Bounded	Operating Surplus Value Available in Database	Exiobase; WorldBank; Eurostat
Employment	1000p	Not Priced	Regional and Sectorial Bounded	Working-age population	ILOSTAT; WorldBank
CO_2 Emissions	kg	Not Priced	Regional Bounded only in Europe	CO2 Value Available in Database	Exiobase; IEA
Land Use	km2	Not Priced	Regional Bounded	Region Area - Inland Water	FAOSTAT; Copernicus
Fossil Fuels Extraction	kt	Not Priced	Regional Bounded	Proven Reserves/Years to depletion	BP; Statista; IEA
Bauxite and Aluminium Ores	kt	Not Priced	Regional Bounded	Proven Reserves	Statista; BGS; USGS; World Mining Data; EU-MKDP
Copper Ores	kt	Not Priced	Regional Bounded	Proven Reserves	Statista; BGS; USGS; World Mining Data; EU-MKDP
Iron Ores	kt	Not Priced	Regional Bounded	Proven Reserves	Statista; BGS; USGS; World Mining Data; EU-MKDP
Non-Metallic Mineral Ores	kt	Not Priced	Regional Bounded	Proven Reserves	Statista; BGS; USGS; World Mining Data; EU-MKDP
Water Consumption	Mm3	Not Priced	Regional Bounded	Wetlands, large lakes, reservoirs and rivers	UNEP Grid-A, AQUASTAT, IWRM

Table 5 - Model factors

As we will see in the next chapters, this assessment of the regional availability of these resources will be crucial in the definition of a reliable baseline case able to replicate reality in a proper way.

3.4 Scenario Definition

The IEA Sustainable Development Scenario (SDS) has been introduced in the "World Energy Outlook 2017", based on the works elaborated in the last decade by the International Energy Agency on energy access, air pollution emissions and energy related CO_2 (International Energy Agency (IEA), 2018). The scenario, by 2040, aims to achieve desired outcomes related to United Nations Sustainable Development Goals (SDGs), indicating the change that the energy sector will face to reach these goals. These are the goals involved in the creation of SDS:

- SDG 7: "By 2030 ensure universal access to affordable, reliable and modern energy services"
- SDG 3: "Ensure healthy lives and promote well-being for all"
- SDG 13: "Take urgent actions to combat climate change and its impact"
- SDG 6: "Ensure availability and sustainable management of water and sanitation for all"

Ensuring universal electricity access, given the huge population growth in lower income countries, results in a substantial increase in electricity production. In this contest the least expensive way to satisfy this additional demand is with renewable energy sources, thanks to the declining costs of solar PV and its inclusion in off-grid and mini-grid projects. This last solution can be particularly interesting in some rural areas or where the lack of a developed infrastructure and the conformation of the region make inconvenient the connection with the existent electric national grid. Another focus of the SDG 7 is on clean cooking technologies. The SDS identifies biomass and liquefied petroleum gas (LPG) as the best options to reach this goal.

As can be observed in Figure 11, the main efforts are located in Sub-Saharan Africa (SSA) and developing countries in Asia, where the percentage of access to electricity and clean cooking technologies are now still far from the developed countries means.

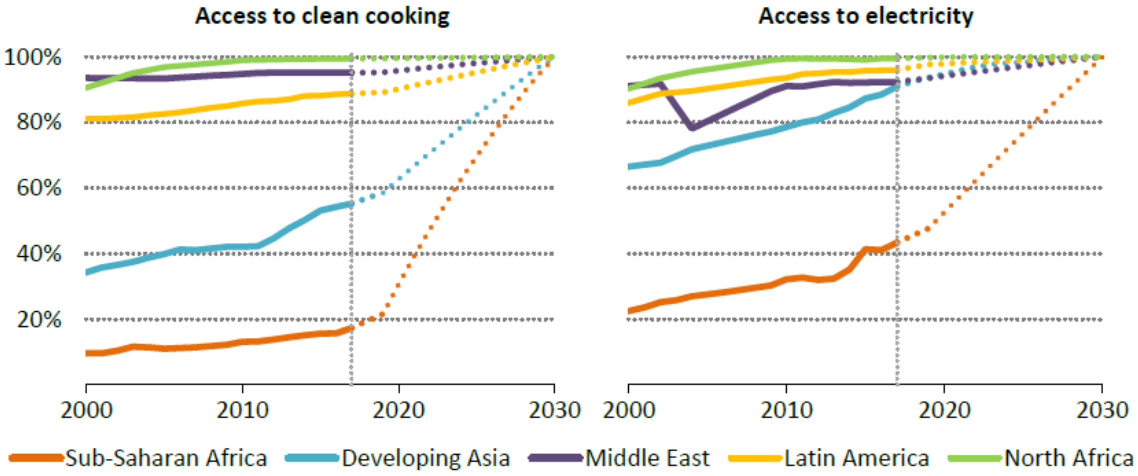


Figure 11 - Access to clean cooking technologies and electricity by region; source: World Energy Outlook 2018

Air pollution and GHG emissions are the SDS environmental impacts analyzed in the IEA report. Outdoor and household air pollution are respectively linked to 2.9 and 2.6 million premature deaths globally each year. These last can be attribute to the traditional use of biomass as cooking fuel, especially in Africa. In SDS, emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x) and particulate matter ($PM_{2,5}$) decline from current levels, despite energy demand remains nearly constant. The same trend is associated to the energy related CO_2 emissions, which reach a peak around 2020 and then start a decline process, in line with the trajectory required to achieve the Paris Agreement goal. For example, emissions from coal-fired power, the main source of CO_2 emissions in 2017, fall by 90% to account for only 5% of total GHG emissions. Also transport related emissions decrease in the IEA previsions, thanks to a gradual electrification and an improvement of efficiencies.

Despite a general increase in population and a significant economic growth, energy consumption stays nearly flat, thanks to a general increased efficiency in the most used technologies in the scenario. To have a better comprehension of the scenario and to allow a better reproduction in our model, we have to consider the different actors of the energy sector separately and study the specific change that they have to face.

Power generation is expected to rise in the next years due to the population growth and to ensure access to electricity to the whole global population. The total electricity generation increase by 45% by 2040, reaching 37000 TWh. To achieve the environmental goals on CO_2 emissions, the share of renewable energy in the power mix must increase. In SDS, renewable energy share triples and reaches about 66% of the total power generation. The main growth comes from solar PV, increased by sixteen times, and from wind, by seven times. Observing only the new capacity installed after 2017, renewable sources account for about 80%, the main part in developing regions, the ones with lower access to electricity. The remaining 34% is covered by traditional fossil fuel power plants, with a change of the main fuel used. Coal power generation, the most used source in 2017, in SDS accounts only for 5% with two-third of coal fired plants equipped with carbon capture utilization and storage (CCUS). Natural gas power plants initially grow, playing a crucial role to balance renewables generation in the first years of the transition. This large use of natural gas is due to the lower impact in air pollution and lower carbon intensity compared to coal or oil. Thanks to these changes in the electricity generation mix the average carbon intensity decline from 500 g CO_2 /kWh to 70 g CO_2 /kWh.

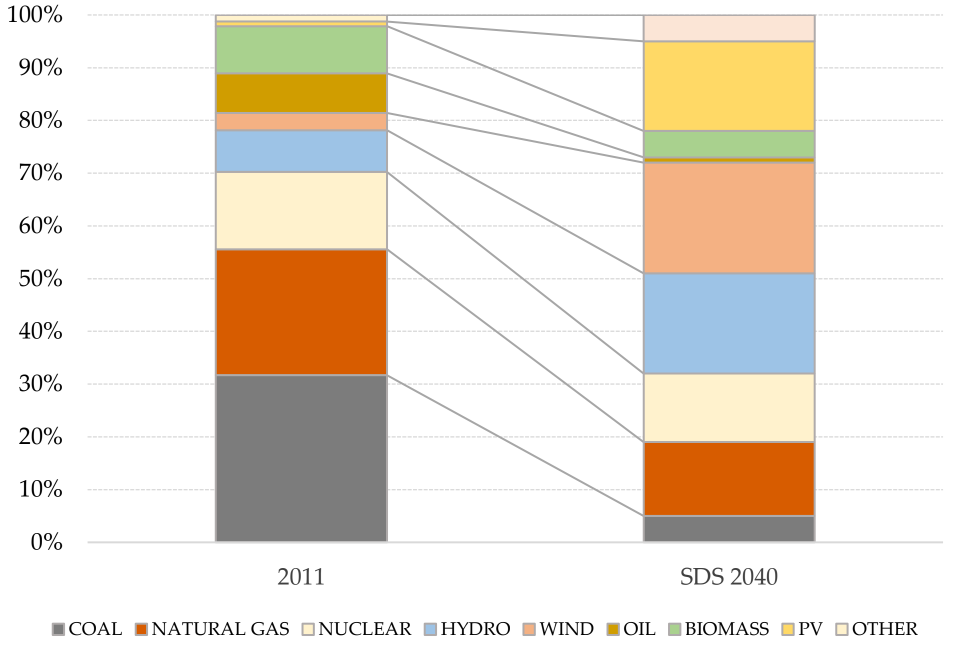


Figure 12 - Power Sector, 2011 vs SDS; source: own elaboration

The others energy demanding activities are described in a less detailed way in the "World Energy Outlook 2018". This is due to the gradual electrification of transport and heating sectors: electricity generation share that is already considered in the power sector analysis. Important changes are predicted in Asia and Africa, where, according to SDS, the traditional biomass will be replaced by natural gas by 2040.

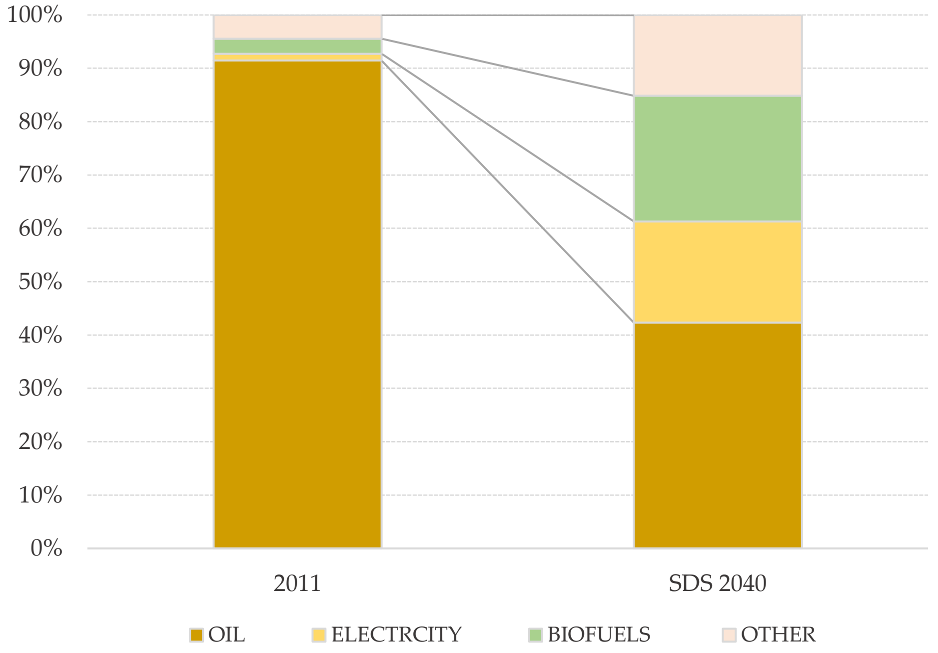


Figure 13 - Transport sector, 2011 vs SDS; source: own elaboration

In 2011 transport sector, oil was the most utilized source, accounted for about 90% of the total transport energy demand. As it is clear in Figure 13, the transport energy demand changes abruptly in SDS. The growth of electrified vehicles and the spreading of biofuels lead to a decrease in the oil share, which drops to 40% of SDS transport energy demand.

A similar discussion can be carried out concerning the building sector, which SDS demand will equally see a significant electrification process.

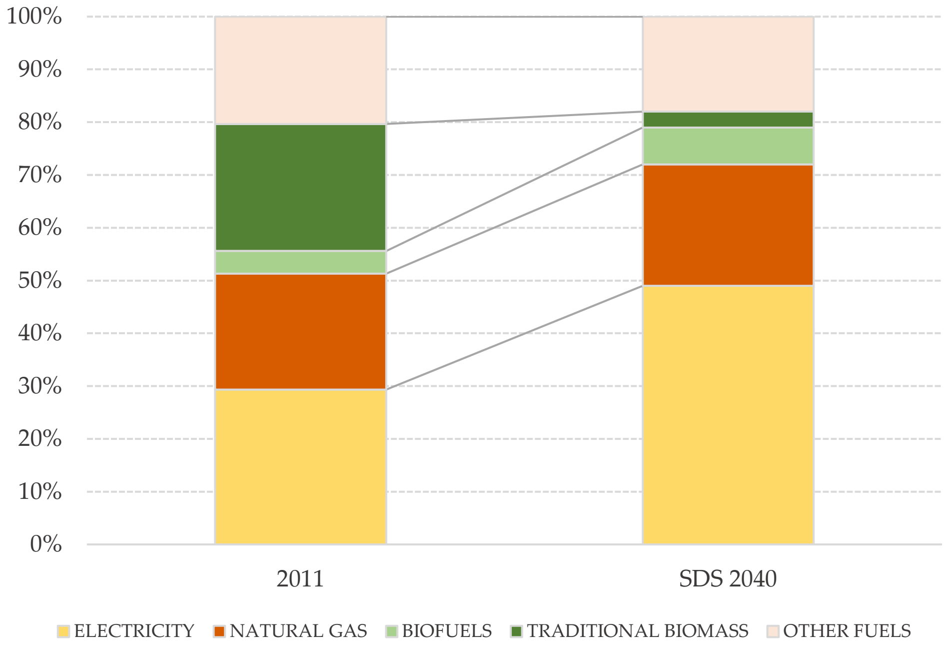


Figure 14 - Building sector, 2011 vs SDS; source: own elaboration

The following table shows the different scenarios developed with the World Trade Model. The methodology used to build them will be explained in detail in the next sections of the work.

