Analysis of the European energy system

under the aspects of flexibility and technological progress

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REflex

Analysis of the European Energy System

D6.3 Social, environmental and external cost assessment of future energy technologies and future energy systems

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EXECUTIVE SUMMARY

This report assesses the social and environmental impacts of EU energy systems according to the REFLEX energy scenarios (Herbst, Michaelis, Brown, Jakob, & Martino, 2017). It also quantifies some of the economic consequences of the environmental impacts.

The overall aim of the REFLEX project is to analyse and evaluate the development towards a low-carbon energy system with focus on flexibility options including power-to-X in the EU up to the year 2050 to support a better system integration of RES. In a first step towards achieving the project aim, two main scenarios up to 2050 were defined (Herbst et al., 2017). The first scenario, termed "Mod-RES" represents a reference scenario. The second, termed "High-RES" meanwhile represents an ambitious policy scenario aiming to limit global temperature rise due to anthropogenic climate change to 2 ^{o}C and depicts an aspiring decarbonisation roadmap for the EU until 2050. The High-RES scenario was further subdivided into a decentralised and a centralised scenario, called High-RES decentral and High-RES central respectively. The High-RES decentral scenario aimed to depict development based on a decentralised energy system, with a focus on e.g. roof-top solar. The High-RES central scenario focused on a centralised energy system, prioritising e.g. large-scale wind generation. Given the scenario definition, the next step in the project was to model the energy systems for the scenarios defined according to Herbst et al. (2017). This was done using a sectoral approach and included modelling electricity generation (with the energy systems model ELTRAMOD), and final energy demand in the transport sector (using the energy model ASTRA), the industry sector and residential and tertiary sectors (using the energy systems model Forecast).

However, as with energy systems models (ESM) in general, the models used in REFLEX (noted in the previous paragraph) do not aim to provide a comprehensive assessment of social and environmental impacts due to modelled energy systems. To fill this gap, the study reported here was carried out.

The study comprised a number of different approaches to social, environmental and economic impact assessment. Firstly, a life cycle approach was applied. The goal of the life cycle-based study was to analyse and compare environmental impacts, social risks and external costs due to life cycle-based environmental impacts related to the European energy systems developed in the REFLEX project in the base year (2014) and the year 2050 for the three envisaged REFLEX scenarios (i.e Mod-RES, High-RES central and High-RES decentral. Secondly, a spatially-disaggregated impact assessment was performed with the aim of estimating health impacts and external costs of direct emissions in the REFLEX scenarios.

In the life cycle-based assessment, it was intended to assess climate change and other relevant environmental impact categories, in particular those showing significant increases or decreases in the 2050 scenarios compared to the current situation using the ReCiPe midpoint life cycle impact assessment method. The life cycle-based social assessment considered five impact categories - child labour, forced labour, fair salary, health and safety and workers' rights – all related to the stakeholder group "workers". Social risk was then evaluated according to risk-weighted worker hours using the method developed for the product social impact life cycle assessment (PSILCA) and SOCA tools (Ciroth & Eisfeldt, 2016; Eisfeldt, 2017). It is assumed that process's social risk profiles do not change between the current case and the 2050 scenarios. This makes the results of the assessment easy to communicate and understand but is also a limitation. The external cost assessment of life cycle-based environmental impacts was performed with the EcoValue12 monetary weighting set (Finnveden, Håkansson, & Noring, 2013).

For life cycle inventory, a starting point for the social and environmental assessment was the output data from the REFLEX energy systems models, particularly data for electricity generation and energy demand in the transport sector, industry sector and residential and tertiary sectors. Figure 1 shows the electricity generation disaggregated by technology type for the four temporal cases considered, an output of ELTRAMOD, used as input for the life cycle-based assessment. For each relevant energy

carrier and scenario, environmental and social life cycle inventory was prepared on the basis of one unit of electricity production or energy demand. Inventory data was taken from a variety of sources, e.g. AEBIOM (2014); Agora Energiewende (2017); Arshi, Vahidi, and Zhao (2018); Eurostat (2019); Fraunhofer ISE (2015); Louwen, Krishnan, Derks, and Junginger (2018); REN21 (2017). Background data for life cycle inventory was used from the ecoinvent database (Wernet et al., 2016) and the SOCA add-on for social assessment (Eisfeldt, 2017). By combining the output of the REFLEX ESMs and environmental and social inventory so established, environmental impacts and social risks could be evaluated.

In the life cycle-based study, environmental impacts and social impacts were evaluated per unit energy demand in the industry sector, transport sector and residential and tertiary sector, and per unit electricity production in the electricity sector. For the sake of comparison, impacts in future scenarios were further normalised in comparison to the impacts in the base year (2014).

Meanwhile, for the spatial assessment of external costs, direct emissions for each scenario were evaluated using firstly the output of the REFLEX energy systems models. For each scenario the ambient concentration of air pollutants across Europe was calculated with the use of the modelling tool Polyphemus. The values used to monetize the external costs due to pollutant concentrations were based on the results of ExternE (Bickel & Friedrich, 2005).

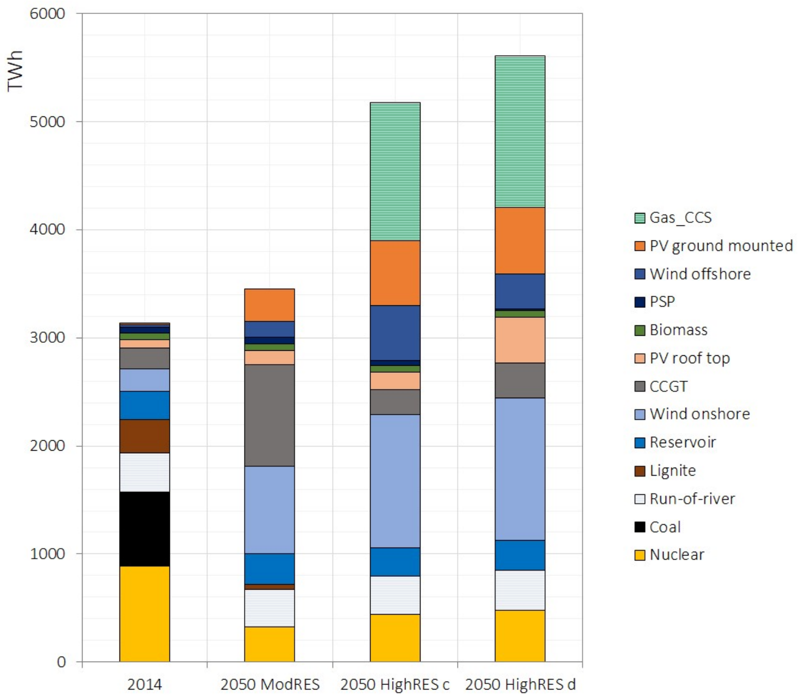

Figure 1: Gross electricity generation for the EU used as input data in this study, for the base year and the 2050 future scenarios.

The results for the life cycle-based social and environmental assessment are presented here for each sector separately, beginning with the electricity sector. As shown in Figure 2, social assessment with LCA showed that in the base year, coal, gas and nuclear fuel supply chains contribute significantly to social risk across all subcategories. Coal and nuclear power each contribute a large portion of total generation, as shown in Figure 1. However, gas has a relatively small proportion of total generation in the base year. In the current situation, wind power and solar photovoltaic (PV) also contribute to social risk, in spite of lower shares in the mix. A significant amount of social risk due to wind power arises due to the global supply chain for steel. Social risk due to solar PV arises to a great extent from the global supply chain and manufacture of solar panels themselves. However, in the health and safety subcategory, social risk due to wind and solar power arises due to onsite construction of the plant themselves. The normalised social risk for electricity generation generally increases in the future scenarios, partly because the number of worker hours increases. It also increases because of the increased proportion of gas-fired generation (with and without carbon dioxide capture and storage) used for EU electricity production. In particular, gas supply from Russia is shown to make a significant contribution to social risk in the subcategories fair salary and forced labour. Wind and solar power play a larger role in total generation in all future scenarios (see Figure 1) and consequently make a larger contribution to social risk in the subcategories as shown in Figure 2, though this is mitigated by assumed increases in worker productivity for these technologies between the base year and 2050. Social risk due to wind and solar power to a great extent arise due to the steel supply chain and the manufacturing of solar panels respectively.

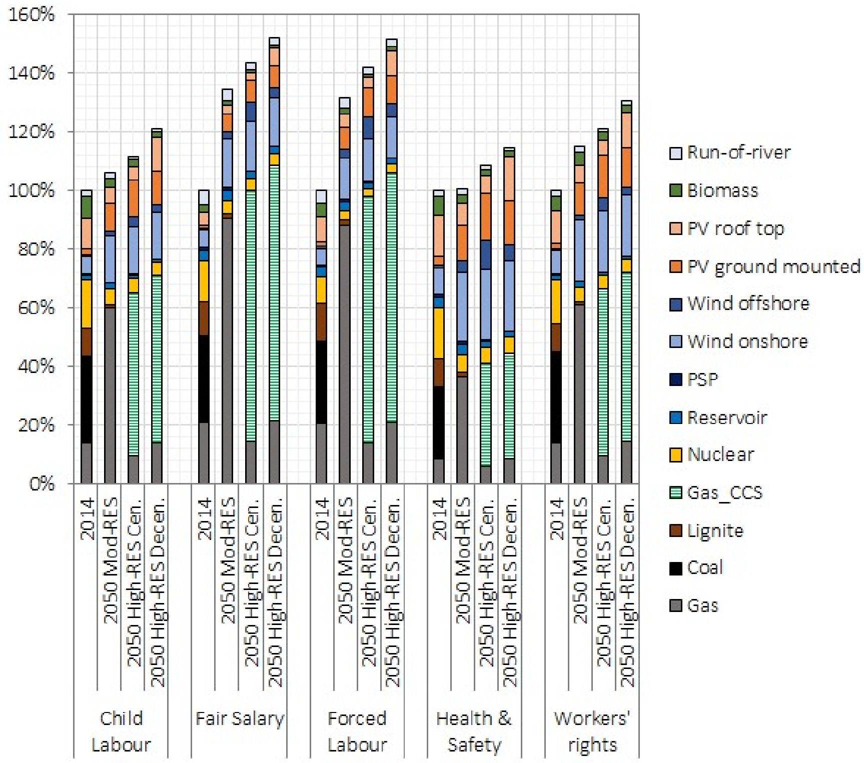

Figure 2: A normalised comparison of the weighted worker hours required to produce 1 kWh of European electricity in the current (2014) and the 2050 scenarios (i.e. Mod-RES, High-RES centralised and decentralised).

From an environmental perspective, climate change impacts due to electricity production reduce significantly; according to the aim of the scenarios (see Figure 3). In the Mod-RES this is principally due to the elimination of coal and lignite from electricity production and the increase in renewables. Further reduction is achieved in the High-RES scenarios through the widespread deployment of gas carbon capture and storage (CCS). Freshwater eutrophication is also shown to decrease significantly in all future scenarios. This is largely due to the elimination of lignite from the electricity mix in all scenarios compared to the current case. Agricultural land occupation is shown to decrease between the base year and 2050 due to a reduced demand for biomass. Meanwhile, particulate matter formation remains relatively constant between the base year and future scenarios. This is because whilst particulate matter related emissions due to coal and lignite combustion decrease between the base year and 2050, relevant emissions due to the natural gas supply chain and the manufacture of wind and solar plant increase over the same period, causing impacts in the category to remain constant. As further shown in

Figure 3, metal depletion impacts increase significantly between the base year and 2050. This is due to increased demand for wind and solar plant, both of which are relatively metal intensive, unless high recycling rates are assumed.

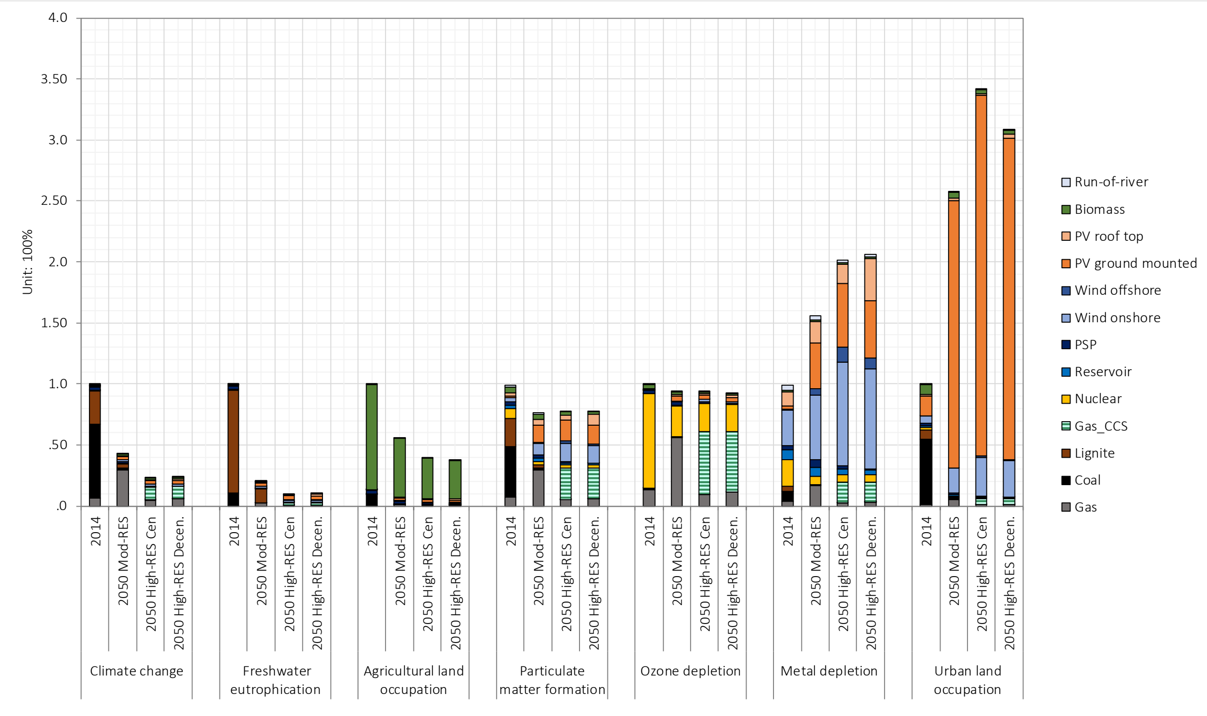

Figure 3: The normalised environmental impacts for 1 kWh of European electricity generation for Mod-RES and both High-RES centralised and decentralised 2050 compared to the base year.