Scenario	Total demand	Technology Mix
Baseline 2011	Reference year: 2011 No change in final demand **y** or in coefficient matrix **A**	2011 technological mix No share change in final energy mix
Business as Usual (BAU) 2040	Reference year: 2040 Increased demand of each sector proportionally to population growth	2011 technological mix No share change in final energy mix
Sustainable Development Scenario (SDS) 2040	Reference year: 2040 Increased demand of each sector proportionally to population growth	Technology share in energy mix in line with SDS Changes in final demand **y** and in **A** matrix

Table 6 - Scenarios Developed

3.5 Shock Implementation

The object of this study is the evaluation of economic and environmental effects and implications of the Sustainable Development Scenario. To recreate the scenario on World Trade Model, several assumptions had to be taken. Because of the database structure, the most critical has been to keep all the coefficients constant, with only a redistribution of some of them as we will see later. This means that no efficiency improvements are expected to occur between 2011 and 2040. For this reason, we will evaluate economic and environmental impacts of a 2040 demand maintaining 2011 technologies.

3.5.1 Business as Usual Scenario

To create a Business as Usual scenario the changes has involved the population and final demand of each sectors, setting them to 2040 projections. Furthermore, to maintain coherence between the population data predicted by IEA and our employment factor, we increased the labour force in each sector and region according to the percentage increase from 2011 to 2040 of the population in the four different macroregions.

Percentage demographic growth 2011-2040	
Europe	13%
America	24%
Asia & Pacific	18%
Africa	96%

Table 7 - Demographic growth by region; source: IEA

The demand of each region has been increased in a proportional way, following the same percentage.

The mathematical equation used is, in case of Europe:

$$y_{Europe,j} = y_{Europe,j} * 1{,}13 \qquad (14)$$

Where j represents all the productive sectors.

3.5.2 Sustainable Development Scenario

To recreate the SDS electricity mix, we acted on some crucial sectors of each region modifying both the intermediate matrix and the final demand vector. The sectors included in these changes are listed in the following table.

EXIOBASE Power Sectors
Electricity production by coal
Electricity production by natural gas
Electricity production by nuclear
Electricity production by hydro
Electricity production by wind
Electricity production by crude oil
Electricity production by biomass
Electricity production by PV
Electricity production by other sources

Table 8 - Power sector in EXIOBASE database

Concerning the final demand, since the EXIOBASE data are expressed in monetary units (M€), we had to assume electricity production costs differentiated by production sources. To calculate these quantities, we assume a perfect overlap among the EXIOBASE monetary data and the electricity generation data available on the IEA site. The equation below is the mathematical representation of the concept expressed above.

$$El_{cost} = \frac{EXIOBASE\ production_{i,j}\ [€\ ]}{Electricity\ prodution\ by\ IEA_{i,j}\ [kWh]} \tag{15}$$

Where:

- i = region
- j = power generation technology

With this assumption we were able to convert all the electricity production changes by each source predicted by IEA in the SDS and adjust the final demand of the abovementioned sectors of each region.

$$y_{i,j} = y_{i,j} + \Delta En * El_{cost\ i,j} \tag{16}$$

In addition to final demand, we had to change also the intermediate demand, the power needed by other productive sectors to complete their production. In this case we acted on the coefficient's matrix, which represent the inter-sectoral relations of the whole economy. After adding up the power generation coefficients, we redistributed them among the different technologies following the shares predicted by IEA for the future power mix. In other words, we are imposing which technology produces electricity for the other sectors.

For each region and each sector, we obtained:

$$A_{tot} = sum(A_j) \tag{17}$$

With j representing each power generation technology.

The redistribution of the power generation coefficients is described by the following table.

Intersectoral Matrix	Sector 1	Sector 2	…
Electricity production by coal	Atot * SDS_coal%	Atot * SDS_coal%	…
Electricity production by natural gas	Atot * SDS_natural gas%	Atot * SDS_natural gas%	…
Electricity production by nuclear	Atot * SDS_nuclear%	Atot * SDS_nuclear%	…
…	…	…	…
…	…	…	…
Electricity production by others	Atot * SDS_others%	Atot * SDS_others%	…

Table 9 - Change in A matrix in power sector

A similar pattern of equations has been used to modify transport and heating sectors. Since there is not a specific sector in EXIOBASE representing the whole transports, more efforts are necessary. The database transport sector accounts only for public transport service energy demand, neglecting the private one. For this reason, we had to find another sector on which act to modify in a complete way the transport sector. The most suitable one was "Oil Refinery" sector, for this reason we left it disaggregated. We focused on its final demand, assuming that it contains the fuel demand of the private transport sector. The changes were carried out following the same logical framework described for the power sector. Firstly, we evaluated the oil production cost and then we used it to convert the decrease of oil consumption in transport sector predicted by the IEA. To pursue these actions, we had to take two important assumptions:

- 45% of the "Oil Refinery" production in 2011 is used for transport scopes (Source: IEA)
- Private car transport accounts for 45% of total energy demand of transport sector (source: eia)

In order to represent the electrification of private cars, we amplified the power generation sectors by the same quantity, with differentiated shares in coherence with the Sustainable Development Scenario.

The mathematical representation of this process is given by these two formulas:

$$Fuel\_cost = \frac{EXIOBASE\ production\ [€\ ]}{Fuel\ \ prodution\ by\ IEA\ [kWh]} \tag{18}$$

$$y_{oil\ refinery} = y_{oil\ refinery} + \Delta En * Fuel\_cost \tag{19}$$

At the same time, to represent the electrification of transport service, we acted on the coefficient matrix. The mathematical formulation has been the same one reported for the intermediate demand of electricity, but here the sum of the technical coefficient included also the oil refinery one.

Intersectoral Matrix	Transport Sector
Electricity production by coal	Atot * SDS_coal%
Electricity production by natural gas	Atot * SDS_natural gas%
Electricity production by nuclear	Atot * SDS_nuclear%
…	…
Electricity production by others	Atot * SDS_others%
…	…
Oil refinery	Atot * SDS_oil%

Table 10 - Change in A matrix in transport sector

The last part of the scenario implementation is referred to heating sector. The heating final demand in IEA report is divided in two different portions: building and industry. The first one is associated with residential consumption, while the latter involves all the energy required by industrial processes.

In EXIOBASE, there is not a specific sector for this final use and for this reason we had to identify a possible sector to modify. Since the heating final demand is satisfied for the major part by natural gas, we took the "Gas Production and Distribution" as a reference sector, assuming that all its final demand was used for space and water heating purposes. Adopting the same approach used in the two previous cases, we calculated the differences between SDS and IEA current energy system about natural gas consumed in heating sector. Then, we modified the final demand in the **y** vector according to this framework. Particular attention has been reserved to African and Asian continents, where in the current situation a large share of final heating demand is satisfied with the use of traditional biomass, reduced in the SDS previsions. From an economic point of view, this decrease is not detectable since firewood is not associated with a real specific market cost. In these countries we only increased the final demand of natural gas and biofuels according to IEA, without decreasing contributions from other sources. Concerning heating demand of industrial sectors, we chose not to act for two main reasons:

- The impossibility to find a specific sector representing the different types of industrial processes;

- The impossibility to electrify every industrial process, in particular high-temperature heating ones, demanding energy quantity not reachable with electricity.

In Figure 15 we can observe the new power generation mix given by the model and how it changes from the baseline to the SDS.

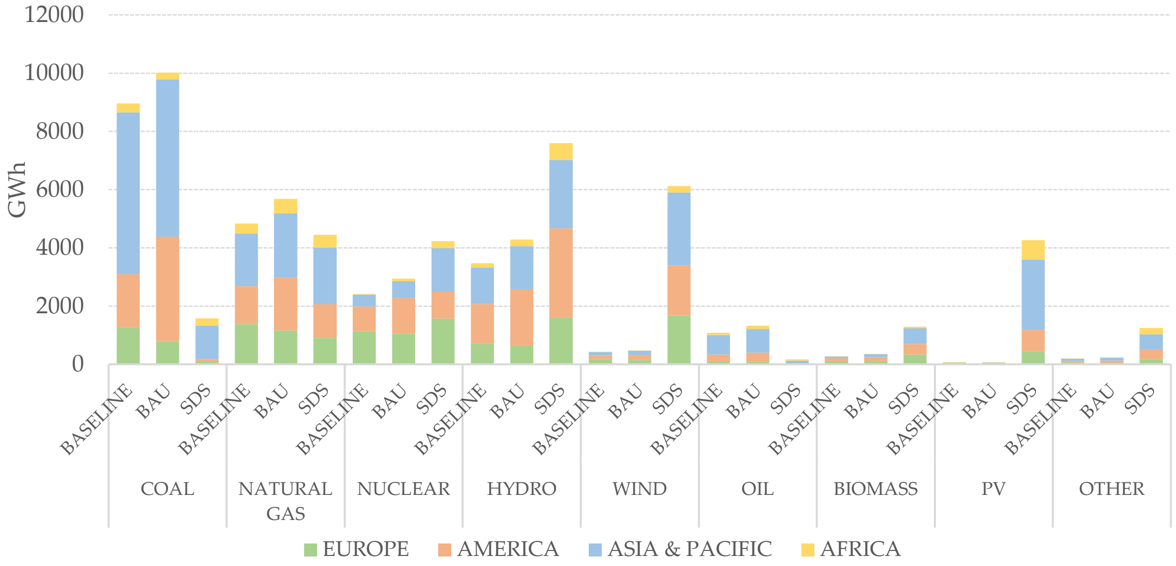


Figure 15 - Global Electricity generation by source and by region

4. Results and discussion

This chapter aims to illustrate the results of our study. In this section, the highlight will be put on the comparison of the outlook before and after the implementation of the two scenarios depicted in the previous phase. In particular, our analysis focuses on energy-related and environmental indicators in order to clarify the impact of a global transition to a cleaner energy. For each indicator presented, will be reported data of baseline case, BAU and SDS. In addition to this, for the SDS, a comparison between IEA prospects and results developed from our work will be add.

4.1 Baseline Case: WTM output

The first scenario implemented in our work is the baseline case, a replication as close as possible of the real 2011 economy. The creation of an accurate baseline case is a critical aspect in scenarios modelling, due to the difficulties to represent with mathematical formulation the complex logics behind human behavior and whole economy.

In the first attempt we run the model only with its intrinsic constraints, without limiting the factor use or adding other restrictions. With this basilar approach the model finds an optimal solution following only three constraints:

- Satisfaction of the final and intermediate demand of each region, net of import and exports;
- Non negativity of the production;
- M€ exported lower than M€ produced per each sector by every region (limit on re-export).

The WTM finds a solution minimizing investment and operational costs and the result of this attempt is the power sector illustrated in Figure 16: a little overestimation of the electricity produced by natural gas and underestimating the coal’s one can be observed.

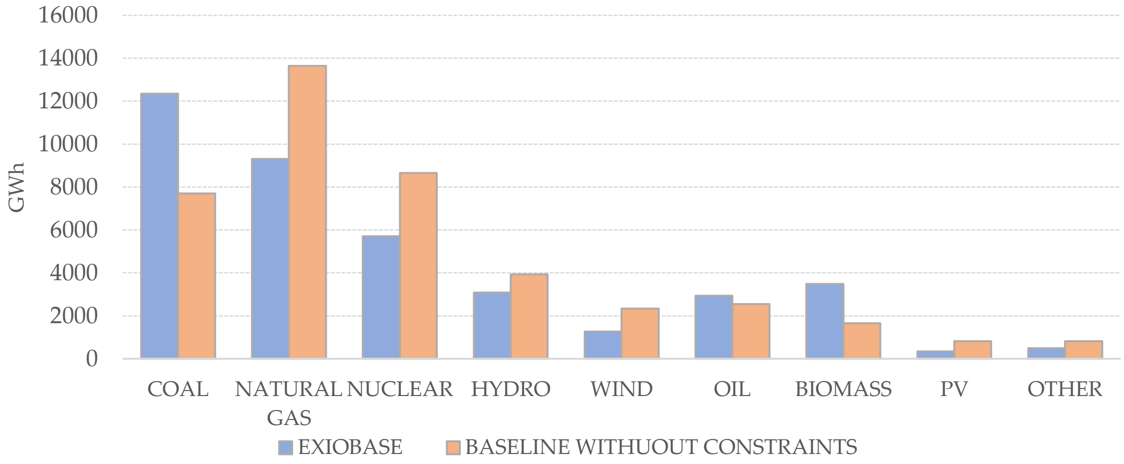


Figure 16 - Global Electricity Generation by source

Considering the global generation mix, these differences are not so relevant and included in an acceptable range. A different picture can be noted deepening results analysis to the single region’s productive sectors. The economic rationality behind the optimization process of the model create a baseline strongly based on import/export; moreover, factors unbounded to real availability permit a productive force potentially infinite for each region. These two aspects lead not competitive regions to import goods instead of producing them, leaving the whole production to a cheaper-cost region. Following this erroneous logic, Europe results to be the only productive region in power sector and its surplus electricity product exported to the other regions of the model.

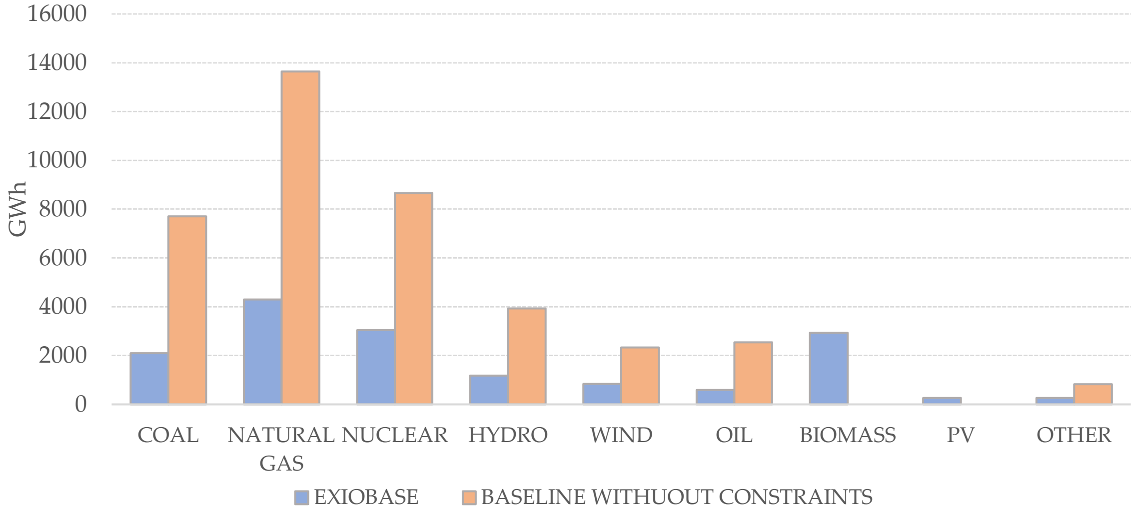


Figure 17 - European electricity generation; EXIOBASE vs. WTM solution

Europe become the unique producer in different sector of the model, since their productive costs are lower than the other region's ones. This situation leads to an over-specialization problem and to a baseline significantly different from EXIOBASE data. This problem affects also other elements of the baseline run, as the CO_2 emissions and the global Gross Domestic Product (GDP).

As concerned the first aspect, we can see in Figure 18 how the model underestimates emissions related to America, Asia & Pacific and Africa. In Asia & Pacific, the most polluting region in 2011, CO_2 emissions are reduced of about the 75%, from 16 Gt to 4 Gt. On the other hand, European CO_2 emissions attest to three times the 2011 amount of 5 Gt from EXIOBASE data to around 14 Gt in the baseline of the WTM.

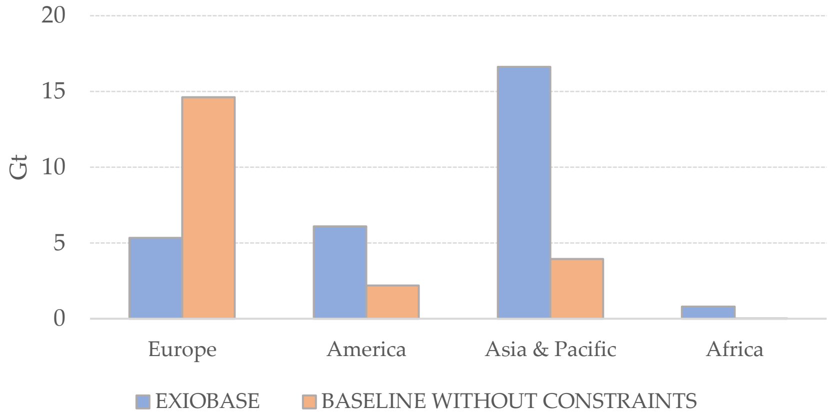


Figure 18 - CO_2 emissions by region; EXIOBASE vs. WTM solution

Another implication is related to the global GDP, strictly affected by the global production. In this case, comparing real 2011 GDP and the one resulting from WTM, is evident that the European role is overvalued, while the America and Asia & Pacific ones are strongly underestimated.

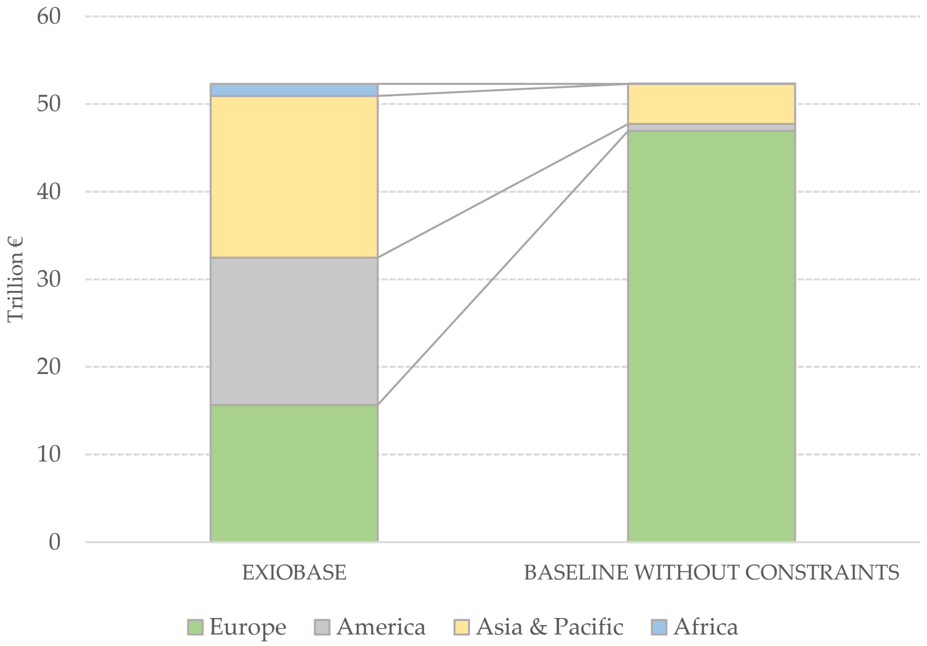


Figure 19 - Global GDP by region

These discrepancies between model results and reality are due to the simplified tunnel vision that lies behind WTM solution finding. The model neglects a multiplicity of reasons guiding the whole economy and, ultimately, human behavior. To reduce these problems, we have added further realistic constraints beside the basic WTM ones.

The first limitation we implemented is the constraint on factor endowment. We have studied in detail the real availability of crucial factors identified and we bound these regionally. In other words, we are imposing to the model that a particular region cannot use a certain factor exceeding real availability. We set this limit for all the factors chosen in the aggregation phase except Taxes & Wages, which is left completely free.

As regard the CO_2 emissions, we impose a cap only in Europe, keeping unbounded the other region's emissions. This choice is due to the presence in 2011 in Europe of a limitation on industrial emissions. In coherence with Emission Trading System (ETS) we set this threshold to 5 Gt of CO_2 industrial emissions.

A new constraint for the employment factor is introduced: we have bounded it in a sectorial way. This constrain represents properly the real situation, where workers are specialized in a determined sector. The risk to set this limit is to excessively tie the model and do not permit it to find a solution. To avoid this risk, we left workers to move in sectors of the same macro-area, for example bounding in the whole energy sector and not to the single specific power sources plants.

Moreover, we minimized trade of electricity among regions. This limitation is imposed due to the macro level of regional aggregation. According to data, the import/export of electricity between continents can be negligible and, to avoid its sudden and unwanted raise, we restricted it manually. The final list of constraints required by the model is:

- Satisfaction of the final and intermediate demand of each region, net of import and exports;
- Non negativity of production;
- Endowment constraints on resource use;
- M€ exported minor to M€ produced per each sector by every region;
- Minimized trade of electricity among regions;
- Limited CO_2 emission in Europe.

With these new constraints the model finds a more accurate solution and the new power sector overlaps almost perfectly the electricity production depicted by EXIOBASE.

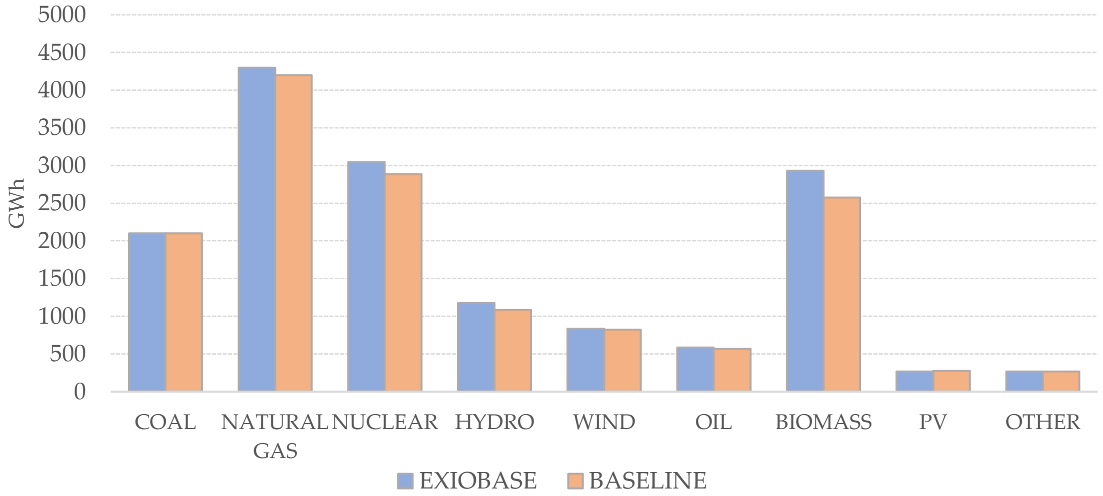


Figure 20 - European Electricity Generation after additional constraints; EXIOBASE vs WTM solution

The case resulted is still more dependent on the trade system than reality, but factor endowements forces a regions to specialize in specific sectors, leaving other goods production to other regions. These redistribution of the production leads to a truthful profile of global GDP and CO_2 emissions, as we can observe in Figure 21.

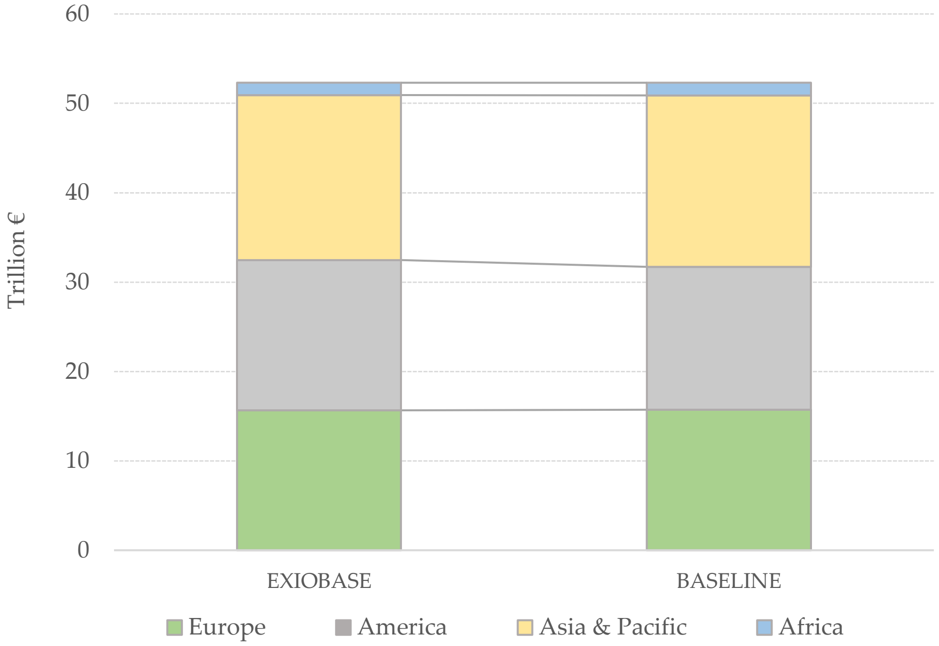


Figure 21 - Global GDP by region

World Trade Model calculates an optimized solution of 52’304’015 M€. This value is only 66 M€ higher than the 2011 GDP value. It can be noted that WTM slightly underestimates American contribute to global GDP, while overestimating European, African and Asian provision.

The differences between the WTM results and real EXIOBASE data in key indicators as CO_2 emissions, power mix and GDP are in acceptable range and for this reason the baseline scenario represent accurately 2011 background.

4.2 Baseline, BAU and SDS: output indicators comparison

In this sub-chapter, the main output indicators of our analysis will be presented. This final part is intended as a summa and tries to perform a comparison among the scenarios taken into account during our analysis.

4.2.1 CO_2 Emissions

CO_2 is nowadays one of the prominent environmental indicators, therefore its presence is indispensable in this work. Carbon Dioxide emissions will be illustrated firstly from a wider perspective and only then we will deepen the analysis on the most emitting sectors.

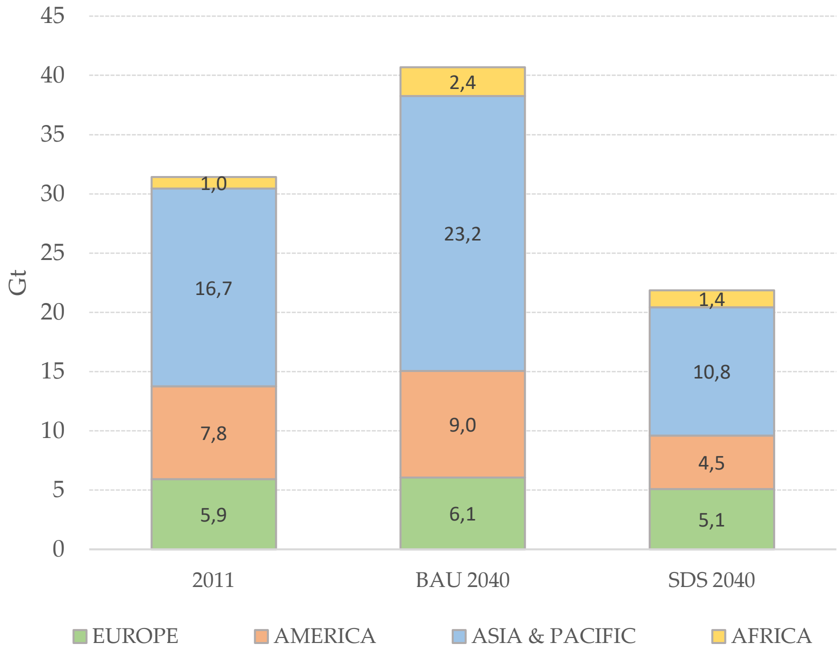


Figure 22 - Total CO_2 emissions by region

Starting from Figure 22, some first considerations can be undertaken. The histogram above clearly highlights the substantial differences of total amount of CO_2 released in each scenario. Starting from a Baseline value of 29.8 Gt, emissions would increase steeply by 2040 in the case of BAU scenario reaching a considerable value of 39.1 Gt; on the other hand, in SDS global carbon dioxide emitted would decline to 22.2 Gt. Paying attention to the regional trends from Baseline to BAU scenario, due to a significant demographic growth, Asia & Pacific and Africa would be the areas with the sharper rise of emissions, meanwhile Europe and America seem to undergo a flattened trend. Asia & Pacific region would be the one experiencing the largest difference between two scenarios: there, emissions would increase of 39% in BAU and decrease of 35% in SDS compared to 2011 values.