Social risk due to energy demand in the transport sector does not change significantly in the impact categories considered between the current case and Mod-RES. This is largely due to continued high demand for fossil liquids in the Mod-RES. However, social risk is shown to increase for the categories forced labour, fair salary and workers' rights for the High-RES compared to the current case. Decreased demand for fossil fuels and increased demand for electricity between the base year and 2050 have the effect of reducing risk in these categories. However, the increased demand for hydrogen and biofuels over the same period cause risks to rise overall in the categories. Risk decreases however in the health and safety subcategory due to the decreased demand for fossil fuels between the base year and the future scenarios. In order to avoid double counting of direct emissions, the environmental assessment in transport considered only impacts from upstream processes. Since future scenarios for transport consider greater shares of electricity and biofuels, all environmental impacts considered (climate change, freshwater eutrophication, particulate matter, ozone depletion, metal depletion and urban land occupation) increase, significantly so in the case of the High-RES.

From a social perspective social risks change very little between the current case and future cases in the industry sector. This is because risks arising in supply chains for fuel oil, gas and electricity in the current case are variously replaced by risk due to electricity supply and gas supply in all future cases. Again, to avoid double counting only upstream impacts are considered in the environmental assessment of the industry sector. There is a notable decrease in upstream impacts for climate change (up to 50 %) but a large increase in metal depletion. This is largely due to the increased demand for electricity in the sector, unless high recycling rates are assumed.

Social risks in the residential and tertiary sectors decrease in the High-RES compared to the current case. This is because of the increased significance of energy carriers of lower risk in the High-RES compared to the Mod-RES, in particular EU-produced solid biomass and ambient heat. Finally, the upstream assessment of environmental impacts in the residential and tertiary sectors notably found a decrease in climate change related impacts, but an increase in metal depletion related impacts.

The calculation of external cost based on the environmental impacts assessed by the LCA study showed that external costs are of a similar order of magnitude to indicative production costs considered for all sectors. Total external costs for average environmental damage values decreased for the electricity sector and the residential and tertiary sectors, remained the same for the industrial sector and increased slightly for the transport sector between the base year and the future scenarios. It should be noted that for the end use sectors, only upstream environmental impacts were considered. By considering impacts from final combustion in the end use sectors it is likely that external costs will be much higher for all scenarios, but less for High-RES scenarios than for Mod-RES or the base year. The external cost assessment for electricity supports the assertion that the transition to an electricity production system with low carbon dioxide emissions is profitable from a societal perspective.

In the spatial assessment, it was shown that health impacts and spatially disaggregated external costs were similar in 2050 scenarios as for the current case. This was considered to be due to the fact that the concentration of particulate matter changed little between the current case and future scenarios. This is because while emissions from the combustion of fossil fuels decreased between 2014 and 2050 according to the scenarios, emissions due to biomass combustion (particularly to provide district heating) increased over the same period.

According to the REFLEX scenarios, electricity becomes an even more important energy carrier in the future compared to today. It also becomes more significant for environmental impacts and social risks. The life cycle-based social assessment demonstrated that gas supply from Russia in future scenarios can lead to increased risk in particular for (lack of) fair salary and for forced labour (in the form of risk for trafficking in persons). It was also shown that the steel production supply chain is important when assessing social risk for wind power and that the production of solar panels themselves is important when considering social risk due to solar photovoltaics. From an environmental perspective it was shown that along with significant reductions in global warming potential through 2050, electricity production in the scenarios with low greenhouse gas (GHG) emissions can also reduce freshwater eutrophication and agricultural land occupation. Meanwhile, environmental impacts increased for electricity production in 2050 compared to the base year for in particular metal depletion, due to increased demand for wind and solar power. Beyond this work it is further interesting to explore different perspectives for the development of new technologies, especially for wind and solar power that are shown to be very important for energy systems with low GHG emissions. This work is also interesting as an application of the SOCA add-on for social assessment. It was shown that with the tool, areas could be identified particularly in the electricity production system where noticeable improvements in social performance can be achieved. To facilitate future studies with the tool, development should be directed towards making it easier to define the geographical location of key processes.

It should be noted that the analysis and the results in this study are highly dependent on the assumptions made when developing the methodology, and the sources used to support the assumptions. A different result might be achieved if different assumptions are made. However, as the objective of this work is to provide comparative results for different scenarios, the consistent assumptions seem reasonable and sufficient to fulfil the objective. Nevertheless, exemplary cases of sensitivity analysis are performed aiming to give insight for addressing potential uncertainties.

LIST OF ABBREVIATIONS

AS – asynchronous generator

AU – Australia (used in names of ecoinvent processes)

CB – chronic bronchitis

CCGT – Combined cycle gas turbine

CH – Switzerland (used in names for ecoinvent processes)

CRF – concentrated response function

CSS – country specific sector

CCS – carbon capture and storage

DE – Germany (used in names for ecoinvent processes)

DZ – Algeria (used in names for ecoinvent processes)

E-DD – electrically excited direct drive (a type of synchronous generator)

eLCA – environmental life cycle assessment

EMEP – European monitoring and evaluation program

ENTSO-E - European Network of Transmission System Operators for Electricity

ESM – energy systems model

FR – France (used in names for ecoinvent processes)

GB – Great Britain (used in names for ecoinvent processes)

GHG – greenhouse gas

GLO – global (used in names for ecoinvent processes)

HTS – high temperature superconductor generator

ISIC - International Standard Industrial Classification

ISO – International Organization for Standardization

LCA – life cycle assessment

LCI – life cycle inventory

LCIA – life cycle impact assessment

NG – Nigeria (used in names for ecoinvent processes)

NMVOC – non-methane volatile organic compound

NO – Norway (used in names for ecoinvent processes)

NOx – Oxides of Nitrogen

PL – Poland (used in names for ecoinvent processes)

PM – particulate matter or permanent magnet

PMG – permanent magnet generator

PSILCA – product social impact life cycle assessment

PSP – pumped storage plan

PV – photovoltaic (solar)

RAD – restricted activity days

RAF – Africa (used in names for ecoinvent processes)

Res – reservoir

RES – renewable energy source

RLA – Latin America (used in names for ecoinvent processes)

RME – Middle East (used in names for ecoinvent processes)

RoR – run of river

RoW – rest of world (used in names for ecoinvent processes)

RU – Russia (used in names for ecoinvent processes)

SNAP – Selected Nomenclature for sources of air pollution

SOCA – add-on for ecoinvent to facilitate social assessment

sLCA - social life cycle assessment

sLCI – social life cycle inventory

SG - synchronous generators

USD – United States Dollar

UVB – ultraviolet B

VOC – volatile organic compound

WEU – Western Europe (used in names for ecoinvent processes)

wh – worker hour

YOLL – years of life lost

ZA – South Africa (used in names for ecoinvent processes)

1 INTRODUCTION AND AIM

In order to meet the challenge of climate change mitigation, greenhouse gas (GHG) emissions will need to be reduced significantly in the coming decades (Pachauri et al., 2014). In order to achieve this positive outcome, the way that energy services are provided will further need to be changed significantly in light of the fact that the global energy system is one of the greatest current contributors to GHG emissions.

EU energy policy acknowledges the significance of the need to transition to a low carbon energy system through the three pillars of its energy policy – security of supply, competitiveness and sustainability (European Commission, 2016a). The EU further recognizes that to achieve the desired energy transition, technological innovation has a significant role to play. To this end, the long-term Integrated Strategic Energy Technology (SET) Plan (European Commission, 2016b) further identifies for example renewable energy generation (such as efficiency and power capacities), energy storage (e.g. as thermal energy or as stationary or vehicle batteries), e-mobility and Information Technology-linked 'smart' solutions as areas where innovation can make a key contribution to climate change mitigation.

In light of the well-appreciated need for energy system transition and the acknowledgement of the significant role that technological development could play in a successful transition, there is nevertheless significant uncertainty about the future development that will take place.

One approach to develop an overall understanding of the mix of technologies and system development needed to significantly contribute to climate change mitigation in the energy sector is scenario-based energy systems modelling (E3MLab, 2016; Fichtner et al., 2013; Fragkos, Tasios, Paroussos, Capros, & Tsani, 2017; Herbst, Toro, Reitze, & Jochem, 2012; IEA/OECD, 2016; Schade et al., 2010). The EU also engages in this, for example directly through developing and evaluating reference scenarios for development of the EU energy system with the PRIMES model (Capros et al., 2016). Another avenue for such modelling with an EU perspective is the Horizon 2020 research program. This report is written as a deliverable in the Horizon 2020 project REFLEX. The overall aim of the REFLEX project is to analyse and evaluate the development towards a low-carbon energy system with focus on flexibility options including power-to-X options in the EU up to the year 2050 to support a better system integration of RES.

1.1 THE REFLEX SCENARIOS

In a first step towards achieving the project aim, two main scenarios up to 2050 were defined (Herbst et al., 2017). The first scenario, termed "Mod-RES" represents a reference scenario. The second, termed "High-RES" meanwhile represents an ambitious policy scenario. Both scenarios assume the same projection for population and economic growth. Beyond that, Mod-RES assumes recent technological projections and moderate integration of renewable energy sources (RES) in the EU. It assumes the continuation of existing policies through 2050, and that no new policy measures are introduced in the system besides those already decided or implemented. The scenario description for the Mod-RES also includes a qualitative description of societal development from a socio-technical perspective, considering such aspects as institutional and political frameworks, value systems in general and technological innovation. In this respect, the Mod-RES is also depicted as a continuation of current trends, and is based on the "Market First" scenario as described in the GEO4 (UNEP, 2007).

Meanwhile a specific target of High-RES is to limit global temperature rise to 2 ^{o}C and depicts an aspiring decarbonisation roadmap for the EU until 2050. The scenario includes stringent CO_2 regulation, higher energy prices and other ambitious climate policies. Major change drivers in the scenario are increased fuel efficiency, high RES integration, improved demand side management and high concentration of low-carbon vehicles with improved powertrain efficiency and lightweight components (Herbst et al., 2017). The High-RES scenario is further subdivided into a High-RES decentral scenario and High-RES central scenario. The aim of this subdivision is to highlight the potential difference in energy system development up to 2050 with a centralized electricity production system (similar to the current system) compared with a system including a greater proportion of decentralized generation (e.g. a greater proportion of rooftop solar). As with Mod-RES, both High-RES sub-scenarios consider sociotechnical developments up to 2050. For both High-RES sub-scenarios this description is based on the GEO-4 scenario “Policy First” (UNEP, 2007). A key background descriptor for the sociotechnical description for High-RES is that global governments become sufficiently aware of the myriad social and environmental challenges facing society to implement policy to yield improvements in these areas. This sociotechnical description therefore differs from the Mod-RES in so far as there is envisaged to be an increased role for government in general, and cooperation on environmental and social issues.

1.2 Scenario-based energy modelling in REFLEX

After defining the scenarios to be considered in the project, energy systems arising in these scenarios were modelled. This was done with models developed by members of the REFLEX consortium. Electricity production was modelled using the ELTRAMOD model (by the Technical University of Dresden). The transport sector was modelled using ASTRA (by TRT Trasporti e Territorio and Fraunhofer ISI in collaboration). Energy demand of the other end use sectors was modelled with the model Forecast (by Fraunhofer ISI).

1.3 Assessing social and environmental impacts and external costs in REFLEX

Energy systems models do not generally include a systematic approach for environmental and social assessment of results. Further, with the exception of the economic cost of direct carbon dioxide emissions arising from combustion, the economic costs of emissions to the environment (e.g. oxides of sulphur and of nitrogen) arising from the energy system are typically not considered in such models either.

Considering the models used in the REFLEX project (see section 1.2) more specifically, ASTRA certainly includes social and socio-economic considerations, assessing such parameters as accident rates, accessibility, transport expenditures (for different income groups, external costs associated with CO_2 emissions and non- CO_2 emissions (i.e NOx, VOC, CO and PM2.5). Having said that, none of the other models consider social or environmental impacts for the systems modelled. Neither do any of the energy systems models consider potential social and environmental impacts arising from the supply chain for the energy systems considered.

The broad goal addressed by the work reported here is to assess the social, environmental and external economic costs arising from the energy systems projected in the REFLEX scenarios.

To this end, a specific assessment of environmental impacts, potential social risks and external environmental costs arising for the energy systems modelled in the REFLEX project has been performed. In order to carry out this work, a literature review was performed and a qualitative framework was developed, see (Brown, Ekener, Fuss, & Xu, 2017). With the support of this framework, the life cycle-based assessment recorded in this report was carried out. Beyond the life cycle based social and environmental assessment, external environmental costs were evaluated according to two complementary methodologies. On the one hand, the external environmental cost arising according to life cycle-based monetary weighting tool EcoValue12 was evaluated (Finnveden et al., 2013). In a second instance, spatially-resolved external environmental costs due to air emissions were evaluated according to the method described in subsequent sections.

2 Methods: LCA-based approach for social and environmental assessment

The LCA-based assessment is taken as a starting point for the methodological framework, “REFLEX SELES” (SELES - Social Environmental Life cycle Energy System) established and presented in the Deliverable 6.1 (Brown et al., 2017) which is itself based on ISO 14040/14044. Figure 4 summarises the framework.