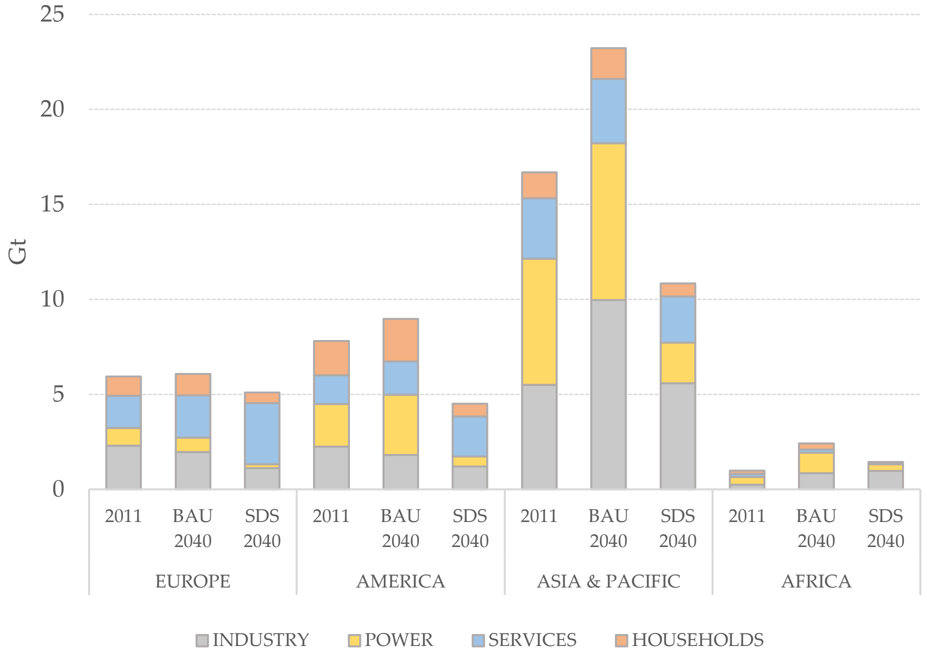


Figure 23 - Total CO_2 emissions by region and by sector

Further considerations can be carried out examining Figure 23, unpacking CO_2 emissions of each region and allocating them to their belonging sector. It is noteworthy how the impact of power sector changes in the two scenarios turning from 13.3 Gt in BAU scenario to 3.2 Gt in SDS.

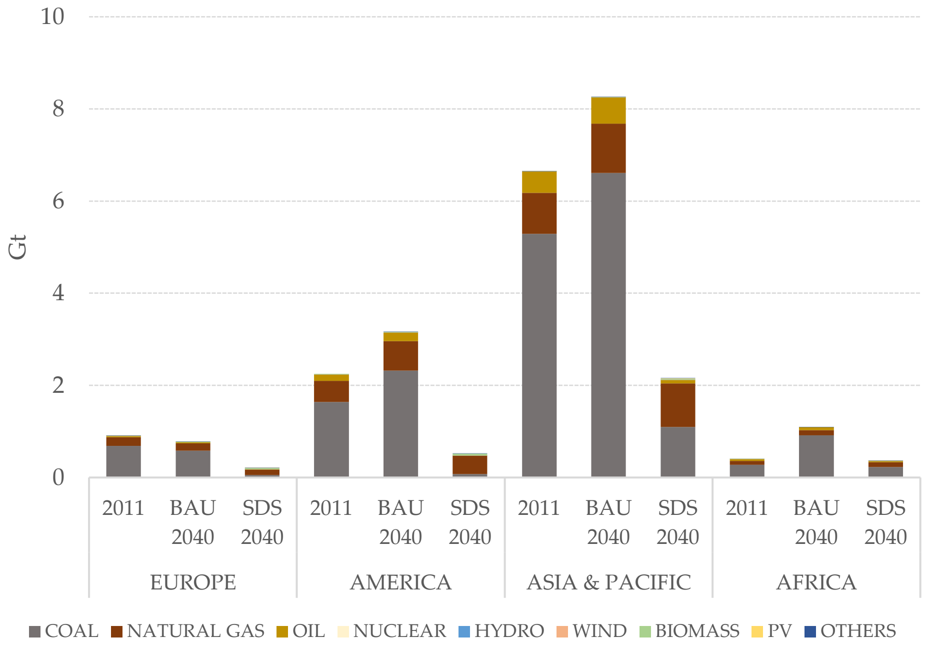


Figure 24 - CO_2 emissions from electricity generation by source

Deepening in those two cumulative numbers, Figure 24 can help to understand the emission sources in regard to electricity generation. In fact, the widely decarbonisation of energy sector described in the previous chapters implies an abrupt switch to renewable power sources and a consequent drop of electricity-related CO_2 emissions.

Besides these representations of results coming from our model, we compared IEA estimates about CO_2 emissions in SDS in 2040 with our WTM output referred to the same scenario.

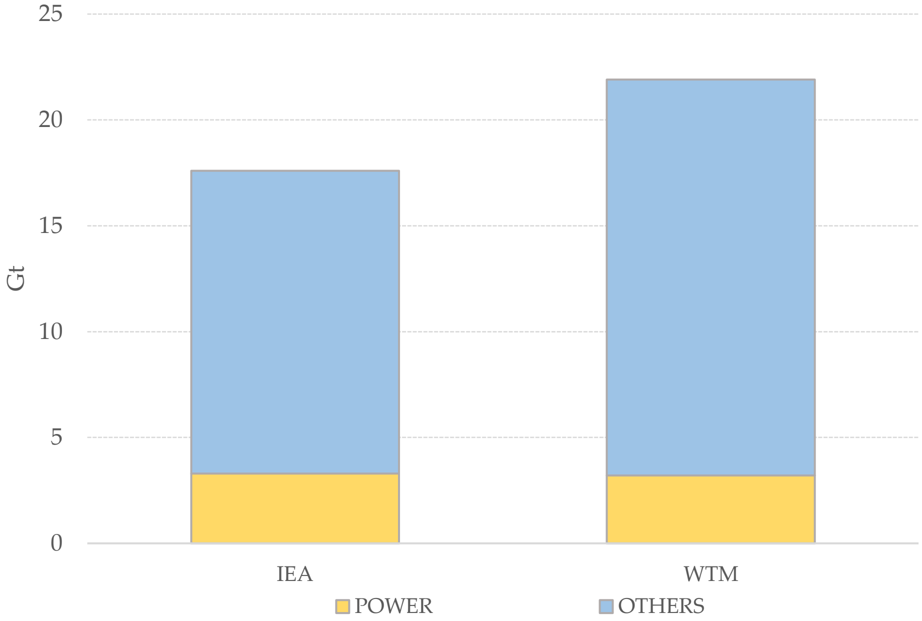


Figure 25 - SDS Global CO_2 emissions, IEA vs WTM

IEA, in their World Energy Outlook 2018, evaluate SDS global CO_2 emissions at 17.6 Gt. This assessment underestimates emissions of about 24% compared to WTM output of 21.9 Gt. In particular, looking at Figure 25, we can observe that there is a nearly complete overlap of power generation emissions, 3.3 Gt for IEA and 3.2 Gt for WTM.

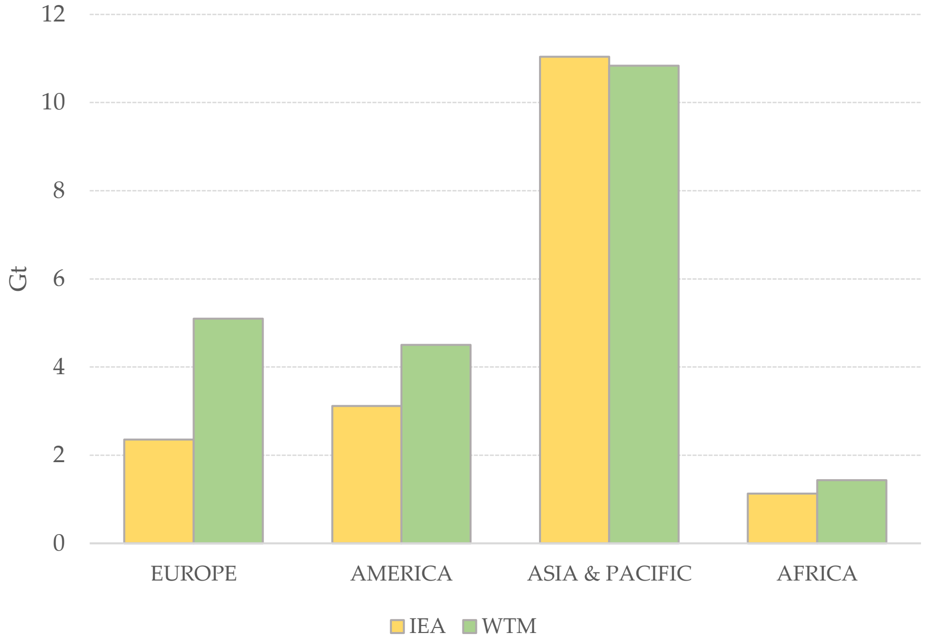


Figure 26 - SDS CO_2 emissions by region, IEA vs WTM

As evident from the last chart, emissions estimates from IEA and WTM almost coincide for Asia & Pacific and Africa but diverge for what concerns Europe and America, with WTM presenting higher values both the times.

4.2.2 Fossil Fuels Extracted

The extraction of fossil fuels has been one of the central points of interest of our analysis. The amount of crude oil, coal and natural gas extracted from soil is strictly related to electricity generation but is also connected to other productive activities. In the baseline case, globally, coal extraction attested to values around 7.6 Gt, crude oil to 5.4 Gt and natural gas to 5.7 Gt. In BAU these values do not change significantly, in exception of coal that reach an extraction of 8.5 Gt. A different variation can be seen implementing SDS, in which extraction amount of crude oil decreases of 65% and natural gas of 44% compared to Baseline.

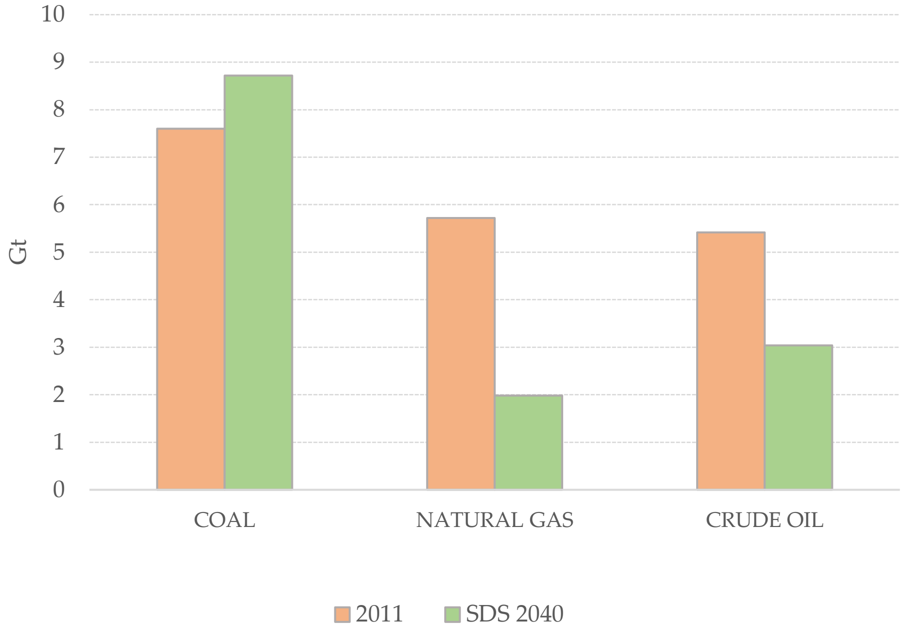


Figure 27 - Fossil Fuels extraction, BASELINE vs. SDS

From Baseline to SDS, our model changes the dynamics of fossil fuels extraction and, for this reason, data are affected from the alteration of extraction site. Given the formulation of EXIOBASE database, each region has a different productive system based on the efficiency of its labor activities. This means that to produce a certain quantity of monetary or material output, the input resources requirements of a region differ from the ones of another one.

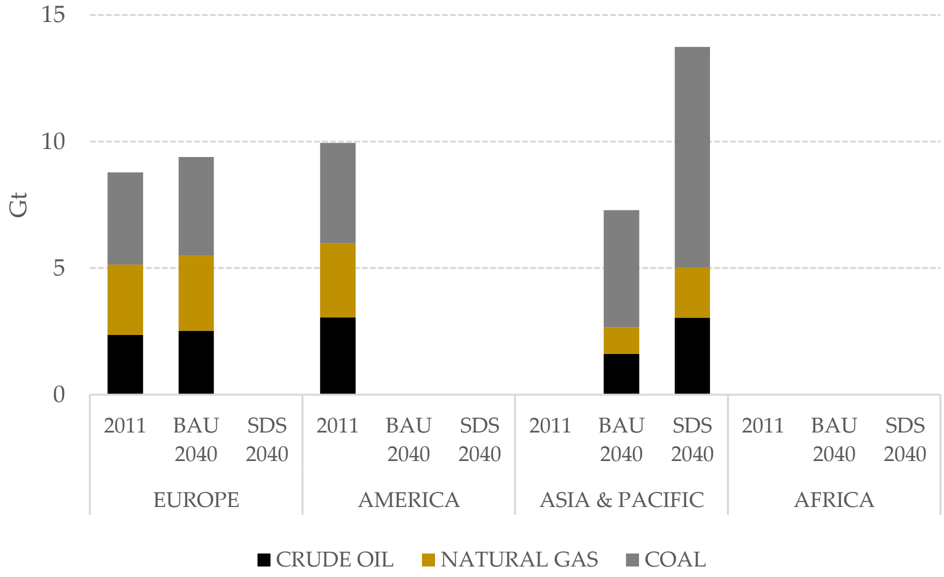


Figure 28 - Fossil fuels extraction by region

As we can notice from Figure 28, moving from Baseline to SDS fossil fuels extraction shifts massively from Europe and America to Asia & Pac. In Exiobase, the latter region is characterized as less efficient in extracting fossil fuels compared to the previous ones and therefore in SDS the specific need of coal increases just to satisfy the demand of extraction sector. This particular difference of resource efficiency among regions is deductible carrying on an investigation on Exiobase natural inputs matrix, where coefficients are expressed per unit of output M€. It is noteworthy that, focusing on the "coal" dedicated row, the quantity required to produce a determined monetary output of extraction sector changes significantly from Europe (3.58 $\frac{kt}{M€}$) to Asia & Pacific (5.91 $\frac{kt}{M€}$). This discrepancy is due to the lower orientation of the latter region to economizing resources in this field and consequently leads to an increase of the global amount of coal unearthed.

4.2.3 Metals and Minerals Depletion

As found in literature and mentioned in the work introduction, one of the possible critical aspects of the clean energy transition could be an increase in metals and minerals mining. As depicted in various studies, these natural resources are likely to become the most used ones in a low carbon energy system, due to their high quantity required by renewable technologies. To control if their effective regional availability is sufficient to achieve the numbers predicted by IEA a detailed study is necessary. According to the WTM, in the SDS the overall extraction of metals and minerals increases to satisfy the demand of renewable energy.