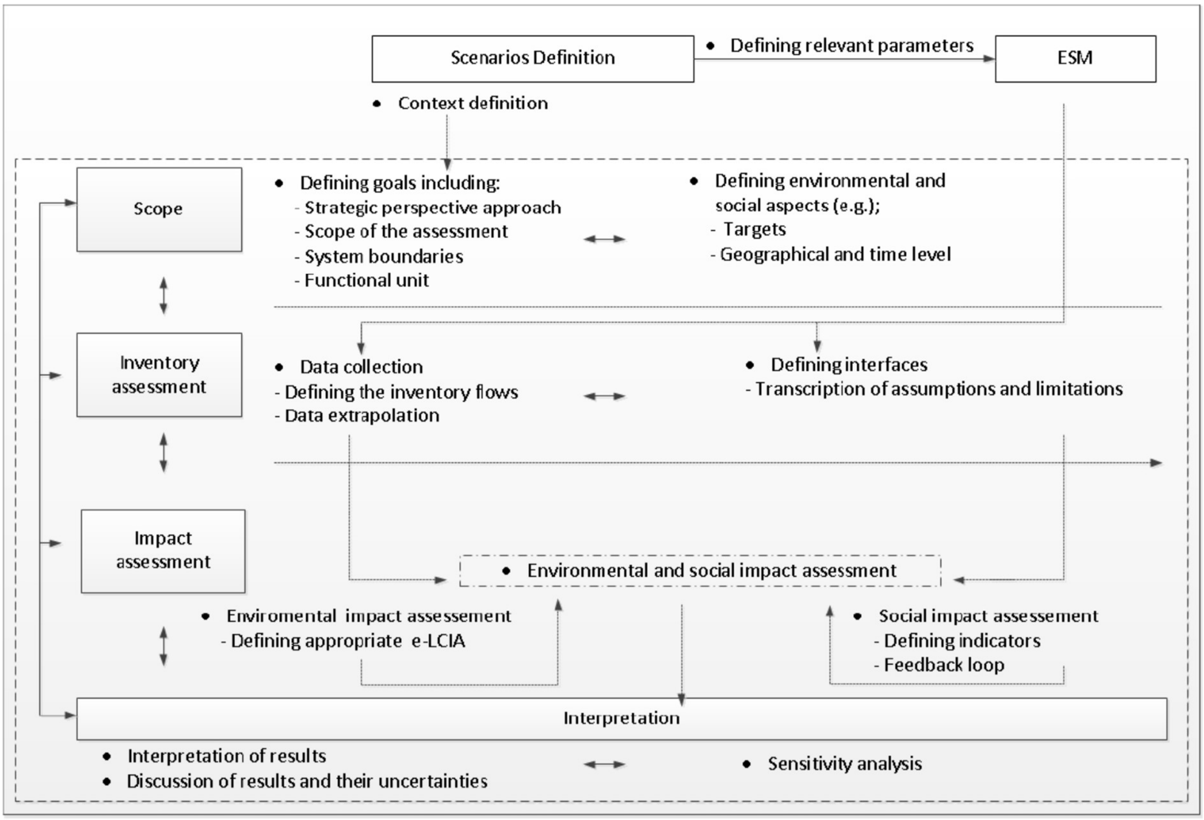

Figure 4: REFLEX SELES method for comparing future energy systems from a life cycle perspective

Considering Figure 4, an assessment carried out according to the framework shown in Figure 4 starts with defining scenarios, as performed in REFLEX according to Herbst et al. (2017). As also shown in the figure, the scenario definition is used for input to energy systems models first, which subsequently provides input for the assessment. Given the input from the energy systems models, the assessment largely follows the steps outlined in the ISO standard for LCA. The scope of the work is first defined in light of the contents of the scenario definition, including the system boundary, functional unit and geographical and temporal scope. In light of this, life cycle inventory (LCI) necessary to fulfil the goal of the assessment is collected, after which life cycle impact assessment is performed. Finally, the outcome of the assessment is interpreted and discussed, and where relevant, sensitivity analyses are performed.

2.1 Goal of LCA-based assessment

The goal of the study is to apply the LCA methodological framework with the objective to analyse and compare environmental and social risks related to the European energy systems developed in the REFLEX project in the base year (2014) and the three envisaged scenarios for 2050. Explicitly this gives four temporal cases to analyse and compare:

The EU energy system in the base year (2014)

The EU energy system in the Mod-RES scenario (2050)

The EU energy system in the High-RES (centralized) scenario (2050)

The EU energy system in the High-RES (decentralized) scenario (2050)

By relating the goal of the study with the REFLEX scenarios, this provides the “scenario definition” as defined according to REFLEX SELES and shown at the top of Figure 4, see also (Herbst et al., 2017) for a full description of the scenarios.

The study is performed in order to provide policy makers, energy industry stakeholders, non-governmental organizations and the public at large with knowledge on potential environmental impacts and social risks for decision making about future energy systems on an EU level.

In this study it is intended to compare the energy system in each of the temporal cases considered with the other, and to compare the potential impacts and risks from each of the end-use sectors in the energy system that are considered.

SED ASSESSMENT

2.2.1 PRODUCT SYSTEM AND FUNCTIONAL UNITS

The product system to be studied is the energy system of the EU28+Norway and Switzerland according to the system boundary described below.

The energy system is further divided into subsectors - the electricity sector (the only specific energy supply and transformation sector considered in the study) and three end use sectors, namely transport, industry and residential & tertiary (the final two are considered as one sector in the assessment). In doing so the assessment reflects the sectoral disaggregation used in the EU’s own energy systems modelling (see the reference scenario, (Capros et al., 2016)) as well as the disaggregation apparent in the energy systems modelling approach in the REFLEX assessment itself. Therefore, this disaggregation follows the principle of establishing the connection with the REFLEX energy systems models as shown in Figure 4.

The functional unit considered in the study is that of the provision of the energy services over the time period of a year. Specifically in the assessment, the following functional units are defined for each sector:

The electricity sector: 1 kWh electricity production in electricity generation plants;

The end-use sectors: 1 kWh supply of final energy carriers (heat production, electricity and fuel supply) from plants used in production of energy carriers.

Given the breakdown into four subsectors described in previous paragraphs, and the four temporal cases considered, this gives a total of 16 separate combinations of temporal cases and subsectors to consider and compare.

2.2.2 SYSTEM BOUNDARIES

System boundaries are established for each specific sub-sector in the energy system. For the electricity sector, the boundary is drawn to consider processes from raw material production and extraction from the biosphere up to and including the production of electricity.

For the transport sector, the system boundary is drawn in order to cover processes from raw material extraction up to and including the delivery of final energy carriers in the form of electricity and fuels. Impacts arising from final transformation in the transport sector are considered in the REFLEX energy systems model used for the transport sector (ASTRA) and are not considered in the environmental or social assessment. The implications of these assumptions are considered in the interpretation of results.

For the industry and residential & tertiary sectors *from a social perspective*, the system boundary is established in order to cover processes from raw material extraction up to and including the delivery of heat and electricity in the sector. This is considered relevant since the final conversion to heat is considered to be part of the energy sector. However, the system boundary from an environmental perspective is established slightly differently in so far as to cover only the delivery of energy carriers in the form of electricity and fuels. This is considered relevant from an environmental perspective since environmental impacts arising from final conversion in these sectors is calculated in the relevant REFLEX energy systems model, i.e. Forecast. Again, the implications of these assumptions are addressed in the discussion and interpretation of results.

For capital goods, only dismantling, demolition and disposal are considered for the end-of-life stage. Therefore, no credits are considered for any potential recycling of capital materials.

2.2.3 Geographical scope

The geographical scope is also very important for the environment and social assessment. A general summary of the starting point for how geographical provenance is considered in the assessment is presented in Table 1 below. More specific assumptions about geographical location of specific processes in the assessment are presented in the section specifically describing life cycle inventory on a process level below. Generally it has been intended firstly to ensure that geographic locations are assigned for the origin of materials, fuels and components used in the energy systems considered. It is further prioritised from a social perspective to ensure that processes for final plant construction and operation are representative of European conditions in all temporal cases considered (see "Operation" in Table 1 below). In light of the global nature of supply chains for such components as steel, concrete and even photovoltaic plant (i.e. "Production", see Table 1), it was further considered for this initial assessment to assume that background data sources with a global scope are adequately representative unless otherwise stated. The implications of these assumptions are further reflected upon in the discussion section of this report.

Table 1: Standard Assumptions regarding resource and energy sources

	Production	Construction	Operation	Disposal
Assumptions	Global market	European Market	European Market	European Market

2.2.4 General considerations for quantitative modelling

Figure 5 shows that the life cycle-based social and environmental assessment for a given temporal case uses two key input datasets. The first key dataset is the output data from the REFLEX energy systems models (box 1, Figure 5), see also Table 2. Each of the models produces data for a particular part of the energy system, as shown in Table 2 below. As shown in Figure 5, the output of the models is aggregated for the entire EU28+2, and disaggregated by production technology for the electricity sector and by final energy carrier for the final demand sectors.

The second key dataset (box 2, Figure 5) is life cycle inventory for each electricity production technology and each end-use energy carrier for the final demand sectors, for which separate inventories are established for the reference flow of a unit of delivered energy (e.g. 1 kWh). Inventory data so produced is then used as an input to calculate a social and environmental impact profile for each electricity production technology and final demand energy carrier for the relevant reference flow (box 3, Figure 5).

Finally, the total environmental and social impact for the energy system for a given temporal case (as shown in box 4, Figure 5) is calculated simply by multiplying the specific impact for the reference flow shown in box 3 in Figure 5 with the energy systems models data shown in box 1, Figure 5. For example, if the global warming potential (GWP) due to the production of 1 kWh of wind power is X kg CO_2-e, and Y kWh of wind power are produced in a certain scenario, then the total GWP due to wind power, Z kg CO_2-e in the scenario is given by the equation:

$$Z = Y \cdot X$$

Equation 1

Table 2: REFLEX energy systems models used to model energy system subsectors

Energy system subsector	REFLEX energy systems model
Electricity production	ELTRAMOD
Transport	ASTRA
Residential and tertiary	Forecast
Industry	Forecast

The primary foreground LCI data in the study are quantities of energy products and energy transformation technologies required in the energy systems on a European level (i.e. box 1, Figure 5). These data are unique to the study and are acquired from the REFLEX energy system models, as shown in Table 2. According to the REFLEX SELES framework, assumptions about future developments in producing inventory for future scenarios should be categorised according to their respective view of the future. In this light, the Mod-RES scenario and data used to calculate the data in the REFLEX models are largely predictive forecasts (see also Borjeson, Hojer, Dreborg, Ekvall, & Finnveden, 2006 for a broad scenario typology). Data for the High-RES scenarios are also predictive to a great extent (i.e. established to answer the question “what will happen?”), though also aim to explore the potential outcomes of a more ambitious policy environment with respect to e.g. energy efficiency and CO_2 prices.

A starting point for background data used in the study for environmental LCI is the ecoinvent 3 database (Treyer & Bauer, 2016). Ecoinvent 3 is also the starting point for background data for the social LCI, in this case using the SOCA add-on for ecoinvent (Eisfeldt, 2017). The view of the future applied when developing social or environmental inventories for each specific technology considered in the assessment varies from technology to technology (see the detailed description of life cycle inventory below). Nevertheless, the general approach applied for the assessment is that a focus for developing future inventory has been firstly on the electricity sector, and within that on technologies that are known to be important in transforming to a low carbon system and for which significant development is expected in the coming decades. Based on these considerations, there has been a focus in the work on developing inventory for wind power, solar photovoltaic and carbon capture and storage technology. Novel processes have also been considered for hydrogen production by electrolysis and for certain biofuels in the transport sector. For such technologies, a technical potential view of the future was applied. For other technologies less significant for decarbonisation, a technologically preserving view was applied, by using inventory for the current situation to model systems in the future. This allowed for an assessment capable of incorporating all of the technologies required in the future European energy system. The implications of these assumptions are further taken up in the discussion of the report.

To a great extent, material life cycle inventory used for environmental and social assessment in the work is identical, largely thanks to using the SOCA add-on for ecoinvent (Eisfeldt, 2017). However on a few occasions, it was necessary to use a simpler material inventory for social assessment as compared to the environmental assessment. This was considered feasible in light of a brief analysis that showed that the small differences in material inventory would not cause significant changes in social risk.

Considering specifically inventory for *social risk* (for a general description of this, see later in this section), a preserving view of the future has been applied where it is assumed that future processes have the same social risk profile as their current counterparts. This is not to say that this is intended as a prediction of what social risks will be in 2050, rather it is an assumption that allows us to answer in a clear and consistent way the question of what social risks might occur in a future energy systems with different technology mixes. Specifically, the assessment analyses the extent to which the transition to a low carbon energy system may contribute to changes in social risk in the supply chain. By so doing, the assessment identifies potential social risks and the possibility to pre-emptively address those areas identified by the assessment to be particularly significant from a social risk perspective.

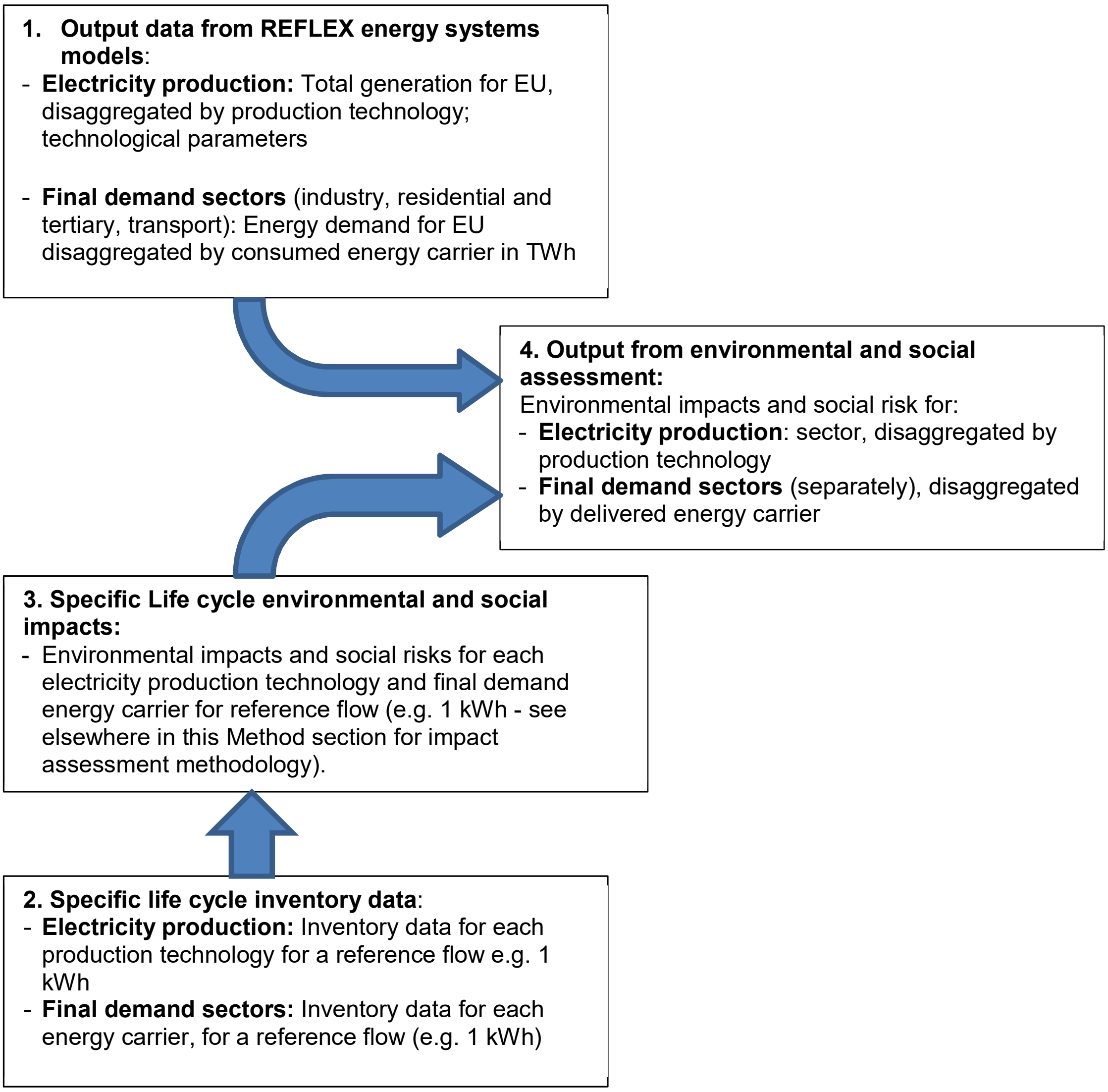

Figure 5: Schematic summary of the calculation method of the life cycle-based social and environmental impacts for REFLEX energy systems. The schematic summarises the procedure applied for each temporal case. As described elsewhere, for temporal cases are considered – the current case (2014), 2050 Mod-RES, 2050 High-RES central and 2050 High-RES decentral. The arrows indicate the the connections between the different types of data used in the assessment.

2.2.4.1 The SOCA add-on for social assessment

The SOCA add-on was used as a starting point for modelling social impacts in this study (Eisfeldt, 2017). This was because of the following considerations. Firstly, the add-on is based on the ecoinvent unit database v3 (ibid.). Therefore, SOCA builds on the broad process coverage of ecoinvent, which is an advantage for this study in light of the scale of the entire EU energy system that is being assessed here. Secondly, SOCA offers the possibility to perform social assessment in light of the stakeholder categories and impacts according to the PSILCA (product social impact life cycle assessment) database (Ciroth & Eisfeldt, 2016), which in turn is based on an approach recommended in UNEP's (United Nations Environment Program) guidelines for social life cycle assessment (sLCA) (UNEP, 2009). Therefore, SOCA facilitates an assessment coordinated with key institutions responsible for developing the sLCA method, which is also valuable for reporting the results of this study to EU decision makers. Thirdly, by relating to PSILCA, SOCA also evaluates social performance based on transparent data sources (Ciroth & Eisfeldt, 2016). Finally, SOCA allows for an activity variable-based approach for social assessment considered appropriate for a system as broad as the EU's energy system (Eisfeldt, 2017). As a highly innovative methodological approach yet to be used in practice to any great extent, the main features of the SOCA add-on are summarized in subsequent sections.

2.2.4.2 Activity variables and social risk profiles for ecoinvent processes according to the SOCA add-on

There are two main steps by which SOCA connects social performance data from the PSILCA database with ecoinvent. In a first step, each unit process in ecoinvent is mapped to a certain country specific sector (CSS) in PSILCA. This is possible in light of the fact that ecoinvent unit processes are already assigned a geographical scope and are allocated to sectors according to the International Standard Industrial Classification (ISIC) (United Nations, 2008). PSILCA meanwhile uses CSS based on the EORA database (Ciroth & Eisfeldt, 2016). Since PSILCA connects each CSS with a certain specific risk profile (see text below), the new connection with PSILCA allows each ecoinvent unit process to also be allocated a social risk profile.

In a second step, an activity variable (in worker hours) for each ecoinvent unit process is calculated. Again, this procedure is based on that used in PSILCA, as described further below. According to the PSILCA methodology for establishing an activity variable for social life cycle assessment, the so-called "unit labour cost" for a given CSS is calculated according to:

$$\boldsymbol{unit\ labour\ cost\ in\ CSS} = \frac{\boldsymbol{total\ employee\ compensation\ in\ CSS}}{\boldsymbol{Gross\ output\ in\ CSS}}$$

Equation 2

As made clear in Equation 2 the unit labour cost in a CSS is simply the proportion of total output (in monetary terms) that is made up of labour cost. Both of the terms on the right hand side of Equation 2 are calculated in PSILCA, using CSS disaggregation according to the EORA database. As a ratio between two parameters both of which are expressed in monetary terms, the unit labour cost is dimensionless. The total worker hours for a given unit of output can then be calculated according to the following equation:

$$worker\ hours\ (wh)\ per\ unit\ output\ for\ given\ CSS = \frac{unit\ labour\ cost\ in\ CSS}{mean\ hourly\ labour\ cost\ in\ CSS}$$

Equation 3

Where "unit labour cost in CSS" is calculated according to Equation 2. "Mean hourly labour cost in CSS" is another parameter established in the PSILCA database in USD/worker hour (wh) The term on the left hand side of Equation 3 therefore has units of wh/USD. Finally, the worker hours necessary to perform a given unit process in ecoinvent is calculated according to Equation 3:

$$\begin{aligned} &wh\ for\ ecoinvent\ process \\ &\quad = (worker\ hours\ per\ unit\ output\ for\ given\ CSS) \\ &\quad \times (cost\ of\ ecoinvent\ unit\ process's\ output) \end{aligned}$$

Equation 4

Where "worker hours per unit output for given CSS" is given by Equation 3. The term "cost of ecoinvent unit process's output" is taken from the recent versions of the ecoinvent database (Wernet et al., 2016) which is given in Euro. Therefore a USD to Euro conversion is also necessary in the assessment. Note that in order to perform the calculation shown in Equation 4, the CSS according to the ecoinvent disaggregation scheme has to have been mapped to the country specific sector according to the PSILCA disaggregation scheme (see description of this procedure earlier in this section).

2.2.4.3 Social risk profiles according to the SOCA add-on

The social risk profiles used by the SOCA add-on are based on those established in the first version of the PSILCA database (Ciroth & Eisfeldt, 2016), using stakeholder categories and indicators recommended by the UNEP guidelines for sLCA (UNEP, 2009). These are shown in Table 3 and Table 4 below.

Finally, the risk score of a given process is multiplied by the activity variable for that process (in work hours) to yield an overall quantitative measure of risk for a given indicator and process. In light of the exponential risk scoring approach shown in Table 5, risk quantification in this way is heavily weighted towards picking out processes with very high risk. Therefore, it is apt for identifying amongst coupled processes those processes that represent “hotspots” for social risk, and a useful tool for assessing social risk in the EU energy system.

Using social performance data from PSILCA is a positive feature for SOCA. By so doing, social performance data for ecoinvent unit processes are presented in SOCA for each of the indicators shown in Table 3 and Table 4. It is further important that data sources are transparently documented, and include amongst others International Labour Organization (2012), World Health Organization (2009), Transparency International (2012) and World Bank (2014) and data from similar organizations.

For each indicator shown in Table 3 and Table 4, reference performance levels are established and calibrated to qualitative risk levels (varying between no risk up to high risk). For explicatory purposes, the risk assessment scale for the indicator “DALYs due to indoor and outdoor air and water pollution” are shown in Table 5 below. Table 5 also shows that each qualitative risk level is assigned a risk score. Risk scores vary exponentially between “very low risk” (a score of 0.01) and “very high risk” (a score of 100).

Finally, the risk score of a given process is multiplied by the total number of worker hours for that process (the activity variable) to yield an overall quantitative measure of risk for a given indicator and process. This gives a total number of so-called “risk-assessed worker hours” by which to quantitatively compare risk levels between different processes. In light of the exponential risk scoring approach shown in Table 5, risk quantification in this way is heavily weighted towards picking out processes with very high risk. Therefore, it is apt for identifying amongst coupled processes those processes that represent “hotspots” for social risk, and a useful tool for assessing social risk in the EU energy system.

Table 3: Subcategories, indicators and their units of measurement as used in the SOCA add-on for the stakeholder "workers"

Stakeholder	Subcategory	Indicator name	Unit of measurement
Workers	Association and bargaining rights	Right of Association	Ordinal 0 - 3
		Right of Collective bargaining	Ordinal 0 - 3
		Right to Strike	Ordinal 0 - 3
	Child Labour, female	Child Labour, female	% of female children ages 7-14
	Child Labour, male	Child Labour, male	% of male children ages 7-14
	Child Labour, total	Child Labour, total	% of children ages 7-14
	DALYs due to indoor and outdoor air and water pollution	DALYs due to indoor and outdoor air and water pollution	DALYs per 1000 inhabitants in the country
	Fair Salary	Living wage, per month	USD/month
		Minimum wage, per month	USD/month
		Sector average wage, per month	USD/month
	Fatal accidents	Fatal accidents	#/year and 100k employees
	Frequency of forced	Frequency of forced labour	Cases per 1000 inhabitants in
	Gender wage gap	Gender wage gap	%
	Goods produced by forced labour	Goods produced by forced labour	Number of goods in sector
	Non-fatal accidents	Non-fatal accidents	#/year and 100k employees
	Safety measures	Safety measures	#/100k employees
	Social security	Social security expenditures	% of GDP
	Trade unionism	Trade union density	% workers in trade union
	Trafficking in persons	Trafficking in persons	Tier of activity according to
	Violations of employment laws and regulations	Violations of employment laws and regulations	# per 1000 employees
	Weekly hours of work per employee	Weekly hours of work per employee	h
	Workers affected by natural disasters	Workers affected by natural disasters	%

Table 4: Subcategories, indicators and their units of measurement as used in the SOCA add-on for all stakeholders other than "workers"

Stakeholder	Subcategory	Indicator name	Unit of measurement
Value chain actors	Anti-competitive behaviour or violation of anti-trust and monopoly legislation	Anti-competitive behaviour or violation of anti-trust and monopoly legislation	# per 10 k employees
	Corruption	Active involvement of enterprises in corruption and bribery	%
		Public sector corruption	Score
Society	Education	Public expenditure on education	% of GDP
	Health expenditure	Health expenditure, external resources	% of total
		Health expenditure, out-of-pocket	% of total
		Health expenditure, public	% of total
		Health expenditure, total	% of GDP
	Illiteracy	Illiteracy rate, female	% of women
		Illiteracy rate, male	% of men
		Illiteracy rate, total	% of population
	Youth illiteracy	Youth illiteracy rate, female	% of young women
		Youth illiteracy rate, male	% of young men
		Youth illiteracy rate, total	% of young people
Local community	Certified environmental management system	Certified environmental management system	# per 10k employees
	Drinking water coverage	Drinking water coverage	% with access
	Fossil fuel consumption	Extraction of fossil fuel	t/cap
	Indigenous rights	Human rights issues faced by indigenous people	Score
		Presence of indigenous population	Y/N
	Industrial water depletion	Level of industrial water use (related to renewable water resources)	% renewable
		Level of industrial water use (related to total withdrawal)	% of total
	International migrant stock	International migrant stock	% of population
	International migrant workers (in the sector/ site)	International migrant workers (in the sector/ site)	%
	Minerals consumption	Extraction of industrial and construction minerals	t/cap
		Extraction of ores	t/cap
	Net migration	Net migration	per mille
	Pollution	Pollution	Index
	Sanitation coverage	Sanitation coverage	% with access
	Unemployment	Unemployment	%
	Biomass consumption	Extraction of biomass (related to area)	t/km^2
		Extraction of biomass (related to population)	t/cap

Table 5: Example of semi-quantitative risk assessment for indicator "DALYs due to indoor and outdoor air and water pollution"

Indicator value, y (DALYs per 1000 inhabitants)	Risk level	Risk score
0	No risk	0
0<y<5	Very low risk	0.01
5≤y<15	Low risk	0.1
15≤y<30	Medium risk	1
30≤y<50	High risk	10
50≤y	Very high risk	100
-	No data	-

2.2.4.4 Risk factor calculation

In final analysis of results a "risk factor" is calculated as the ratio between the total number of risk-assessed worker hours for a given process and the total number of (non-risk assessed) worker hours. This gives a value that is comparable to the qualitative risk scale shown in Table 5.

2.2.5 *Allocation*

Allocation issues are addressed in the ecoinvent/SOCA background data for the assessment by using consistently the cut-off system model for unit processes (Ecoinvent Centre, 2019a). According to this method, burdens associated with the primary product are all allocated to that product. No benefit is assigned to the primary product from recycling. The product to be recycled is then available to the secondary product burden free.