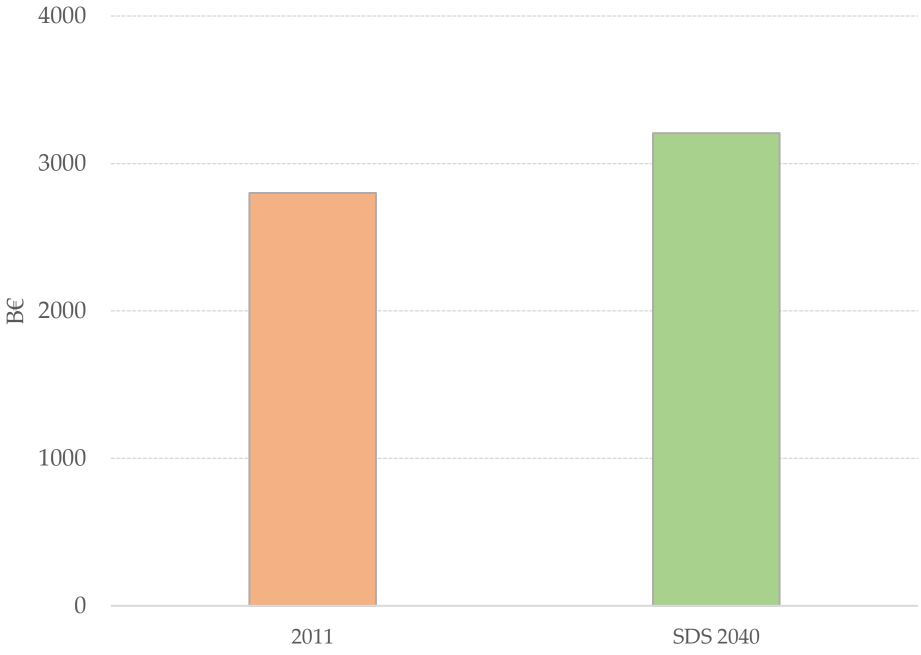


Figure 29 - Metals and minerals extraction sector production

In particular, looking to the inter-sectoral demand of metals extraction required by the power generation sectors, Figure 30 evidences how a high renewable penetration would increase energy sector metals demand, mainly for wind and solar PV.

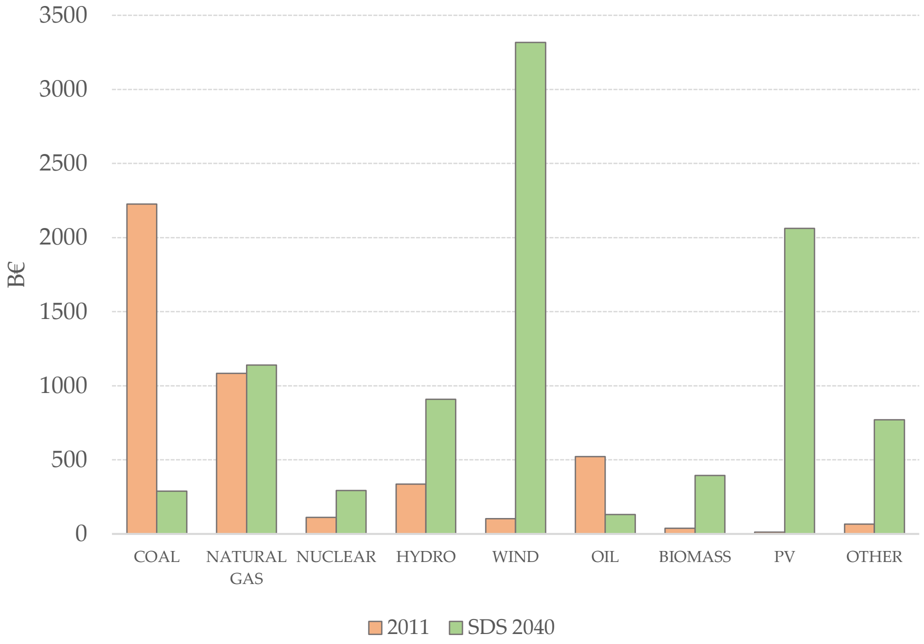


Figure 30 - Demand of metals by power generation sectors

To have a better detail of which particular metal or mineral could be the most critical in this transition we have calculate the usage percentage difference between baseline and SDS. Results are shown in Figure 31.

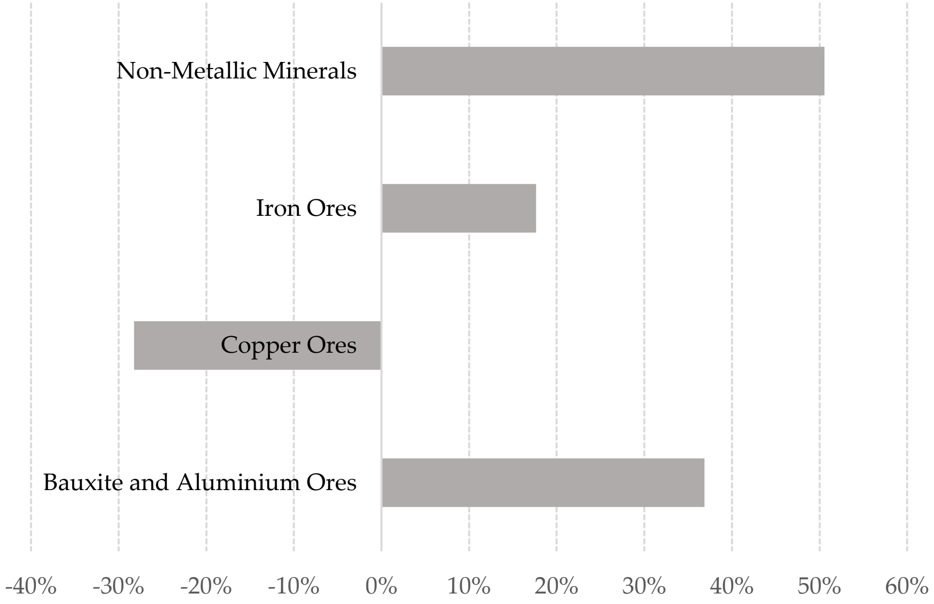


Figure 31 - Percentage increase in global factor use from Baseline to SDS

These results suggest that “non-metallic minerals” and “bauxite and aluminium ores” mining increases significantly, respectively of 51% and 37%. The opposite trend can be associated to the copper ores, which use decreases shifting to SDS. This effect would appear to be in contrast with some studies in literature and with the concepts introduced in the introduction of this work. Like the fossil fuel trend, this particular aspect can be explained looking to the environmental impact coefficients of EXIOBASE database and the region that mines minerals and metals. In fact, investigating mining processes we can notice a shift in the producer region from Baseline to SDS. In baseline the main producer is America, followed by Asia & Pacific, meanwhile in SDS the main part of the production is carried out by Asia & Pacific, which doubles its production. The American production is therefore split among Asia and Africa. Looking at copper environmental coefficients, we can notice that in America 1.67 kt of copper are required to achieve one unit of mining output, defining it as a low efficient sector. In particular, in the baseline case America’s mining sector accounts for around 1300 B€, resulting in 2171 kt of copper extracted. This coefficient in Asia & Pacific is 0.57 $\frac{kt}{B€}$, significantly lower than the American one. This difference is even more pronounced if we consider African continent, which stood to 0.44 $\frac{kt}{B€}$. This coefficients discrepancy lead to a higher demand of mining sector output, but with a lower use of copper thanks to more efficiency of the region in charge. To make a comparison, African mining production in SDS is about 1300 B€, about the same of the American one in the baseline. In contrast the copper necessary to satisfy this demand is 572 kt, a significant lower quantity than the American one.

Figure 32 - Mining production by region in baseline and in SDS case

As explained in the methodology part, our model, in addition to a prediction of the required effective quantity of each factor, compares it with the real region availability. This feature is particularly important and useful in the analysis of metals depletion, one of the resources that some studies indicated as possible bottleneck of the transition, without, however, assessing it.

To evaluate this aspect, we calculated a particular indicator called 'Factor Use Percentage' which mathematical representation is the following equation:

$$Factor\ Use\ \% = \frac{Factor_i\ Used}{Maximum\ quantity\ factor_i} \tag{20}$$

Calculating this indicator for each factor, the result is the following table:

	Europe	**America**	**Asia & Pacific**	**Africa**
Bauxite and Aluminium Ores	0%	0%	2%	1%
Copper Ores	0%	0%	6%	8%
Iron Ores	0%	0%	4%	6%
Non-Metallic Minerals	2%	0%	22%	100%

Table 11 - Factor use percentage for metals and minerals resources

As we can see from the Table 11, no resource seems to become a bottleneck in a high renewable penetration scenario. The only critical situation is in Africa, considering the extraction of non-metallic minerals, but due to the large resource availability in other region this should not be a problem. For the model, this resource extraction is more convenient in Africa, thanks to a more efficient sector. For this reason, non-metallic minerals are extracted there until reaching a sufficient regional availability.

4.2.4 Land Use

Another indicator at the center of our analysis is the occupation of soil. The global land use, as it was easy to predict, is composed on almost its entirety by exploited soil accounted to agriculture and farming activities. These values are subject to a variation from baseline to BAU and SDS following a similar trend observed in the demographic growth forecasted by 2040. From a global occupation of land devoted to agriculture and farming of 50 Million km^2 in the Baseline we pass to 81 Million km^2 in BAU and SDS. Given these data, our focus passed on land used by electricity generation.

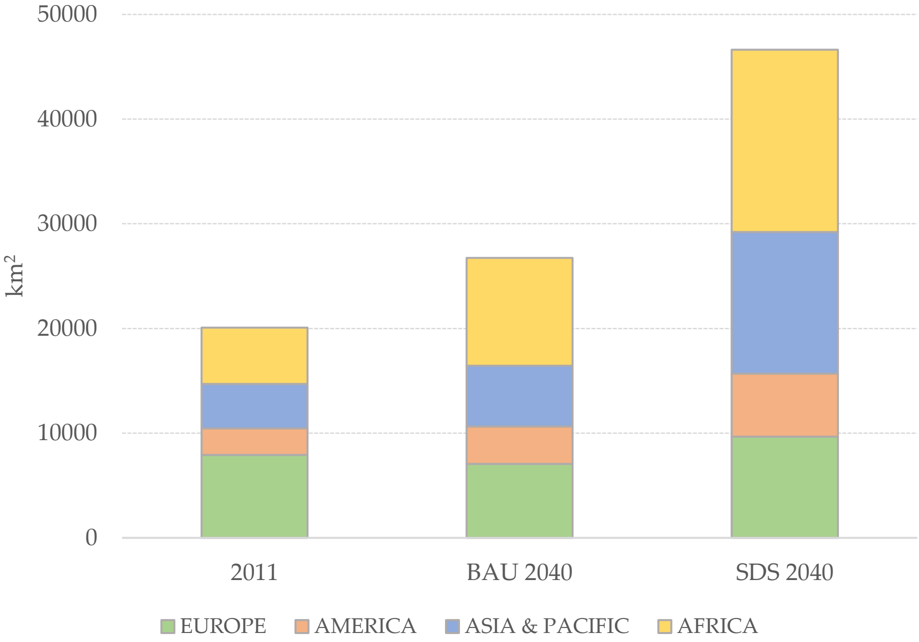


Figure 33 - Electricity generation land use

It is clear in Figure 33 the growing trend also of electricity land use passing from baseline to BAU and then to SDS. The steeper increase happens in Asia & Pacific and Africa, continents characterized by a massive demographic growth until 2040. Besides this, we can even notice the significant difference between BAU and SDS columns; these results suggest a larger land use derived from some renewable sources compared to the occupation coming from traditional energy sources.

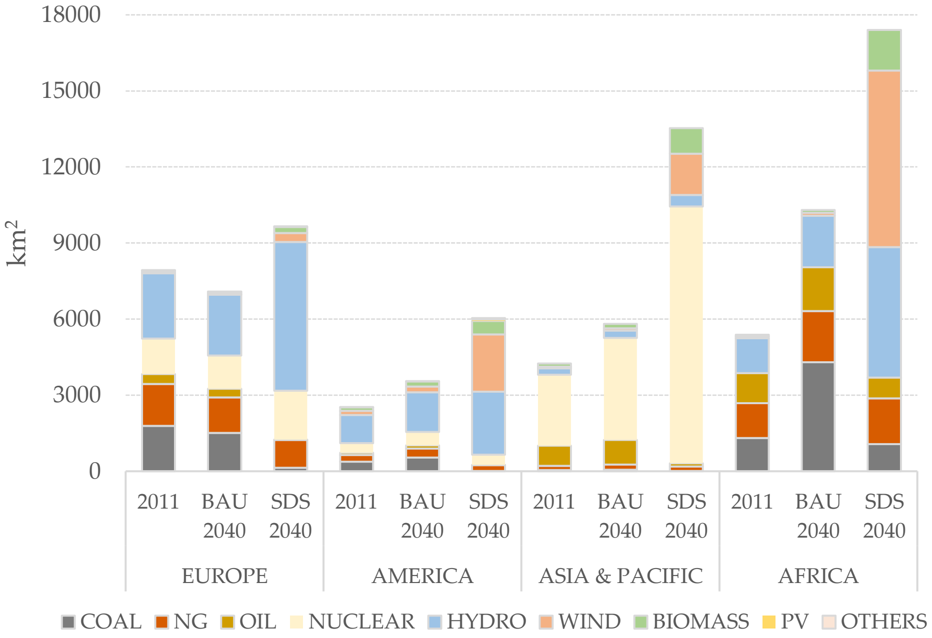


Figure 34 - Electricity generation land use by source

Generally, it is recognizable from Figure 34 a rising trend from 2011 to BAU and a steeper one from 2011 to SDS. This latter scenario presents the lowest land use footprint accounted to traditional fossil fuels sources but has instead a considerable soil occupation deriving from renewable sources, in particular hydropower and wind power besides the significant land use of nuclear plants in Asia & Pacific, according to Exiobase.

4.2.5 Water Consumption

The last aspect considered in our environmental analysis is water consumption. Also considering the whole global productive system, this resource would not become scarce in terms of industrial activities. We have focused our analysis on water consumption related to electricity generation, in order to compare it with IEA previsions about SDS published in World Energy Outlook 2018.

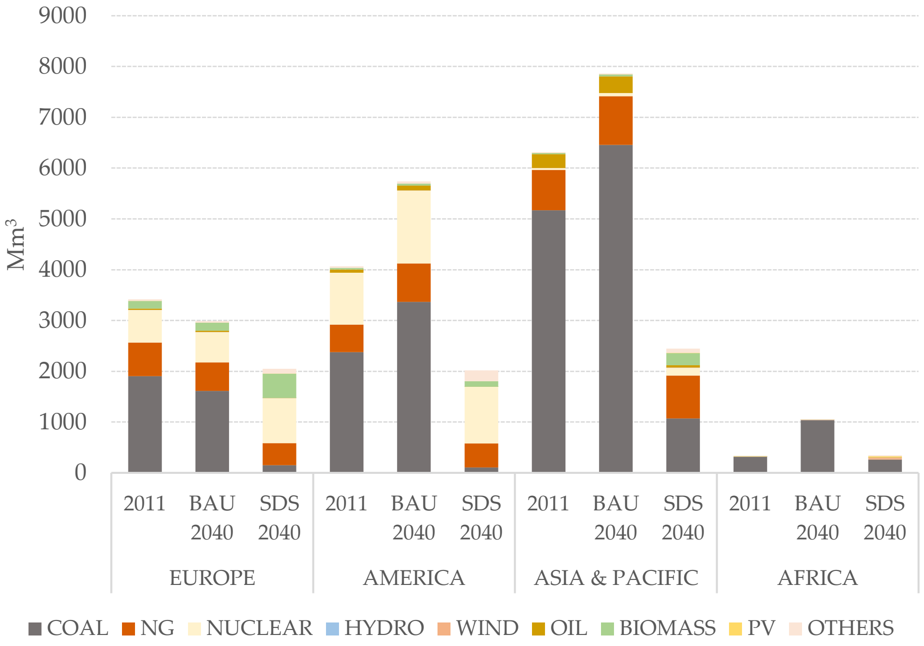


Figure 35 – Electricity generation water consumption by source

It is noteworthy that in the SDS water consumption decreases significantly, in particular the one related to coal power plants which was the main consumer before shock implementation.

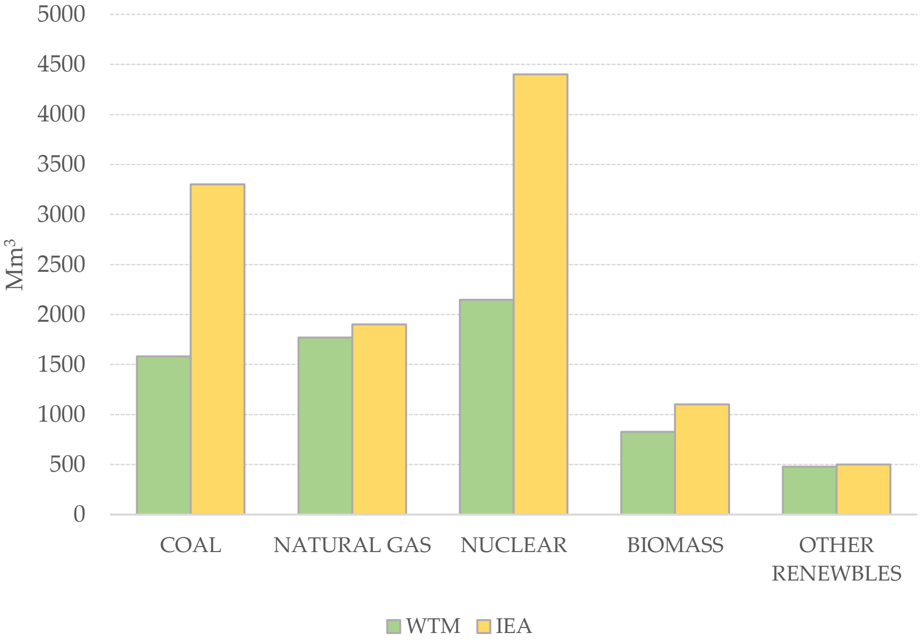


Figure 36 - Electricity generation water consumption by source, IEA vs WTM

As show in Figure 36, compared to IEA forecasts our result underestimates overall water consumption, particularly coal and nuclear needs.

5. Conclusions and further developments

The main results obtained in this work are a deep review of different high renewable scenarios in literature, an improvement in the accuracy of the World Trade Model, and a feasibility analysis based on real resources availability.

Concerning the taxonomy of energy scenarios, we classified 46 different low carbon scenarios based on different categories, as geography and model adopted. The research highlighted a lack in literature about environmental impacts evaluation, often neglected or carried out in a superficial way. In many works these impacts are assessed considering only CO_2 emissions avoided, neglecting possible drawbacks of a low carbon transition, as mineral and metals depletion.

According to WTM, the implementation of SDS would lead to CO_2 emissions decrease of about 35%, with the remaining quantity attributable to the raw materials working, necessary to produce wind turbines and PV modules. The implementation of these technologies would require a higher materials demand than fossil fuel power plants, in particular metals and minerals. In SDS, aluminum and non-metallic minerals mining increases by 40% and 50% respectively, still remaining far below global proven reserves. On contrast, the electrification of final use, as transport and heating, combined with a higher exploitation of renewable technologies allows to achieve a lower extraction of fossil fuels, in particular oil and natural gas. Our work estimates also the impact on land use and water consumption. These two indicators are strictly dependent from agriculture sector; however, energy transition would be able to affect them. In fact, energy-related land use doubles in SDS due to higher exploitation of impactful resources as biomass and wind. This happens mainly in Africa and Asia, where the steep population growth requires a huge additional renewable capacity. On water consumption clean energy transition would have a positive impact thanks to the drop of electricity produced by coal power plant, the main water consuming source.

Analyzing further possible developments of this work, adding transport cost is the first that comes to mind. In our model, thanks to the free charge transport is often more convenient the importation of final goods instead of producing internally. To limit this logic the World Trade Model with Bilateral Trade (WTMBT) can be adopted, as reported in F. Duchin paper (Duchin et al., 2016).

Our aggregation level can be improved increasing the detail level both in regional and sectoral aggregations. In addition, having relied our work on EXIOBASE data, we could not consider technological development occurred during last years. This can lead to an overestimation of the transition impact, due to lower efficient technologies used to satisfy 2040 demand.

Other crucial aspects of a transition to a high renewable penetration energy system are grid stability and energy storage, neglected in our study. I-O tables depict a static picture of a determined whole year and cannot be used to predict an overlap of supply and demand in each moment. The improvement of I-O tables could be important also on the factor side: future integration of crucial resources for energy transition, like lithium or cobalt, could support a more complete feasibility analysis.

Lastly, WTM could be combined with Rectangular Choice of Technology (RCOT). An integration of these two tools would allow the model to choose which renewable source would be better to develop.

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Appendix A

Here is presented a reduced taxonomy of the scenario reviewed. In this one the only categories are the analytical approach, the geography of the model and the technological detail in the energy sector.

Reference	Year of Publication	Model Type	Geography	Sector Considered
Mason et al.	2010	Bottom-Up	Regional	Power
Cosic et al.	2012	Bottom-Up	Regional	Power, Heating, Transport
M. Child and C.Breyer	2016	Bottom-Up	Regional	Power, heating, Transport
Hansen et al.	2019	Bottom-Up	Regional	Power, Heating, Transport
Rocco et al.	2018	Hybrid	Regional	Power
C. Oliveira, C.H. Antunes	2011	Top-Down	Regional	Power
A.S. Oyewo, et al.	2019	Bottom-Up	Regional	Power
Williams et al.	2012	Hybrid	Regional	Power
H.K. Jacobsen	1998	Hybrid	Regional	Power, Heating
H. Dorotić et al.	2019	Bottom-Up	Regional	Power, Heating, Transport
Child et al.	2018	Bottom-Up	Regional	Power, Heating
Liu et al.	2018	Bottom-Up	Regional	Power
Esteban et al.	2018	Bottom-Up	Regional	Power
M. Child et al.	2019	Bottom-Up	Multiregional	Power
C. Taliotis et al.	2016	Bottom-Up	Multiregional	Power
Brown et al.	2019	Bottom-Up	Multiregional	Power, Heating, Transport
G. Pleßmann, P. Blechinger	2017	Bottom-Up	Multiregional	Power
Barbosa et al.	2017	Bottom-Up	Multiregional	Power
Berrill et al.	2016	Hybrid	Multiregional	Power
Heide et al.	2010	Bottom-Up	Multiregional	Power
H. Lund, B.V.Mathiesen	2016	Bottom-Up	Multiregional	Power, Heating, Transport
D.P. Schlachtberger et al.	2019	Bottom-Up	Multiregional	Power
M. Barasa et al.	2018	Bottom-Up	Multiregional	Power
A. Aghahosseini et al.	2019	Bottom-up	Multiregional	Power
A. Gulagi, D. Bogdanov, C. Breyer	2017	Bottom-Up	Multiregional	Power, Heating

D. Bogdanov, C. Breyer	2016	Bottom-Up	Multiregional	Power, Heating
Gulagi et al.	2017	Bottom-Up	Multiregional	Power, Heating
D. Connolly et al.	2016	Bottom-Up	Multiregional	Power, heating
Tröndle et al.	2020	Bottom-Up	Multiregional	Power
Luderer et al.	2019	Hybrid	Global	Power
Jacobson et al.	2019	Bottom-Up	Global	Power, Heating
Jacobson et al.	2018	Bottom-Up	Global	Power, Heating
Jacobson et al.	2018	Bottom-Up	Global	Power, Heating
Bogdanov et al.	2019	Bottom-Up	Global	Power
Teske et al.	2018	Bottom-Up	Global	Power, Heating, Transport
E. Pursiheimo et al.	2018	Bottom-Up	Global	Power, heating, Transport
Loffler et al.	2017	Bottom-Up	Global	Power, Heating, Transport
Deng et al.	2012	Bottom-Up	Global	Power, Heating, Transport
Sgouridis et al.	2016	Hybrid	Global	Power
Pehl et al.	2017	Hybrid	Global	Power
G. Luderer et al.	2017	Hybrid	Global	Power
BP p.l.c.	2019	Bottom-Up	Global	Power, Heating, Transport
Greenpeace	2015	Bottom-Up	Global	Power, Heating, Transport
IIASA	2013	Bottom-Up	Global	Power, Heating, Transport
IEA	2018	Bottom-Up	Global	Power, heating, Transport

Appendix B

Here the codes implemented on Spyder is reported. Python 3.6 has been used as programming language.