2.2.6 *Life cycle impact assessment*

2.2.6.1 Social impact assessment

For evaluation of social risk, the impact assessment method used according to the SOCA add-on is applied (see earlier sections in this methodology for a broad presentation of SOCA). Five impact subcategories pertaining specifically to the stakeholder category workers are considered, as shown in Table 6. The stakeholder category workers is selected because this is considered to be a group of primary importance in assessing energy supply chains. Further, in accordance with the REFLEX SELES framework recommendations, the specific subcategories assessed are chosen partly because they are relevant for the UN sustainable development goals, and specifically goal 8: Decent work and economic growth (see Table 6).

Table 6: Subcategories chosen for which to assess social risk in this assessment, see Ciroth and Eisfeldt (2016).

Subcategory	Indicators	Connection to UN Sustainable Development Goal 8 Decent work and economic growth
Forced labour	Frequency of forced labour	8.7 Take immediate and effective measures to eradicate forced labour, end modern slavery and human trafficking and secure the prohibition and elimination of the worst forms of child labour, including recruitment and use of child soldiers, and by 2025 end child labour in all its forms
	Trafficking in persons	
Child labour	Child labour, total	
Health and safety	DALYs due to indoor and outdoor air and water pollution	8.8 Protect labour rights and promote safe and secure working environments for all workers, including migrant workers, in particular women migrants, and those in precarious employment
	Non-fatal accidents	
	Safety measures	
Workers' rights	Right of association	
	Right of collective bargaining	
	Right to strike	
Fair salary	Living wage, per month	8.5 By 2030, achieve full and productive employment and decent work for all women and men, including for young people and persons with disabilities, and equal pay for work of equal value
	Minimum wage, per month	
	Sector average wage, per month	

2.2.6.2 Environmental impact assessment

For the environmental assessment, the life cycle impact assessment method ReCiPe (Goedkoop et al., 2012) is used. ReCiPe is one of the latest methods and evaluates 18 different environmental life cycle impact indicators. Environmental impact results are normalised, i.e., the finding of each scenario for 2050 are divided by the base year (2014). Through normalised results, the magnitude of the impacts is analysed. The in-depth analysis followed the magnitude of the results to identify process drivers for the impacts in light of the following considerations:

- A significant advantage for the environment: scenarios differ from each other significantly demonstrating a large decrease in the environmental impacts between 2014 and future scenarios (more than 70% reduction);
- No significant change in total normalised impacts: the total normalised environmental impacts in future scenarios do not differ significantly from 2014.
- A significant disadvantage for the environment: scenarios differ from each other significantly demonstrating a large increase in total normalised environmental impacts (above 70%).

Based on these considerations, the environmental impacts selected in this study are climate change, particulate matter formation, freshwater eutrophication, ozone depletion, agricultural land occupation, urban land occupation, and metal depletion. For climate change GHG emissions lead to an increase in the atmosphere's radiative forcing which increases the global mean temperature. The Global Warming Potential (GWP) expresses the amount of additional radiative forcing caused over time by the emissions of 1 kg of GHG varies for different GHGs. Particulate matter formation is the formation of a complex mixture of particles with a size of less than 10um, including both organic and inorganic chemicals. Such particles are linked to a number of health problems such as respiratory morbidity. Freshwater eutrophication relates to nutrient enrichment of freshwater bodies. It leads to excessive plant growth (e.g. algae) in water bodies which subsequently causes reductions in water quality and biodiversity. Ozone depletion occurs due to the emission of ozone-depleting gases such as NO_x and Non-Methane Volatile Organic Compounds (NMVOCs). These substances cause damage to ozone layer reducing its ability to prevent UVB light from reaching the earth's surface, leading to a subsequent increased frequency and severity of human health problems. Agricultural land occupation and urban land occupation respectively refer to the occupation of a certain area agricultural and urban land respectively for a certain time period. It is expressed as m^2a (square meter of land per year).

2.2.6.3 Evaluation of external costs for electricity production

In a final impact assessment step connected to the life cycle based assessment of the scenarios, external environmental costs were calculated according to the LCA-based valuation method EcoValue12 (Finnveden et al., 2013). The external costs per functional unit for this method are shown in Table 7. The values for climate change are based on earlier studies (Ackerman & Stanton, 2012; Anthoff, Tol, & Yohe, 2009; Botzen & van den Bergh, 2012) and incorporate a larger range than considered in REFLEX models. The maximum is higher than that in the earlier version of the weighting tool (Ahlroth & Finnveden, 2011) and the range shown is based on judged significant uncertainty. Values for photochemical oxidant formation, terrestrial acidification and eutrophication (freshwater and marine) are as for the earlier version of the tool (Ahlroth & Finnveden, 2011). For other impact categories, the selection of the values are described further in (Finnveden et al., 2013).

Table 7: The EcoValue 2012 monetary weighting set for LCA (Finnveden et al., 2013)

Impact category	Unit	Min	Mean	Max
Climate Change	Euro/kg CO_2 eq	0.30	0.0105	0.5895
Photochemical oxidant formation	Euro/kg	2.84	1.4737	4.2105
Terrestrial acidification	Euro/kg SO_2 eq	3.16	3.1579	
Marine eutrophication	Euro/kg N eq	9.47	9.4737	
Freshwater eutrophication	Euro/kg P eq	70.53	70.5263	
Human toxicity	Euro/kg 1,4-DB	0.30	0.0021	0.5147
Marine ecotoxicity	Euro/kg 1,4-DB	1.26	1.2632	
Particulate matter formation	Euro/kg PM10	28.74	28.7368	

To provide an understanding of the magnitude of external costs compared to internalized production costs, indicative data were assembled from elsewhere in the REFLEX consortium and other sources as summarised in Table 8 and Table 9 below. Note that the values shown are intended to facilitate order-of-magnitude comparisons rather than to provide highly accurate cost data.

Table 8: Indicative values for production costs for different energy carriers used for comparison with estimates for external environmental costs (see Table 7)

End use energy carrier	2015 (2013 Euro)	2050, all scenarios (2013 Euro)	References
Biomass	0.020	0.020	(Maniatis, Landälv, Waldheim, van den Heuvel, & Kalligeros, 2017)
Electricity	0.061	0.086	Internal REFLEX estimates
Hydrogen	0.094	0.132	Based on value for electricity
Biokerosene	0.100	0.100	(Maniatis et al., 2017)
Bioethanol	0.080	0.080	(Maniatis et al., 2017)
Biodiesel	0.100	0.100	(Maniatis et al., 2017)
Natural gas	0.014	0.023	(International Energy Agency, 2018)
Coal	0.005	0.010	(International Energy Agency, 2018)
Fuel oil	0.024	0.063	(International Energy Agency, 2018)
Diesel	0.037	0.097	(Maniatis et al., 2017)
Gasoline	0.037	0.097	(Maniatis et al., 2017)
Solar Energy	0.031	0.043	Own estimate
Ambient	0.031	0.043	Own estimate

Indicative cost values for electricity production (levelised cost of electricity) were based on (International Energy Agency, 2018) and (IEA, NEA, & OECD, 2015) and are shown in Table 9. Note that these costs are shown excluding external costs.

Table 9: Indicative values for cost of electricity production used for comparison with estimates for external environmental costs (IEA et al., 2015; International Energy Agency, 2018)

Electricity production technology	2015, Euro/MWh	2050, all scenarios Euro/MWh
CCGT	65.7	
Gas CCS	N/a	94.9
Coal	43.3	
Lignite	35.6	
Nuclear	62.6	62.6
Reservoir	114.1	
PSP	78.5	
Wind onshore	74.8	67.3
Wind offshore	120.1	72.1
PV ground	89.6	47.6
PV roof top	126.9	67.4
Biomass	82.4	61.8
Run-of-river	96.8	

2.2.7 Assumptions, limitations and interpretation

Alongside other limitations and assumptions noted previously in this section and in the specific life cycle inventory descriptions noted below it should be further noted that LCA is a steady-state method from a temporal perspective that shows results on a year level, rather than a dynamic method like energy system models to present findings on an hour level (Guldbrandsson & Bergmark, 2012). A general lack of spatial considerations is another limitation of LCA. At the moment, there is no database available to assess impacts on local scale and to identify which effects could be expected in a small-scale location due to the operation of a facility. Normally, country (region) average impacts are presented (Guinée, 2002). It should be pointed out that in this report a complementary modelling approach is applied to consider spatial effects of environmental emissions.

It is finally noted that conclusions from the study are drawn by interpreting the assessed social risks and environmental impacts in light of assumptions made about the future of the technologies considered, the impact assessment methods applied and the limitations noted here.

2.3 Life cycle Inventory

2.3.1 Terminological note

Very often in describing life cycle inventory in the following text, processes in the ecoinvent database are referred to. For a high level of transparency, the full process name is given when this is done. Certain terms and abbreviations occur quite often in these names.'

In particular, the term "cut-off" is used to refer to the way that recycled content is considered in the process. When used in an ecoinvent process name, "cut-off" refers to the idea that the burdens of primary production are always assigned to the primary product, whether or not it is recycled. The product is thus available for secondary use burden free. See Ecoinvent Centre (2019a) for more information.

Also the abbreviation "U" occurs. This refers the fact that so-called unit processes are being used, see also Ecoinvent Centre (2019c) for more information. Information on country and regional abbreviations is also available from the Ecoinvent Centre (2015)

For further information about ecoinvent process names, the reader is welcome to consult the ecoinvent website in general (Ecoinvent Centre, 2019b) and other documents (Wernet et al., 2016).

2.3.2 Electricity sector

Foreground data, which are technology specific used in the assessment (e.g. efficiencies, life time, electricity generation by technology), are harmonised with input and output data from REFLEX energy system models (ESM) used for the electricity sector, ELTRAMOD. In particular, foreground data for gross electricity generation shown for all temporal cases considered are taken from the output of ELTRAMOD and shown in Figure 6 below.

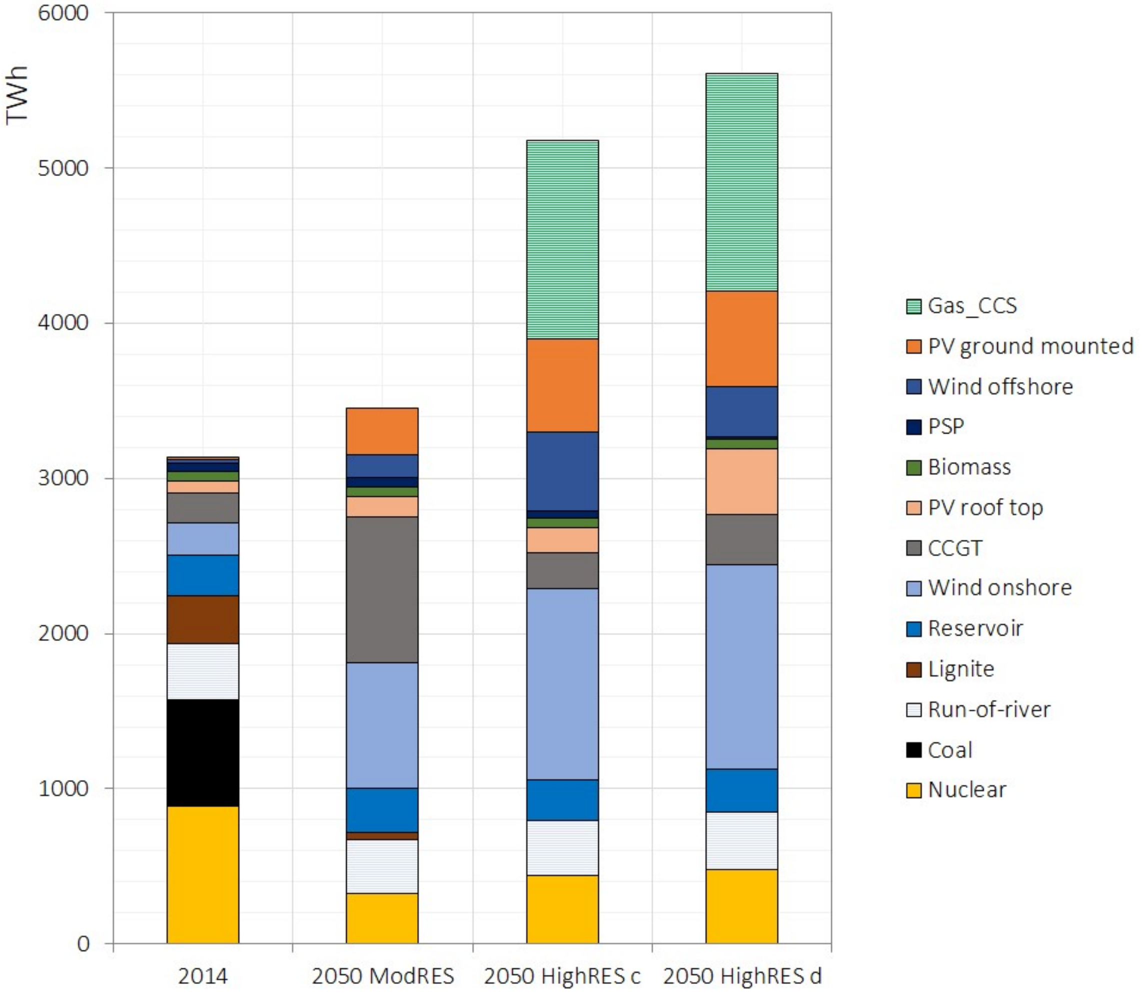

Figure 6: Gross electricity generation for the EU used as input data in this study, for the base case and the 2050 future scenarios.

LCI for each of the generation technologies shown in the figure are established according to the procedures recorded under the following sub-headings.

2.3.2.1 Wind power

Environmental LCI

Wind turbines are composed of different components such as foundation, tower, nacelle, generator, yaw control and others. The main consideration of this study are the moving-parts (nacelle and generator) that are exclusively responsible for transforming the kinetic energy into electricity and the fixed-part (the tower). Many factors affect the selection of the generator depending on its specifications in order to match the location, such as maintenance intervals, design, size, spare parts, and operation temperature. Broadly, there are two significant groups of generators: Asynchronous generators (AG) - the conventional turbines - and Synchronous generators (SG) - the most sophisticated ones with growing market acceptance due to higher efficiency than AGs. Under the SG, there are electrically excited direct drive (SG-E-DD), permanent magnet (PMGs) and superconductor (high-temperature superconductors - HTS) generators. Among these, PMGs and HTS generators are the most promising technologies for the future (Maples, Hand, & Musial, 2010).

A key parameter implemented in environmental LCI for wind power in the scenarios considered is the future market share regarding the above mentioned wind technologies. This parameter is directly connected to the REFLEX scenarios based on technological roadmap and bandwidth extrapolations by (Viebahn et al., 2015). Table 10 shows the respective market share adopted for each type of wind energy. Through varying the market share of different types of wind power technology for future scenarios, a “technical potential” approach to developing future inventory (see the earlier report on the REFLEX SELES framework (Brown et al., 2017)) is applied for environmental LCA for wind power plants.

Table 10. Market share of wind technologies according to the REFLEX scenarios

Wind energy	Technology	Market share Base year	Market share 2050		
			Mod-Res	HIGH-RES Central	HIGH-RES Decen.
onshore	HTS[1]	-	-	-	12%
	SG-PM[2]	25%	35%	94%	82%
	SG-E-DD[3]	57%	53%	4%	4%
	AG[4]	18%	12%	2%	3%
offshore	HTS[1]	-			17%
	SG-PM[2]	15%	50%	98%	81%
	SG-E-DD[3]	-	-	-	-
	AG[4]	85%	50%	2%	2%

1 High-temperature superconductors 2 Synchronous Generator - Permanent Magnet 3 Synchronous Generator - Electrically Excited Direct Drive 4. Asynchronous Generator

As seen in Table 10, in the Mod-RES scenario, the business-as-usual market of wind technologies prevails. There is a continued market dominance of SG-E-DD for onshore plant and of AG for offshore plant. High-RES Central is characterised by high demand of large-scale onshore wind power plants (Poganietz, Kühn, Reiter, & Fermi, 2017). According to this, it is assumed in this scenario that a strong market preference for permanent magnet turbines develops, as per the up-scaling roadmap determined by Viebahn et al. (2015).

This market preference is justified in this scenario because permanent magnet turbines are judged to provide higher current production, with less required maintenance and less noise than conventional technologies (AG, SG-E-DD). In the High-RES decentralized scenario an increase of onshore wind power plant at all possible locations is expected (Poganietz et al., 2017). Based on this it is further assumed that competing technologies for permanent magnets will enter the market as the high-temperature superconductor (HTS) generators.

For each of the technology types shown in Table 10, the background LCI are held constant across all scenarios for 2050. The LCI for each of the technology types are described in more detail below.

The ecoinvent background model for wind turbines are based on the AG turbine type. Accordingly, in this assessment, background LCI data for AG-based wind turbines are based directly on the ecoinvent processes shown in Table 11.

Table 11: Background environmental LCI processes used to model wind turbines with asynchronous generators (AG) for all scenarios

Offshore	wind power plant construction, 2MW, offshore, fixed parts | wind power plant, 2MW, offshore, fixed parts | cut-off, U- GLO
Onshore	wind turbine construction, 2MW, onshore | wind turbine, 2MW, onshore | cut-off, U – GLO

For the purposes of the assessment the original background LCI for wind turbines is adapted for different turbine types. For SG-E-DD, it is expected that glass fibre currently used in generators will in the run-up to 2050 be replaced with carbon fibre, with a substitution rate of 100% in 2050 according to NEEDS (2008). In light of this, an input product and respective material/fuel inputs (carbon fibre reinforced plastic production) are added to the original background LCI datasets “wind turbine construction, 2MW, onshore | wind turbine, 2MW, onshore | cut-off, U – GLO” and “wind turbine construction, 2MW, onshore | wind turbine, 2MW, onshore | cut-off, U – GLO” respectively. Meanwhile, a corresponding quantity of glass fibre is removed.

For SG-PMs, materials and energy required follows the study by Arshi et al. (2018). The challenge for modelling SG-PMs turbines is that they require a certain quantity of rare earth metals for the generators’ magnet gears. According to Arántegui and Gonzáles (2014), the main rare earth metals required are neodymium (Nd), praseodymium (Pr) and dysprosium (Dy).

Table 12 shows the LCI for magnet gears added to the original background ecoinvent processes, including the rare earth metals mentioned above. Despite the fact that those rare earth elements are taken into account in the LCI, the upstream processes for neodymium is the only one available in ecoinvent database. The total demand for dysprosium and praseodymium were taken into account, therefore the impacts of upstream (related to mining activities, for example) are neglected in this study due to lack of a database and literature. The implications of this lack of data are considered in the discussion of the assessment.

Table 12. Material and energy demand for SG-PMs turbines per MW

Material/Energy	Amount	Unit
neodymium oxide to generic market for mischmetal | mischmetal | cut-off, U[1]	2.22E+02	kg
market for praseodymium oxide[1]	5.27E+01	kg
Dysprosium (Dy) production[1]	3.18E+01	kg
electricity, medium voltage	8.36E+03	MJ
refractory, high aluminium oxide	2.04E+00	kg
steel, unalloyed	2.38E+02	kg
Copper, primary	4.50E-02	kg
Gadolinium Iron alloy, Ion Adsorption Clays, at Jiangxi	2.25E+01	kg
Argon, liquid	1.28E+01	kg
lubricating oil	4.65E-01	kg
nitrogen, liquid	2.36E+01	kg
hydrogen, liquid	1.19E+00	kg
water, deionised, from tap water	1.69E+04	kg
Ferroboron Alloy	1.83E+01	kg
Aluminium, primary	8.82E-01	kg
Silica sand, at plant	3.07E-02	kg
Cobalt, at plant	4.49E+00	kg
packaging film, low density polyethylene	5.37E-01	kg

Source: [1]Arshi et al. (2018), Arántegui and Gonzáles (2014)

HTS turbines do not need magnet gears and therefore weigh less compared to otherwise equivalent technologies. For that, another magnetic field is required (Arántegui & Gonzáles, 2014). HTS turbines are however still innovative technologies and few studies are available. For this study, simplified material requirements for the HTS conductor are modelled based on the work by Lloberas-Valls, Pérez, and Gomis-Bellmunt (2015). For an installed capacity of 15 MW, Lloberas-Valls et al. (2015) assumed the weight of HTS conductor as 1700 tons with the material requirements given in Table 13, where the upstream processes were added for the LCI for HTS turbines.

Table 13. Materials required for HTS wind turbines (Lloberas-Valls et al., 2015)

Materials	%	Ecoinvent upstream process
Copper	43	YBCO yttrium barium copper oxide
YBCO yttrium barium copper oxide	1.3	market for copper | copper | cut-off, U - GLO
Silver	2.7	market for silver | silver | cut-off, U-GLO
HastelloyC276-nickel–molybdenum–chromium alloy	53	Hastelloy C276 - nickel–molybdenum–chromium alloy

Social LCI

The original background process for wind power (offshore) together with a summary of the changes made for social LCI for this assessment are shown in Table 15. Electricity production and power plant construction are assumed to be carried out at conditions as shown in Table 14. In addition, the excavation process (which is an input into the original ecoinvent process for power plant production shown in Table 10) is assumed for the purpose of this assessment to be carried out at average European conditions (as opposed to global conditions as in the original ecoinvent process). Investment costs for significant components were also changed so as to bring the costs more in line with current conditions and to make a good estimate for future cases, according to the method described below.

Table 14: The ISIC sectors and geographical regions used for modelling social impacts for plant production and electricity production for electricity from natural gas in all temporal cases.

Production stage	ISIC sector	Geographical region, see (Ecoinvent Centre, 2015)
Power plant production	4220a: Construction of utility projects for electricity production, except for liquid fuels	RER - Europe
Electricity production	3510:Electric power generation, transmission and distribution	ENTSO-E (the European transmission grid)

Table 15: The original background process for offshore wind power with a summary of the changes made to the process (used in all scenarios in this assessment)

Original background process	Adaptions made for social life cycle inventory (sLCI) in this assessment
electricity production, wind, 1-3MW turbine, offshore | electricity, high voltage | cut-off, U – DE	- The following processes are adapted so as to represent an activity variable and risk profile suited to EU average conditions: - Electricity production itself (i.e. turbine operation) - Final wind turbine construction - Excavation (an input to the wind turbine construction process) - Investment costs for wind turbines and network connections

Meanwhile, for onshore wind generation, the original background process was chosen to be “electricity production, wind, 1-3MW turbine, onshore | electricity, high voltage | cut-off, U – DE”. As for all other electricity generation, the electricity production and plant construction processes are represented for the social assessment by average European conditions according to the ISIC sectors shown in Table 14. In addition, the investment costs for significant components were changed for the current situation and for the future scenarios, in order to make the number of worker hours more representative of conditions relevant for each temporal case. This is discussed further in paragraphs below.

The costs of installed capacity for wind in ecoinvent is based on price data from the early 2000s. In light of recent price volatility in the market for wind systems (especially offshore), in particular work in REFLEX a price update is required (Louwen et al., 2018).

For onshore wind power in this study the global weighted average of installed costs of wind farms was estimated to 1,477 $/kW or approximately 1,327 €/kW (IRENA, 2018b). In ecoinvent, the two main capital costs of onshore wind are the wind turbine and the network connection. This is consistent with reports investigating the cost of wind power, which state that the wind turbine makes up between 64-84% and network/grid connection between 9-14% of the total system costs (Agora Energiewende, 2017; IRENA, 2012). For the cost calculations in this study, the average values of 74% and 11% are assumed, respectively. The remaining 15% are unspecified capital costs, which are classified as “other” (see Table 16).

For offshore wind power, the global weighted average of installed costs was estimated to 4,487 $/kW or 4,031 €/kW (IRENA, 2018b). In ecoinvent, system costs for offshore wind are split into two categories: fixed- and moving parts. These account for 75% and 25% of total system costs, respectively. Hence, the updated total system cost is allocated accordingly (see Table 16).

To estimate future price developments of system costs, a learning rate is used. In short, the learning rate is expressed as a percentage 0-100% and represents the proportion by which the cost of a product will decrease for each doubling of the cumulative production of that product. It is estimated by fitting a linear regression model to empirical price data. The slope of the resulting curve (i.e. the experience curve) is then used to estimate the learning rate. For the s-LCA model, learning rates, along with future installed capacity projections, are used to project the future cost of technologies. See REFLEX Deliverable 3.2 and Junginger, Van Sark, and Faaij (2010) for further details on experience curves and learning rates.

According to the aforementioned study, both onshore and offshore learning rates are found to be highly variable, largely dependent on the studied market and time frame. In a recent study by IRENA, a learning rate of 9% is estimated for onshore wind (IRENA, 2018b). This rate is derived from the global weighted average of installed onshore wind capacity, based on price data from 1983-2017. For simplicity, this learning rate is assumed for both technologies (onshore and offshore) to estimate system costs for wind 2050 for the s-LCA model.

With regards to installed capacity, global installed wind capacity in 2016 reached 467 GW, of which 454 GW onshore and 13 GW offshore (IRENA, 2018b). These are used as base-year values for installed capacity. By 2050, IRENA estimates that the total installed wind capacity will increase to 5445 GW, of which 4923 GW onshore and 521 GW offshore (IRENA, 2018a). These projections are used as 2050 values of installed capacity and are used for the cost estimations, along with the 9% learning rate. The results are shown in Table 16.

Table 16. Cost projections (EUR per kW) for installed wind systems in 2050, assuming a 9% learning rate.

Wind energy	Breakdown of system costs (%)	Updated costs for base-year	Projected costs 2050
Onshore	Total (100%)	1,327 €/kW	963 €/kW
	Turbine (74%)	982 €/kW	713 €/kW
	Grid connection (11%)	146 €/kW	106 €/kW
	Other (15%)	199 €/kW	144 €/kW
Offshore	Total (100%)	4,031 €/kW	2440 €/kW
	Fixed parts (75%)	3,023 €/kW	1830 €/kW
	Moving parts (25%)	1,008 €/kW	610 €/kW

Source: own calculations

By incorporating the learning curve approach for LCI for social assessment for wind power, a technological trend extrapolation approach is applied, according to the different views of the future discussed in the REFLEX SELES framework (Brown et al., 2017).

2.3.2.2 Solar power

Environmental LCI

According to storylines for the REFLEX scenarios, solar PV electricity generation is subdivided into solar PV rooftop and ground-mounted. For the environmental LCI, there is a need to identify which specific PV technology will be used in both cases. It is expected for example that materials used in today´s conventional PV technologies might be substituted and that energy efficiencies might increase in the future. Conventional PV technologies rely on crystalline cells (mono and multi-silicon). Silver is a critical material in producing these cells because price fluctuations affect access to the raw materials. According to a recent report (ITRPV, 2018) and previous LCA studies, the amount of silver (used for electric contacts in Single-Si cells, for example) will reduce for conventional PV cells in the coming years (Tschümperlin, 2016).

For the environmental LCI, the process called “electricity production, photovoltaic, 570kWp open ground installation, multi-Si | electricity, low voltage | cut-off, U” was chosen for modelling the ground mounted technologies and “electricity production, photovoltaic, 3kWp flat-roof installation, multi-Si | electricity, low voltage | cut-off, U” was chosen to represent roof-top systems. As observed in the LCI of those two processes, ecoinvent does not include the demand for silver. For REFLEX environmental LCI modelling, the amount of silver is proportionally calculated for 570 kW and inserted as a material input (with upstream modelled by the process “market for silver | silver | cut-off, U- GLO”). The quantities of silver are based on a calculation of the average of quantities given in the sources shown in Table 17.