2 main codes are used: main.py and pyioa.py

pyioa.py

```
class mrio:

    def __init__(self, path, v, aggregation, reg, sec, fac):
```

```
            print('I am importing the EXIOBASE database and aggregating according to your choices')

            import pandas as pd
            import pymrio

            self.v = v
            if self.v == 3:
                self.data = pymrio.parse_exiobase3(path=path)

            if self.v == 2:
                self.data = pymrio.parse_exiobase2(path=path, charact=True, popvector=None)

            # self.data.calc_all()
            self.Z_dis = self.data.Z
            self.Y_dis = self.data.Y
            self.E_dis = self.data.satellite.F
            self.data.calc_all()
            self.Agg = aggregation
            Reg_agg = pd.read_excel(self.Agg, sheet_name=reg, index_col=0)
            self.Reg_lis = list(Reg_agg)
            Sec_agg = pd.read_excel(self.Agg, sheet_name=sec, index_col=0)
            self.Sec_lis = list(Sec_agg)
            reg_agg_matrix = Reg_agg.transpose().values
            sec_agg_matrix = Sec_agg.transpose().values
            self.data.aggregate(reg_agg_matrix, sec_agg_matrix, self.Reg_lis, self.Sec_lis)
            self.data.calc_all()
            self.nReg = len(self.Reg_lis)
            self.nSec = len(self.Sec_lis)

            self.Z = self.data.Z
            self.Y = self.data.Y
            self.Y_agg = self.Y.groupby(level=0, axis=1).sum()
            self.E_tot = self.E_dis
            self.E_tot = self.data.satellite.F # Extensions factors in max disaggregation

            Fac_dis = pd.read_excel(self.Agg, sheet_name=fac).loc[:,'Disaggregated_factors']
            Fac_agg = pd.read_excel(self.Agg, sheet_name=fac).loc[:,'Macro_factor']
            Fac_uni = pd.read_excel(self.Agg, sheet_name=fac).loc[:,'Unit_of_measure']

            E_index = pd.MultiIndex.from_arrays([Fac_dis.values,Fac_agg.values,Fac_uni.values])

            self.E = pd.DataFrame(self.E_tot.values, index=E_index,
columns=self.E_tot.columns).groupby(level=1, axis=0, sort=False).agg('sum').drop('unused')

            self.F_reg = pd.read_excel(self.Agg, sheet_name='Endowments_reg',
index_col=[0]).T.stack().to_frame()
            self.F_sect = pd.read_excel(self.Agg, sheet_name='Endowments_sect', index_col=[0],
header=[0,1])

            SecAgg_Trade= pd.read_excel(self.Agg, sheet_name='Trade')
            self.Trade = SecAgg_Trade.drop(['Sec', 'Region'], axis = 1).squeeze()
```

```
            self.X = pymrio.calc_x(self.Z, self.Y)
            self.z = pymrio.calc_A(self.Z, self.X)
            self.l = pymrio.calc_L(self.z)
            self.e = pymrio.calc_S(self.E, self.X)

        def set_wtm(self):
            import pandas as pd
            import numpy as np

            takeall = slice(None)


            self.Y_wtm = pd.DataFrame(0, index=self.Y_agg.index, columns=self.Y_agg.columns)
            for i in self.Reg_lis:
                self.Y_wtm.loc[(i,takeall),i] = sum(self.Y_agg.loc[(j,takeall),i].values for j in 
self.Reg_lis)

            self.z_wtm = pd.DataFrame(0, index=self.z.index, columns=self.z.columns)
            for i in self.Reg_lis:
                self.z_wtm.loc[(i,takeall),(i,takeall)] = 
sum(self.z.loc[(j,takeall),(i,takeall)].values for j in self.Reg_lis)

            self.e_wtm = pd.DataFrame(0, pd.MultiIndex.from_product([self.Reg_lis,self.e.index]), 
columns=self.e.columns)
            for i in self.Reg_lis:
                self.e_wtm.loc[(i,takeall),i] = self.e.loc[takeall,(i,takeall)].values

            self.F_wtm = pd.DataFrame(0, 
pd.MultiIndex.from_product([self.Reg_lis,self.F_sect.index]), columns=self.F_sect.columns)
            for i in self.Reg_lis:
                self.F_wtm.loc[(i,takeall),i] = self.F_sect.loc[takeall,(i,takeall)].values

            for i in self.Reg_lis:
                for j in self.Sec_lis:
                    if sum(self.z_wtm.loc[(i,takeall),(i,j)]) == 0:
                        self.z_wtm.loc[(i,takeall),(i,j)] = 9999



            self.pi = pd.read_excel(self.Agg, sheet_name='Factor costs', index_col 
=[0]).T.stack().to_frame()
            self.p = pd.DataFrame(np.dot(np.linalg.inv(np.eye(self.nReg*self.nSec)-
self.z.T),self.E.iloc[0,:]), index=self.X.index)

            with pd.ExcelWriter('EXIOBASE.xlsx',
                       mode='w') as writer:
                self.X.to_excel(writer, sheet_name='EXIOBASE Production')
                self.z_wtm.to_excel(writer, sheet_name='EXIOBASE Technical Coefficients')
                self.e.to_excel(writer, sheet_name='EXIOBASE e')
                self.E.to_excel(writer, sheet_name='EXIOBASE Factor Production')
                self.Y_wtm.to_excel(writer, sheet_name='EXIOBASE Final Demand')
```

```
def increase_demand(self, verbose=True):

        self.Y_wtm.iloc[0:25,:] = self.Y_wtm.iloc[0:25,:] * 1.13
        self.Y_wtm.iloc[25:50,:] = self.Y_wtm.iloc[25:50,:] * 1.24
        self.Y_wtm.iloc[50:75,:] = self.Y_wtm.iloc[50:75,:] * 1.18
        self.Y_wtm.iloc[75::,:] = self.Y_wtm.iloc[75::,:] * 1.96

def power_sector(self, verbose=True):
        import numpy as np
        import pymrio
        import pandas as pd

for i=region, j=electricity production sector
self.Y_wtm.loc[('i','j'),('i')] = self.Y_wtm.loc[('i',’j’), ('i')] + ΔM€

self.sum_z_EU = self.z_wtm.iloc[10:19,0:25].sum()
        self.z_wtm.loc[('Europe','EL_COAL'),0:25] = 0.01 * self.sum_z_EU
        self.z_wtm.loc[('Europe','EL_GAS'),0:25] = 0.13 * self.sum_z_EU
        self.z_wtm.loc[('Europe','EL_PETR'),0:25] = 0 * self.sum_z_EU
        self.z_wtm.loc[('Europe','EL_W'),0:25] = 0.27 * self.sum_z_EU
        self.z_wtm.loc[('Europe','EL_PV'),0:25] = 0.08 * self.sum_z_EU
        self.z_wtm.loc[('Europe','EL_BIO'),0:25] = 0.08 * self.sum_z_EU
        self.z_wtm.loc[('Europe','EL_NU'),0:25] = 0.21 * self.sum_z_EU
        self.z_wtm.loc[('Europe','EL_HY'),0:25] = 0.18 * self.sum_z_EU
        self.z_wtm.loc[('Europe','EL_OTH'),0:25] = 0.03 * self.sum_z_EU

        self.sum_z_AM = self.z_wtm.iloc[35:44,25:50].sum()
        self.z_wtm.loc[('America','EL_COAL'),25:50] = 0.01 * self.sum_z_AM
        self.z_wtm.loc[('America','EL_GAS'),25:50] = 0.14 * self.sum_z_AM
        self.z_wtm.loc[('America','EL_PETR'),25:50] = 0 * self.sum_z_AM
        self.z_wtm.loc[('America','EL_W'),25:50] = 0.24 * self.sum_z_AM
        self.z_wtm.loc[('America','EL_PV'),25:50] = 0.12 * self.sum_z_AM
        self.z_wtm.loc[('America','EL_BIO'),25:50] = 0.05 * self.sum_z_AM
        self.z_wtm.loc[('America','EL_NU'),25:50] = 0.13 * self.sum_z_AM
        self.z_wtm.loc[('America','EL_HY'),25:50] = 0.27 * self.sum_z_AM
        self.z_wtm.loc[('America','EL_OTH'),25:50] = 0.04 * self.sum_z_AM

        self.sum_z_AS = self.z_wtm.iloc[60:69,50:75].sum()
        self.z_wtm.loc[('Asia & Pacific','EL_COAL'),50:75] = 0.08 * self.sum_z_AS
        self.z_wtm.loc[('Asia & Pacific','EL_GAS'),50:75] = 0.15 * self.sum_z_AS
        self.z_wtm.loc[('Asia & Pacific','EL_PETR'),50:75] = 0.01 * self.sum_z_AS
        self.z_wtm.loc[('Asia & Pacific','EL_W'),50:75] = 0.19 * self.sum_z_AS
        self.z_wtm.loc[('Asia & Pacific','EL_PV'),50:75] = 0.21 * self.sum_z_AS
        self.z_wtm.loc[('Asia & Pacific','EL_BIO'),50:75] = 0.05 * self.sum_z_AS
        self.z_wtm.loc[('Asia & Pacific','EL_NU'),50:75] = 0.12 * self.sum_z_AS
        self.z_wtm.loc[('Asia & Pacific','EL_HY'),50:75] = 0.16 * self.sum_z_AS
        self.z_wtm.loc[('Asia & Pacific','EL_OTH'),50:75] = 0.04 * self.sum_z_AS


        self.sum_z_AF = self.z_wtm.iloc[85:94,75::].sum()
        self.z_wtm.loc[('Africa','EL_COAL'),75::] = 0.04 * self.sum_z_AF
```

```
        self.z_wtm.loc[('Africa','EL_GAS'),75::] = 0.15 * self.sum_z_AF
        self.z_wtm.loc[('Africa','EL_PETR'),75::] = 0.02 * self.sum_z_AF
        self.z_wtm.loc[('Africa','EL_W'),75::] = 0.1 * self.sum_z_AF
        self.z_wtm.loc[('Africa','EL_PV'),75::] = 0.31 * self.sum_z_AF
        self.z_wtm.loc[('Africa','EL_BIO'),75::] = 0.02 * self.sum_z_AF
        self.z_wtm.loc[('Africa','EL_NU'),75::] = 0.03 * self.sum_z_AF
        self.z_wtm.loc[('Africa','EL_HY'),75::] = 0.23 * self.sum_z_AF
        self.z_wtm.loc[('Africa','EL_OTH'),75::] = 0.1 * self.sum_z_AF

def transport_sector(self, verbose=True):
        import numpy as np
        import pymrio
        import pandas as pd

for i=region
self.Y_wtm.loc[('i','OIL REF'),('i')] = self.Y_wtm.loc[('i','OIL REF'),('i')] + ΔM€
self.Y_wtm.loc[('i','BIOGAS'),('i')] = self.Y_wtm.loc[('i','BIOGAS'),('i')] + ΔM€
self.Y_wtm.loc[('i','GAS DISTR'),('i')] = self.Y_wtm.loc[('i','GAS DISTR'),('i')] + ΔM€
     for j= electricity production sector
self.Y_wtm.loc[('i','j'),('i')] = self.Y_wtm.loc[('i',’j’),('i')] + ΔM€

self.z_wtm.loc[('Europe','OIL REF'),('Europe','TRANSPORT')] = 0.015
        self.z_wtm.loc[('Europe','EL_COAL'),('Europe','TRANSPORT')] = 0.00015
        self.z_wtm.loc[('Europe','EL_GAS'),('Europe','TRANSPORT')] = 0.0013
        self.z_wtm.loc[('Europe','EL_NU'),('Europe','TRANSPORT')] = 0.0021
        self.z_wtm.loc[('Europe','EL_HY'),('Europe','TRANSPORT')] = 0.0018
        self.z_wtm.loc[('Europe','EL_W'),('Europe','TRANSPORT')] = 0.00266
        self.z_wtm.loc[('Europe','EL_PETR'),('Europe','TRANSPORT')] = 0.000019
        self.z_wtm.loc[('Europe','EL_BIO'),('Europe','TRANSPORT')] = 0.00083
        self.z_wtm.loc[('Europe','EL_PV'),('Europe','TRANSPORT')] = 0.00076
        self.z_wtm.loc[('Europe','EL_OTH'),('Europe','TRANSPORT')] = 0.00026
        self.z_wtm.loc[('Europe','BIOGAS'),('Europe','TRANSPORT')] = 0.00004
        self.z_wtm.loc[('Europe','GAS DISTR'),('Europe','TRANSPORT')] = 0.00007

        self.z_wtm.loc[('America','OIL REF'),('America','TRANSPORT')] = 0.011
        self.z_wtm.loc[('America','EL_COAL'),('America','TRANSPORT')] = 0.0000057
        self.z_wtm.loc[('America','EL_GAS'),('America','TRANSPORT')] = 0.00006
        self.z_wtm.loc[('America','EL_NU'),('America','TRANSPORT')] = 0.000059
        self.z_wtm.loc[('America','EL_HY'),('America','TRANSPORT')] = 0.00012
        self.z_wtm.loc[('America','EL_W'),('America','TRANSPORT')] = 0.0001
        self.z_wtm.loc[('America','EL_PETR'),('America','TRANSPORT')] = 0.0000013
        self.z_wtm.loc[('America','EL_BIO'),('America','TRANSPORT')] = 0.00002
        self.z_wtm.loc[('America','EL_PV'),('America','TRANSPORT')] = 0.000053
        self.z_wtm.loc[('America','EL_OTH'),('America','TRANSPORT')] = 0.000019
        self.z_wtm.loc[('America','BIOGAS'),('America','TRANSPORT')] = 0.024
        self.z_wtm.loc[('America','GAS DISTR'),('America','TRANSPORT')] = 0.008

        self.z_wtm.loc[('Asia & Pacific','OIL REF'),('Asia & Pacific','TRANSPORT')] = 0.062
        self.z_wtm.loc[('Asia & Pacific','EL_COAL'),('Asia & Pacific','TRANSPORT')] = 0.0016
        self.z_wtm.loc[('Asia & Pacific','EL_GAS'),('Asia & Pacific','TRANSPORT')] = 0.003
        self.z_wtm.loc[('Asia & Pacific','EL_NU'),('Asia & Pacific','TRANSPORT')] = 0.0024
```

```
        self.z_wtm.loc[('Asia & Pacific','EL_HY'),('Asia & Pacific','TRANSPORT')] = 0.0031
        self.z_wtm.loc[('Asia & Pacific','EL_W'),('Asia & Pacific','TRANSPORT')] = 0.0037
        self.z_wtm.loc[('Asia & Pacific','EL_PETR'),('Asia & Pacific','TRANSPORT')] = 0.00011
        self.z_wtm.loc[('Asia & Pacific','EL_BIO'),('Asia & Pacific','TRANSPORT')] = 0.00097
        self.z_wtm.loc[('Asia & Pacific','EL_PV'),('Asia & Pacific','TRANSPORT')] = 0.004
        self.z_wtm.loc[('Asia & Pacific','EL_OTH'),('Asia & Pacific','TRANSPORT')] = 0.00074
        self.z_wtm.loc[('Asia & Pacific','BIOGAS'),('Asia & Pacific','TRANSPORT')] = 0.0062
        self.z_wtm.loc[('Asia & Pacific','GAS DISTR'),('Asia & Pacific','TRANSPORT')] = 0.0155

        self.z_wtm.loc[('Africa','OIL REF'),('Africa','TRANSPORT')] = 0.057
        self.z_wtm.loc[('Africa','EL_COAL'),('Africa','TRANSPORT')] = 0.000055
        self.z_wtm.loc[('Africa','EL_GAS'),('Africa','TRANSPORT')] = 0.00019
        self.z_wtm.loc[('Africa','EL_NU'),('Africa','TRANSPORT')] = 0.000035
        self.z_wtm.loc[('Africa','EL_HY'),('Africa','TRANSPORT')] = 0.000305
        self.z_wtm.loc[('Africa','EL_W'),('Africa','TRANSPORT')] = 0.00012
        self.z_wtm.loc[('Africa','EL_PETR'),('Africa','TRANSPORT')] = 0.000025
        self.z_wtm.loc[('Africa','EL_BIO'),('Africa','TRANSPORT')] = 0.00003
        self.z_wtm.loc[('Africa','EL_PV'),('Africa','TRANSPORT')] = 0.0004
        self.z_wtm.loc[('Africa','EL_OTH'),('Africa','TRANSPORT')] = 0.000126
        self.z_wtm.loc[('Africa','BIOGAS'),('Africa','TRANSPORT')] = 0.0039
        self.z_wtm.loc[('Africa','GAS DISTR'),('Africa','TRANSPORT')] = 0.0026

def heating_sector(self, verbose=True):
        import numpy as np
        import pymrio
        import pandas as pd
for i=region
self.Y_wtm.loc[('i','GAS DISTR'),('i')] = self.Y_wtm.loc[('i','GAS DISTR'),('i')] + ΔM€

     for j= electricity production sector
self.Y_wtm.loc[('i','j'),('i')] = self.Y_wtm.loc[('i',’j’),('i')] + ΔM€

def run_wtm(self, verbose=True):
        import cvxpy as cv
        import numpy as np
        import pymrio
        import pandas as pd
        import seaborn as sns
        import matplotlib.pyplot as plt


        X = cv.Variable((self.nReg*self.nSec, 1),nonneg=True)
        T = cv.Variable((self.nReg*self.nSec, self.nReg), nonneg=True)

        EX = cv.sum(T, 1, keepdims=True)              # exports (by sector, by country)
        IM = np.zeros([self.nSec, self.nReg])         # imports (by sector, by country)
        for i in range(self.nReg):
            IM += T[(i*self.nSec):(i*self.nSec+self.nSec), :]

        IM = cv.reshape(IM,(self.nReg*self.nSec, 1))
```

```
            ObjFun = cv.matmul(cv.matmul(self.pi.T,self.e_wtm), X) #Minimization of global factor
cost
            objective = cv.Minimize(ObjFun)


            constraints = [cv.matmul(np.eye(self.nReg*self.nSec)-self.z_wtm, X)+ IM - EX >=
np.sum(self.Y_wtm.values, 1, keepdims=True),
                           -cv.matmul(self.e_wtm, X) >= -self.F_reg,
                           X <=
(self.F_sect.loc['Employment'].to_frame())/(self.e.loc['Employment'].to_frame()),
                           X >= 0.0001,
                           EX <= X
                           ]


            for i in self.Trade.index:
                if self.Trade.loc[i] == 0  :
                    constraints += [
                        T[i] <= 1.4
                        ]

            prob = cv.Problem(objective, constraints)
            self.result = prob.solve(solver=cv.GUROBI, verbose=verbose)
            self.X_s = pd.DataFrame(X.value, index=self.X.index, columns=self.X.columns)
            self.X_s_diag = pd.DataFrame(np.diagflat(X.value), index=self.z.index,
columns=self.z.columns)
            self.EX_s = pd.DataFrame(T.value, index=self.z.index, columns=self.Reg_lis)
            self.EX_s_sum = self.EX_s.sum(axis = 1).to_frame()


self.X_EL_s=self.X_s.loc[(slice(None),['EL_COAL','EL_GAS','EL_NU','EL_HY','EL_W','EL_PETR','EL_BIO'
,'EL_PV','EL_STH','EL_WAVE','EL_GEO','EL_OTH']),:]

self.X_EL=self.X.loc[(slice(None),['EL_COAL','EL_GAS','EL_NU','EL_HY','EL_W','EL_PETR','EL_BIO','EL
_PV','EL_STH','EL_WAVE','EL_GEO','EL_OTH']),:]

self.X_OTH_s=self.X_s.loc[(slice(None),['FOOD','RES','MAN','CHEM','MAT','CONS','EL_T&D','TER','TRAN
','WAS']),:]

self.X_OTH=self.X.loc[(slice(None),['FOOD','RES','MAN','CHEM','MAT','CONS','EL_T&D','TER','TRAN','W
AS']),:]

            # Print solution of the dual model
            self.p_s = pd.DataFrame(constraints[0].dual_value, index=self.z.index)
            self.p_s_diag = pd.DataFrame(np.diagflat(self.p_s.values), index=self.z.index,
columns=self.z.columns)
            self.r_s = pd.DataFrame(constraints[1].dual_value, index=self.F_reg.index,
columns=self.F_reg.columns).T
            self.E_s = pymrio.calc_F(self.e, self.X_s)
            self.FU_s = self.E_s.groupby(axis=1, level=0, sort=False).sum()
```

```
            self.FUp_s = pd.DataFrame(self.FU_s.values/self.F_reg.unstack(level=0).values, 
index=self.FU_s.index, columns=self.FU_s.columns)

            self.DX_s = pd.DataFrame((self.X_s.values - self.X.values)/self.X.values, index = 
self.X_s.index, columns=self.X_s.columns)
            self.EXvsX = pd.DataFrame((self.EX_s_sum.values/self.X_s.values) * 100 , index = 
self.X_s.index, columns = self.X_s.columns)

            self.Z_s = pymrio.calc_Z(self.z_wtm, self.X_s)
            # Plotting main chart solutions
            plt.ylabel('Use of factors by Region [%]')
            sns.heatmap(self.FUp_s)
            plt.show()

            ax = self.X.plot(kind='bar', color='blue', alpha=0.5, figsize=(15,7))
            self.X_s.plot(ax = ax, kind='bar', color='red', alpha=0.5)
            ax.legend(["Exiobase Production", "Optimized Production"])

            ax = self.X_EL.plot(kind='bar', color='blue', alpha=0.5, figsize=(10,5))
            self.X_EL_s.plot(ax = ax, kind='bar', color='red', alpha=0.5)
            ax.legend(["Exiobase Production", "Optimized Production"])

            ax = self.X_OTH.plot(kind='bar', color='blue', alpha=0.5, figsize=(10,5))
            self.X_OTH_s.plot(ax = ax, kind='bar', color='red', alpha=0.5)
            ax.legend(["Exiobase Production", "Optimized Production"])

            #ax = self.DX_s.plot(kind='bar', color='blue', alpha=1, figsize=(20,7))

            print("optimal value:", prob.value)



        def results(self):

            import pandas as pd

            with pd.ExcelWriter('Model Results.xlsx',
                        mode='w') as writer:
                self.X_s.to_excel(writer, sheet_name = 'Production')
                self.EX_s.to_excel(writer, sheet_name = 'Export')
                self.E_s.to_excel(writer, sheet_name = 'Factor Production')
                self.E.to_excel(writer, sheet_name = 'Factor Production_Exio')
                self.r_s.to_excel(writer, sheet_name = 'r')
                self.p_s.to_excel(writer, sheet_name = 'p')
                self.FU_s.to_excel(writer, sheet_name = 'Factor Use')
                self.FUp_s.to_excel(writer, sheet_name = 'Factor Use Percentage')
                self.EXvsX.to_excel(writer, sheet_name = '% export')
                self.DX_s.to_excel(writer, sheet_name = 'Production %diff')
                self.Y_wtm.to_excel(writer, sheet_name='Final Demand')
                self.e.to_excel(writer, sheet_name='Factor Production Coefficients')
                self.Z_s.to_excel(writer, sheet_name='Z')
```