Table 17. Expected amount of silver (Ag) for multi-Si photovoltaic

Ag Multi Si (kg/MW)	2015	2030	2050
	22.41	12.32	8.96

Source: (ITRPV, 2018; Moss, Tzimas, Kara, Willis, & Kooroshy, 2013)

It is further assumed that thin-film cells are also used. This technology is further divided into 4 sub-groups; amorphous silicon “a-si”, cadmium telluride “CdTe”, copper indium gallium selenide “CIGS” and multi-junction cells “MJ”. According to Lee and Ebong (2017) thin-film cells are becoming favourable for industrial processes because of their low material usage and improving efficiencies. Lee and Ebong (2017) also highlight in their study that longevity, reliability, consumer confidence and greater investments must be made before thin film solar cells are developed on building integrated photovoltaic systems. The ecoinvent database provides a process for modelling thin film PV called “*electricity production, photovoltaic, 3kWp slanted-roof installation, CIS, panel, mounted | electricity, low voltage | cut-off, U*”. This process is used to model thin film usage for environmental LCA for this model.

As with wind power, a key element of foreground environmental LCI for solar PV are the market shares of different technologies in the future scenarios. In the KRESSE project, Viebahn et al. (2015) investigated the long-term development of relevant PV technologies for the German energy transition. The technological roadmap developed in the KRESSE Project has been merged to the REFLEX storyline, resulting in the technology shares for solar PV in the REFLEX scenarios shown in Table 18.

Table 18. Market share of solar PV technologies for REFLEX scenarios

Solar energy	Technology	Market share Based-year	Market share 2050		
			Mod-Res	HIGH-RES Central	HIGH-Decen.
Roof top	crystalline	3%	1%	32%	32%
	thin-film	97%	99%	68%	68%
Ground-mounted	crystalline	3%	2%	50%	50%
	thin-film	97%	98%	50%	50%

Source: K. Arnold (2014)

For Mod-RES the “continuity” roadmap from Viebahn et al. (2015) is assumed, through the continued dominance of crystalline PV. The “thin film renaissance” roadmap is merged to REFLEX High-RES. In this scenario, it is assumed future developments of the thin film sector are based on the extrapolation of the recent market shares within the KRESSE project.

The approach used to develop environmental inventory in this case is based in the technical potential perspective on possible future developments when compiling inventory for future technologies, according to the terminology developed for the REFLEX SELES framework earlier in the project (Brown et al., 2017).

Social LCI

As with environmental LCI, social LCI for solar PV distinguishes between roof-top and ground-mounted systems. The original background process in ecoinvent for ground-mounted PV is taken to be “electricity production, photovoltaic, 570kWp open ground installation, multi-Si | electricity, low voltage | cut-off, U – DE” according to the terminology used to name processes in ecoinvent. The original background process for roof-top PV is assumed to be “electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | electricity, low voltage | cut-off, U” Both processes are amended according to Table 14 in order to assume European average conditions for the electricity production process itself and plant construction. In addition, the cost data in ecoinvent for production and installation of solar PV in ecoinvent is updated to account for the current situation as well as for the future scenarios considered.

Similar to the approach used for wind power generation, costs of solar PV systems in ecoinvent are slightly outdated (~ 4000 €/kWp) for the current situation and were updated when creating social inventory for this assessment. This is largely due to the rapid growth of the solar PV market over the last decade. Between the years 2006 and 2016, the cumulative global installed PV capacity grew from around 6 GW to 300 GW, representing an average annual growth of 50% (IRENA, 2017; REN21, 2017). As a consequence, prices for PV systems (both utility- and residential-scale) have declined significantly. By the end of 2016, costs for solar PV system in EU-28 countries (e.g. Germany, France, Italy and UK) range between 900 and 2000 €/kWp, depending on market and scale (IRENA, 2018b).

For the s-LCA model, ground mounted solar PV systems are categorised as utility-scale PV projects and are priced at 1000 €/kWp for base-year (i.e. 2016). This pricing is in line with a study by (Fraunhofer ISE, 2015) and is deemed to be a representative cost per kWp for ground mounted PV systems on the EU-28 market. The roof top solar PV systems are categorised as residential-scale PV projects, which tend to be slightly more expensive per kWp (IRENA, 2018b). Hence, these are assumed to cost 1500 €/kWp in the base-year which is deemed to be a conservative value for the EU-28 market (see

Table 19). In contrast to wind, the total system costs for solar PV are contained within one single process in ecoinvent (containing costs for balance of system, PV modules, inverter, etc.). Consequently, it is deemed sufficient to only consider the costs of the system as a whole.

With regards to installed capacity, the exponential growth of solar PV is expected to continue, with installed PV capacity projected to increase from the 300 GW in 2016 to 7122 GW in 2050 (IRENA, 2018a). Hence, it is important to consider learning effects (i.e. cost reductions due to economies of scale and technological improvements) when modelling future PV systems. To account for price development, a learning rate is assumed for both ground mounted and roof top PV systems. According to the findings of Deliverable 3.2, there is a slight deviation between learning rates for residential- (systems <10kW) and utility-scale (systems 10-100 kW), ranging between 19 and 23 %. This range is also comparable with the estimations of the Fraunhofer ISE report from 2015 (19-23%). For simplicity, an average value of 21% is assumed for both ground mounted and roof top PV systems. This is deemed to be representative, as their future capacity shares (residential- vs. utility-scale) are not known and because they are expected to benefit from each other's development/capacity increase (decreasing price of modules being a large driver which benefits both). As can be seen in

Table 19, a capacity increase from 300 GW to 7122 GW at a learning rate of 21% corresponds to a 66% cost improvement of solar PV systems in 2050 scenarios.

By incorporating the learning curve approach for LCI for social assessment for solar PV, a technological trend extrapolation approach is applied, according to the different views of the future discussed in the REFLEX SELES framework.

Table 19. Cost projections (EUR per kW) of solar PV systems in 2050, assuming a 21% learning rate.

Solar energy	Updated system costs for base-year	Projected costs 2050
Roof top	1,500 €/kWp	510 €/kWp
Ground-mounted	1,000 €/kWp	340 €/kWp

Source: own calculations

2.3.2.3 Fossil-based electricity generation

The key parameters implemented in LCI for fossil-based electricity generation are the generation efficiencies, life time and the development of these parameters over time.

According to the scenarios, the electricity production efficiencies and lifetime are amended to be in line with that given in the REFLEX electricity system model, ELTRAMOD. Key efficiencies used in the assessment are shown in Table 20 and used in both environmental and social LCI. This applies a technical potential perspective according to the views of the future considered in the REFLEX SELES methodology. The reference processes of eLCA, which are further adapted based on the ESMs and assumptions in terms of geographical boundaries, are from ecoinvent and shown in sections below.

Table 20: Generation efficiencies for fossil technologies implemented in the model for both sLCI and eLCI. From the energy systems model ELTRAMOD.

	Current case	2050 scenarios
Natural gas (combined cycle)	61%	62%
Coal	49%	52%
Lignite	44%	47%
Natural Gas (CCS)	58%	59%

Non-CCS electricity generation from natural gas

The electricity generation with natural gas is mainly carried out in combined cycle gas turbines (CCGT) with and without CCS (see Figure 6). For sLCI, a custom natural gas supply mix with specific countries of origin was created based on the most recent data for fuel sources from Eurostat (Eurostat, 2019). The mixes used are shown in Table 21 below. This mix is used for all temporal cases. For the future scenarios this is primarily in light of a lack of data from REFLEX ESMs and elsewhere considering potential supply mixes for natural gas for the EU in the future. The implications of these assumptions are considered in the interpretation of results below.

Table 21: The supply mix of natural gas assumed for electricity generation in all temporal cases considered in the assessment. Based on (Eurostat, 2019).

Country of origin	Proportion of supply	Background LCI process used, ecoinvent/SOCA
Russia	32%	natural gas, high pressure, import from RU | natural gas, high pressure | cut-off, U - DE
Norway	21%	natural gas, high pressure, import from NO | natural gas, high pressure | cut-off, U - DE
Netherlands	12%	natural gas, high pressure, import from NL | natural gas, high pressure | cut-off, U - DE
Rest of world	11%	natural gas production | natural gas, high pressure | cut-off, U - RoW
UK	10%	natural gas, high pressure, import from GB | natural gas, high pressure | cut-off, U - CH
Algeria	10%	natural gas, high pressure, import from DZ | natural gas, high pressure | cut-off, U - CH
Germany	2%	natural gas production | natural gas, high pressure | cut-off, U - DE
Nigeria	2%	petroleum and gas production, on-shore | natural gas, high pressure | cut-off, U - NG

Foreground sLCI data unique to this study was also developed for electricity generation from natural gas for the process of electricity production itself and for the production of the plant. The aim of this foreground data was to model social conditions (number of worker hours and social risk profile) associated with average European production. The ISIC categories and geographical region codes used in the model for these processes are shown in Table 14.

Finally, all processes mentioned in the preceding text are as for the background process used to model electricity production with natural gas, which is "electricity production, natural gas, combined cycle power plant | electricity, high voltage | cut-off, U – DE".

Electricity generation from coal

For electricity generation from coal, the generation efficiency given in Table 20 is used for both environmental and social LCI. In addition, for social LCI, a fuel mix with specific countries of origin was created based on the most recent data for fuel sources from Eurostat (Eurostat, 2019) and shown in Table 22.

Table 22: The supply mix of coal assumed for electricity generation in all temporal cases considered in the assessment, by proportion of supply. Based on (Eurostat, 2019).

Country of origin	Proportion of supply	Background LCI process used, ecoinvent/SOCA
Canada	1%	market for hard coal | hard coal | cut-off, U - RNA - RNA
Rest of World	1%	market for hard coal | hard coal | cut-off, U - RoW - RoW
Australia	9%	market for hard coal | hard coal | cut-off, U AU - AU
Western Europe	5%	market for hard coal | hard coal | cut-off, U - WEU - WEU
Poland	35%	market for hard coal | hard coal | cut-off, U - PL - PL
South Africa	3%	market for hard coal | hard coal | cut-off, U - ZA - ZA
Columbia	15%	market for hard coal | hard coal | cut-off, U - RLA - RLA
Russia	19%	market for hard coal | hard coal | cut-off, U - RU - RU
United States	9%	market for hard coal | hard coal | cut-off, U - RNA - RNA
Indonesia	2%	market for hard coal | hard coal | cut-off, U ID - ID

As with other technologies for electricity generation, the specific processes of electricity generation and power plant production are modelled according to European average social risk in the sectors given in Table 14.

All processes not identified specifically for foreground data in the preceding text are as for the background process used to model electricity production with coal, which is "electricity production, hard coal | electricity, high voltage | cut-off, U – DE", from environmental and social perspectives.

Electricity generation from lignite

The generation efficiencies for lignite-generated electricity used in the model are given in Table 20, used for both social and environmental LCI.

From a social perspective, and as with other technologies for electricity generation, the specific processes of electricity generation and power plant production are modelled according to European average social risk in the sectors given in Table 14. In contrast to coal and natural gas, lignite is combusted at or close to the mining site. Therefore, supply mixes with different countries of origin are not relevant for lignite as they are for coal and natural gas (see Table 21 and Table 22). The process for lignite supply is therefore based on a European average (region code RER, see Ecoinvent Centre (2015)), which is the default in the background process used (see text below).

For social LCI, the process specifically for electricity production and power plant production are modelled according to the ISIC sector and geographical region as given in Table 14 above.

For social LCI, it became apparent in initial modelling that the assumptions made in SOCA with respect to producing an activity variable for waste material yielded unreasonably high social risks for overburden from lignite mining (Eisfeldt, 2017). Therefore, it was assumed in the model that the social risks connected to lignite overburden are already included in the risks as evaluated for lignite extraction itself.

All processes not identified specifically in the preceding text are as for the process used to model electricity production with lignite, which is “electricity production, lignite | electricity, high voltage | cut-off, U - DE” for both social and environmental LCI.

Electricity generation with natural gas including carbon capture and storage

The electric generation efficiency for natural gas including carbon capture and storage is given in Table 20 and used in both environmental and social LCI.

Foreground LCI for the carbon capture process for social and environmental LCI is taken from the amine-based process for carbon capture given in (Volkart, 2011) and (Volkart, 2013). Foreground LCI for transportation of captured carbon dioxide and storage in an underground aquifer is taken from (Wildbolz, 2007). Since Volkart (2011), Volkart (2013) and Wildbolz (2007) present LCI data from an environmental perspective, they were complemented with processes to better reflect the CCS process from a social perspective. In particular, the activity variable (i.e. amount of worker hours) for electricity production was increased by 25 % compared to other processes for electricity production in order to reflect the increased complexity of the CCS generation process. The activity variable for plant production (not considered in the eLCI) was included by assuming a 25 % increase in the activity variable for that process aslo reflecting the increased complexity of the plant. Furthermore, sLCI for CO_2 transport was included by assuming that transport was carried out with a number of worker hours equivalent to that in the ISIC sector 4930 transport in pipeline according to European average conditions. sLCI for the electricity production process itself and for plant production are described in Table 14.

All processes not identified specifically in the preceding text are as for the background process used to model electricity production with natural gas, which is “electricity production, natural gas, combined cycle power plant | electricity, high voltage | cut-off, U – DE” for both social and environmental LCI.

The incorporation of new processes for CCS applies a technical potential perspective according to the approaches for developing future LCI discussed in the REFLEX SELES framework.

2.3.2.4 Nuclear electricity generation

The efficiency of new nuclear power installations assumed by ELTRAMOD in REFLEX hardly changes over the period considered (from 2014 through 2050 efficiency increases by 1%). In light of this it was judged appropriate given the scope of the assessment to assume the same efficiency for all temporal cases for both environmental and social LCI. As with all other processes for electricity generation, sLCI data for plant production and plant operation were modelled as for European conditions according to Table 14.

Background data in the assessment is taken from the ecoinvent process “Electricity, high voltage, electricity production, nuclear, boiling water reactor - DE” for environmental and social LCI. Though nuclear power can be produced using a variety of technologies it was judged that from the perspective of the system-wide assessments being performed, this assumption could reflect adequately the data needs. In any case, initial modelling showed that the boiling water reactor process as selected consistently showed higher environmental impacts than the other dominant technology in current use, the pressurised water reactor. Therefore, this assumption provides a conservative estimate for environmental impacts from nuclear power production.