main.py

```
import pymrio
import pandas as pd
import numpy as np
import cvxpy as cv
import pyioa

sec = 'Sectors'
reg = 'Regions'
fac = 'Factors'
v3_11 = pyioa.mrio(path)
v3_11.set_wtm()
v3_11.increase_demand()
v3_11.power_sector()
v3_11.transport_sector()
v3_11.heating_sector()
v3_11.run_wtm()
v3_11.results()
```

Appendix C

	Agriculture, Farming and Fishing
1	Cultivation of paddy rice
2	Cultivation of wheat
3	Cultivation of cereal grains nec
4	Cultivation of vegetables, fruit, nuts
5	Cultivation of oil seeds
6	Cultivation of sugar cane, sugar beet
7	Cultivation of plant-based fibers
8	Cultivation of crops nec
9	Cattle farming
10	Pigs farming
11	Poultry farming
12	Meat animals nec
13	Animal products nec
14	Raw milk
15	Wool, silk-worm cocoons
16	Manure treatment (conventional), storage and land application
18	Forestry, logging and related service activities

19	Fishing, operating of fish hatcheries and fish farms; service activities incidental to fishing

	Extraction of fossil fuels
20	Mining of coal and lignite; extraction of peat
21	Extraction of crude petroleum and services related to crude oil extraction, excluding surveying
22	Extraction of natural gas and services related to natural gas extraction, excluding surveying
23	Extraction, liquefaction, and regasification of other petroleum and gaseous materials

	Mining of metals
24	Mining of uranium and thorium ores
25	Mining of iron ores
26	Mining of copper ores and concentrates
27	Mining of nickel ores and concentrates
28	Mining of aluminium ores and concentrates
29	Mining of precious metal ores and concentrates
30	Mining of lead, zinc and tin ores and concentrates
31	Mining of other non-ferrous metal ores and concentrates

	Quarrying
32	Quarrying of stone
33	Quarrying of sand and clay
34	Mining of chemical and fertilizer minerals, production of salt, other mining and quarrying n.e.c.

	Manufacturing
35	Processing of meat cattle
36	Processing of meat pigs
37	Processing of meat poultry
38	Production of meat products nec
39	Processing vegetable oils and fats
40	Processing of dairy products
41	Processed rice
42	Sugar refining
43	Processing of Food products nec
44	Manufacture of beverages
45	Manufacture of fish products
46	Manufacture of tobacco products
47	Manufacture of textiles

48	Manufacture of wearing apparel; dressing and dyeing of fur
49	Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear
50	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
51	Re-processing of secondary wood material into new wood material
52	Pulp
53	Re-processing of secondary paper into new pulp
54	Paper
55	Publishing, printing and reproduction of recorded media
70	Re-processing of ash into clinker
85	Manufacture of fabricated metal products, except machinery and equipment
86	Manufacture of machinery and equipment n.e.c.
87	Manufacture of office machinery and computers
88	Manufacture of electrical machinery and apparatus n.e.c.
89	Manufacture of radio, television and communication equipment and apparatus
90	Manufacture of medical, precision and optical instruments, watches and clocks
91	Manufacture of motor vehicles, trailers and semi-trailers
92	Manufacture of other transport equipment
93	Manufacture of furniture; manufacturing n.e.c.

Chemical Industries

58	Processing of nuclear fuel
59	Plastics, basic
60	Re-processing of secondary plastic into new plastic
61	N-fertiliser
62	P- and other fertiliser
63	Chemicals nec
64	Manufacture of rubber and plastic products

Material Processing

65	Manufacture of glass and glass products
66	Re-processing of secondary glass into new glass
67	Manufacture of ceramic goods
68	Manufacture of bricks, tiles and construction products, in baked clay
69	Manufacture of cement, lime and plaster
71	Manufacture of other non-metallic mineral products n.e.c.
72	Manufacture of basic iron and steel and of ferro-alloys and first products thereof
73	Re-processing of secondary steel into new steel

74	Precious metals production
75	Re-processing of secondary preciuos metals into new preciuos metals
76	Aluminium production
77	Re-processing of secondary aluminium into new aluminium
78	Lead, zinc and tin production
79	Re-processing of secondary lead into new lead
80	Copper production
81	Re-processing of secondary copper into new copper
82	Other non-ferrous metal production
83	Re-processing of secondary other non-ferrous metals into new other non-ferrous metals
84	Casting of metals

Construction

113	Construction
114	Re-processing of secondary construction material into aggregates

Services and Finance

111	Steam and hot water supply
112	Collection, purification and distribution of water
115	Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts and accessoiries
116	Retail sale of automotive fuel
117	Wholesale trade and commission trade, except of motor vehicles and motorcycles
118	Retail trade, except of motor vehicles and motorcycles; repair of personal and household goods
119	Hotels and restaurants
126	Supporting and auxiliary transport activities; activities of travel agencies
127	Post and telecommunications
128	Financial intermediation, except insurance and pension funding
129	Insurance and pension funding, except compulsory social security
130	Activities auxiliary to financial intermediation
131	Real estate activities
132	Renting of machinery and equipment without operator and of personal and household goods
133	Computer and related activities
134	Research and development
135	Other business activities
136	Public administration and defence; compulsory social security
137	Education
138	Health and social work
159	Activities of membership organisation n.e.c.

160	Recreational, cultural and sporting activities
161	Other service activities
162	Private households with employed persons
163	Extra-territorial organizations and bodies

	Transport
120	Transport via railways
121	Other land transport
122	Transport via pipelines
123	Sea and coastal water transport
124	Inland water transport
125	Air transport

	Biogas Production
17	Manure treatment (biogas), storage and land application
146	Biogasification of food waste, incl. land application
147	Biogasification of paper, incl. land application
148	Biogasification of sewage slugde, incl. land application

	Waste Management
94	Recycling of waste and scrap
95	Recycling of bottles by direct reuse
139	Incineration of waste: Food
140	Incineration of waste: Paper
141	Incineration of waste: Plastic
142	Incineration of waste: Metals and Inert materials
143	Incineration of waste: Textiles
144	Incineration of waste: Wood
145	Incineration of waste: Oil/Hazardous waste
149	Composting of food waste, incl. land application
150	Composting of paper and wood, incl. land application
151	Waste water treatment, food
152	Waste water treatment, other
153	Landfill of waste: Food
154	Landfill of waste: Paper
155	Landfill of waste: Plastic
156	Landfill of waste: Inert/metal/hazardous
157	Landfill of waste: Textiles
158	Landfill of waste: Wood

Appendix D

Taxes and Wages:

Code	Synonym	Name
w01	T_TLSA	Taxes less subsidies on products purchased: Total
w02	V_ONTP	Other net taxes on production
w03.a	V_WALS	Compensation of employees; wages, salaries, & employers social contributions: Low-skilled
w03.b	V_WAMS	Compensation of employees; wages, salaries, & employers social contributions: Medium-skilled
w03.c	V_WAHS	Compensation of employees; wages, salaries, & employers social contributions: High-skilled

Consumption of fixed capital:

Code	Synonym	Name
w04.a	V_COFC	Operating surplus: Consumption of fixed capital
w04.b	V_RENL	Operating surplus: Rents on land
w04.c	V_ROYR	Operating surplus: Royalties on resources
w04.d	V_NOPS	Operating surplus: Remaining net operating surplus

Employment:

Code	Synonym	Name
s01.a_m	E_NRLS_m	Employment: Low-skilled male
s01.a_f	E_NRLS_f	Employment: Low-skilled female
s01.b_m	E_NRMS_m	Employment: Medium-skilled male
s01.b_f	E_NRMS_f	Employment: Medium-skilled female
s01.c_m	E_NRHS_m	Employment: High-skilled male
s01.c_f	E_NRHS_f	Employment: High-skilled female

CO_2 emissions:

Code	Substance Synonym	Substance Name
124-38-9c	E_CO2_c	CO2 - combustion

Land Use:

Land Type Name
Cropland - Cereal grains nec
Cropland - Crops nec
Cropland - Fodder crops-Cattle
Cropland - Fodder crops-Meat animals nec

  Cropland - Fodder crops-Pigs
  Cropland - Fodder crops-Poultry
  Cropland - Fodder crops-Raw milk
  Cropland - Oil seeds
  Cropland - Paddy rice
  Cropland - Plant-based fibers
  Cropland - Sugar cane, sugar beet
  Cropland - Vegetables, fruit, nuts
  Cropland - Wheat
  Forest area - Forestry
  Other land Use: Total
  Permanent pastures - Grazing-Cattle
  Permanent pastures - Grazing-Meat animals nec
  Permanent pastures - Grazing-Raw milk
Infrastructure land
Forest area - Marginal use

Bauxite and aluminium, Copper and Iron ores:

Abbreviation	Physical Type Name
DEU_2.5	Domestic Extraction Used - Metal Ores - Bauxite and aluminium ores
DEU_2.3	Domestic Extraction Used - Metal Ores - Copper ores
DEU_2.2	Domestic Extraction Used - Metal Ores - Iron ores

Non-metallic minerals:

Abbreviation	Physical Type Name
DEU_3.6	Domestic Extraction Used - Non-Metallic Minerals - Building stones
DEU_3.1	Domestic Extraction Used - Non-Metallic Minerals - Chemical and fertilizer minerals
DEU_3.2	Domestic Extraction Used - Non-Metallic Minerals - Clays and kaolin
DEU_3.7	Domestic Extraction Used - Non-Metallic Minerals - Gravel and sand
DEU_3.3	Domestic Extraction Used - Non-Metallic Minerals - Limestone, gypsum, chalk, dolomite
DEU_3.8	Domestic Extraction Used - Non-Metallic Minerals - Other minerals
DEU_3.4	Domestic Extraction Used - Non-Metallic Minerals - Salt
DEU_3.5	Domestic Extraction Used - Non-Metallic Minerals - Slate

Water Consumption:

Abbreviation	Physical Type Name
WCB_1.1	Water Consumption Blue - Agriculture - rice
WCB_1.2	Water Consumption Blue - Agriculture - wheat

...	... [103 factors]
WCB_3.2.11	Water Consumption Blue- Electricity - once-through - Electricity by Geothermal
WCB_3.2.12	Water Consumption Blue- Electricity - once-through - Electricity nec

Coal, Natural Gas and Crude Oil:

Abbreviation	Physical Type Name
DEU_4.1	Domestic Extraction Used - Fossil Fuels - Coal
DEU_4.7	Domestic Extraction Used - Fossil Fuels - Crude oil
DEU_4.8	Domestic Extraction Used - Fossil Fuels - Natural gas