By using unchanged inventory for nuclear power, a technical preserving perspective is used to develop future LCI according to the approaches discussed in the REFLEX SELES framework.

2.3.2.5 Hydropower

Background data for hydropower production not otherwise stated in the above text is based on ecoinvent processes as shown in Table 23. This is a technical preserving perspective according to approaches used by the REFLEX SELES framework.

Table 23: Overview of background LCI data used to model hydropower of different types in the assessment performed

type of hydropower technology	Name of process used in modelling
pumped storage	electricity production, hydro, pumped storage | electricity, high voltage | cut-off, U - DE
run-of-river	electricity production, hydro, run-of-river | electricity, high voltage | cut-off, U - DE
reservoir	electricity production, hydro, reservoir, non-alpine region | electricity, high voltage | cut-off, U - DE

As with all other processes for electricity production, sLCA for the processes for electricity generation itself and for plant production are based on the ISIC sectors and geographical region given in Table 14.

2.3.2.6 Biomass electricity generation

Environmental LCI

The biomass used to generate power and heat can be converted in several ways, including: (1) direct combustion of biomass materials especially woody biomass such as wood chips and wood pellets, and (2) other methods of gasification, pyrolysis, and anaerobic digestion, which intend to convert biomass to other energy carriers, e.g. biogas.

Different conversion technologies work best with different types of biomass, which means the technological choices for biomass depend on the types of biomass being used. Typically, for instance, wood materials are combusted directly, as assumed in the ecoinvent database. For the environmental LCI, we followed the assumption in the ecoinvent database in this study, i.e., wood materials, mainly wood pellets and wood chips, are directly combusted to generate power and heat while other types such as biowaste, manure, residues are assumed to be converted to biogas firstly and then to generate power or heat. AEBIOM (2014) investigated biomass consumption in Europe for the year of 2014, which is a base for us to create the LCI of biomass feedstocks and the relative conversion technologies for the current situation, as shown in Table 24.

Table 24: Shares of biomass for the current situation

Feedstocks	Shares	Conversion technologies	Shares
Wood pellets	10%	Direct combustion	69 %
Wood chips	59%		
Biowaste	0%	Biogas conversion	31 %
Manure	9%		
Energy crops	1%		
Industrial and agricultural residues	9%		
Municipal waste	11%		

The biomass feedstocks for future energy markets are a result of various factors, e.g. prices, potential, accessibility, import, etc. The recent literature (e.g. Ruiz et al., 2015) focused merely on one of the factors "biomass potential", which seems not enough to give us a good picture of how future biomass will be consumed and how consumption might differ in different scenarios. In this case, we made an adaption of the shares of conversion technologies referring to technical biomass potentials acquired from (Ruiz et al., 2015), but kept the same assumption for the specific shares of biomass feedstocks used in the technology alternatives in 2050, as shown in Table 24. The assumptions are the same for all Mod-RES, High-RES central and decentral scenarios.

Table 25: shares of biomass for 2050 (for all Mod-RES, High-RES central and decentral scenarios)

Feedstocks	Shares	Conversion technologies	Shares
Wood pellets	6%	Combustion	40 %
Wood chips	34%		
Biowaste	1%	Biogas conversion	60 %
Manure	23%		
Energy crops	3%		
Industrial and agricultural residues	25%		
Municipal waste	8%		

Social LCI

The disaggregation of electricity from biomass into different energy carriers and conversion types are given in Table 26 below. This breakdown is used for the current situation and all future scenarios. For biogas-produced electricity, the original background process shown in Table 26 has been changed only by applying European average conditions for the activity variable (in worker hours) and the social risk profile for the electricity production process itself and for the plant production as shown in Table 14. Likewise the process for electricity generation for wood *chips.*

For electricity generation with wood *pellets* shown in Table 26, the process for fuel supply in the original wood chip based process, "market for wood chips, wet, measured as dry mass | wood chips, wet, measured as dry mass | cut-off, U - Europe without Switzerland" has been changed to an appropriate process for wood pellet supply, namely "market for wood pellet | wood pellet, measured as dry mass | cut-off, U – RER". Since the aim is to model for European conditions, and as for other processes, for wood pellet-based electricity production, the original background process is changed by applying European average conditions for the activity variable (in worker hours) and the social risk profile for the electricity production process itself and for the plant production as shown in Table 14.

Social LCI for biomass-based electricity therefore uses a technical preserving perspective for the development of social LCI, according to the approach discussed in REFLEX SELES framework. This is considered feasible in light of the relatively small proportion of electricity production that comes from biomass.

Table 26: Disaggregation of electricity production using biomass used for sLCI in this assessment. The changes made to the original background processes are described in the text in this section.

Proportion of electricity production	Original background process	Name of background process for sLCI in this assessment
50 %	heat and power co-generation, biogas, gas engine | electricity, high voltage | cut-off, U - DE	heat and power co-generation, biogas, gas engine | electricity, high voltage | cut-off, U - DE
25 %	heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | electricity, high voltage | cut-off, U - DE	REFLEX heat and power co-generation, wood pellets, 6667 kW, state-of-the-art 2014 | electricity, high voltage | cut-off, U (see text for inventory features unique to this study)
25 %	heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | electricity, high voltage | cut-off, U - DE	REFLEX heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | electricity, high voltage | cut-off, U (see text for inventory features unique to this study)

2.3.3 *Transport Sector*

In the assessment of the transport sector, two main considerations influence the drawing of the system boundary. Firstly, the assessment considers the *supply chain for energy* to the transport sector and not other transport-associated processes. Processes for other elements necessary for transport such as the production and maintenance of vehicles and the production and maintenance of roads are excluded from the assessment since they are judged not to be relevant for energy supply to the sector. The assessment focuses only on the road transport and aviation sub-sectors, i.e., waterways or sea transport are out of the boundary. This is considered a reasonable assumption in light of the fact that together these two transportation subsectors account for over 90 % of the total energy demand in all the temporal cases considered. The effect that these assumptions have on results is considered in interpretation.

The foreground data for the assessment in terms of the quantities of different fuels used in the transport sector for the base year and the 2050 scenarios are shown Figure 7. These data are based on the output from the ASTRA model in the REFLEX consortium. Assumptions about the scenarios for transportation sector are given in (Herbst et al., 2017)

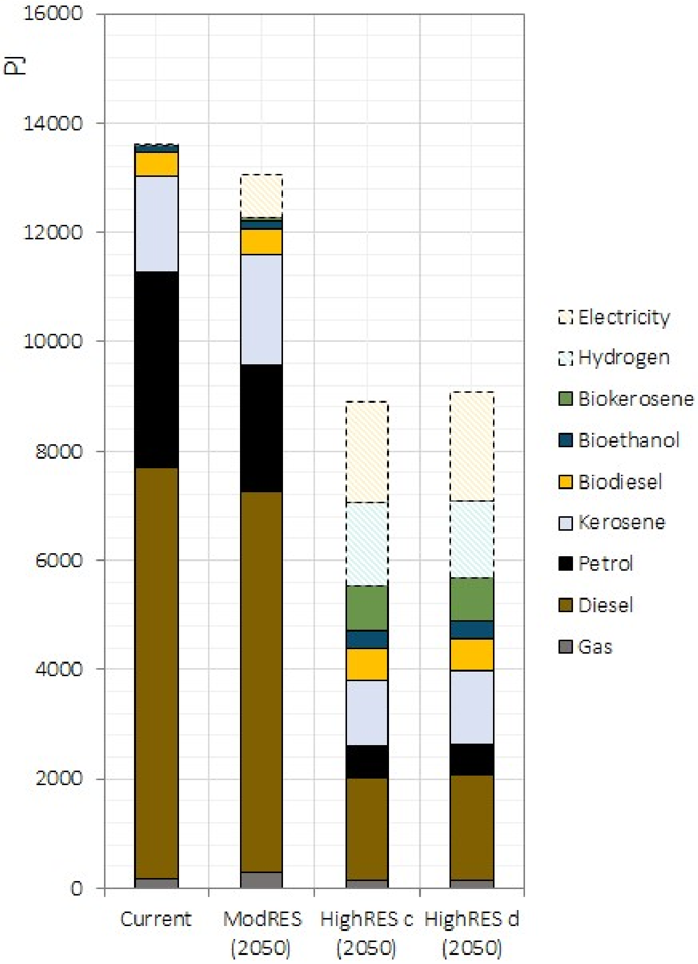

Figure 7: Final energy demand in the transport sector for all scenarios. Based on output from the ASTRA model in the REFLEX project.

2.3.3.1 Liquid fossil fuels in the transport sector

All of the liquid fossil fuels used in the transport sector use crude oil as the main input from the biosphere in their production. Therefore the same countries of origin for crude oil in their production are assumed, shown in Table 27, based on current Eurostat data (Eurostat, 2019). This mix of countries of origin is then used as the crude oil input to the EU market for crude oil, using the ecoinvent/SOCA process “market for petroleum | petroleum | cut-off, U – GLO” as the background process, where all processes other than the crude oil input described above are unchanged. This is used as a starting point for sLCI data for liquid fossil fuels in the transport sector. Due to a lack of data this same mix is assumed for all temporal perspectives – a preserving perspective for the production of LCI for future technologies according to the approach proposed in the REFLEX SELES framework. The consequences of this assumption are reflected upon in interpretation of numerical results.

Table 27: Countries of origin for crude oil (based on (Eurostat, 2019)) used to produce diesel, gasoline and kerosene for the transport sector. The table shows the background Ecoinvent/SOCA model used in the modelling. This mix is used in all temporal cases in the assessment.

Country of origin	Proportion	Ecoinvent/SOCA process
Russia	27%	petroleum production, onshore | petroleum | cut-off, U - RU
Norway	10%	petroleum and gas production, off-shore | petroleum | cut-off, U - NO
Iraq	7%	petroleum production, onshore | petroleum | cut-off, U - RME
Saudi Arabia	7%	petroleum production, onshore | petroleum | cut-off, U - RME
Kazakhstan	6%	petroleum production, onshore | petroleum | cut-off, U RoW
Nigeria	5%	petroleum and gas production, on-shore | petroleum | cut-off, U - NG
Azerbaijan	4%	petroleum production, onshore | petroleum | cut-off, U RoW
Iran	2%	petroleum production, onshore | petroleum | cut-off, U - RME
Algeria	2%	petroleum production, onshore | petroleum | cut-off, U - RAF
Mexico	2%	petroleum production, onshore | petroleum | cut-off, U RoW
Angola	2%	petroleum production, onshore | petroleum | cut-off, U - RAF
Other countries, non-EU	14%	petroleum production, onshore | petroleum | cut-off, U RoW
UK	7%	petroleum and gas production, off-shore | petroleum | cut-off, U - GB
Other EU	4%	petroleum production, onshore | petroleum | cut-off, U RoW

Crude oil from this market process is then used as the input into processes for production of the specific fuels in question. The background LCI processes used for these production processes for environmental and social assessment are shown in Table 28.

Table 28: Background LCI processes for liquid fossil fuels used in the transport sector. These processes are used in all temporal cases in the assessment. RER is the Ecoinvent term used to refer to the region of Europe.

Fuel type	Background LCI process in ecoinvent/SOCA
petrol	market for petrol, low-sulfur | petrol, low-sulfur | cut-off, U - Europe without Switzerland
diesel	market group for diesel, low-sulfur | diesel, low-sulfur | cut-off, U - RER
kerosene	market for kerosene | kerosene | cut-off, U - Europe without Switzerland

2.3.3.2 Bioethanol

According to data from (Flach, Lieberz, Lappin, & Bolla, 2018) the European Union is almost self-sufficient in bioethanol in the current situation. In light of this, it is assumed that all bioethanol is produced in the European Union and therefore according to European working conditions.

The original background process to represent 1 kg of ethanol production was selected to be "dewatering of ethanol from biomass, from 95% to 99.7% solution state | ethanol, without water, in 99.7% solution state, from fermentation | cut-off, U – Europe without Switzerland".

In sLCA, this in turn was customised by using an original background ecoinvent/SOCA process for bioethanol production from rye as an input – "ethanol production from rye | ethanol, without water, in 95% solution state, from fermentation | cut-off, U – RER".

In eLCA, the shares of European bioethanol produced from each feedstock type are further considered, based on recent statistics (ePure, 2017) for the year 2016, as shown in Table 29.

Table 29: Shares of pathways for biodiesel production used for environmental LCI. Shares based on recent statistics (ePure, 2017).

Proportion of total feedstocks	Ecoinvent processes
32%	ethanol production from rye | ethanol, without water, in 95% solution state, from fermentation | cut-off, U – RER
31%	ethanol production from maize | ethanol, without water, in 95% solution state, from fermentation | cut-off, U – CH
24%	ethanol production from sugarcane | ethanol, without water, in 95% solution state, from fermentation | cut-off, U – GLO
8%	ethanol production from sweet sorghum | ethanol, without water, in 95% solution state, from fermentation | cut-off, U – GLO
5%	ethanol production from wood | ethanol, without water, in 95% solution state, from fermentation | cut-off, U – GLO

It is further assumed that these LCI data are representative of potential activity variables and environmental or social risk for all scenarios - a preserving perspective for the production of LCI for future technologies according the approach proposed in the REFLEX SELES framework. This perspective is considered appropriate in light of the significant uncertainty in the future development of bioethanol demand and production in the EU. Furthermore, the demand in the scenarios considered here is still relatively low (see Figure 7).

In any case, the potential effect that this assumption has on the finally assessed social risks are taken up in the discussion section of the report.

2.3.3.3 Biodiesel

It is assumed that all biodiesel consumed in all scenarios is produced in the EU. In the current case, this is supported by the most recent statistics (Flach et al., 2018).

In eLCA, biodiesel production is assumed to be adequately represented by the production of vegetable oil methyl ester, based on the Ecoinvent database, considering the desire for a simplified modelling approach to address the broad scope of the assessment. The original background process to represent 1 kg of biodiesel production was selected to be “treatment of waste cooking oil, purified, esterification | vegetable oil methyl ester | cut-off, U -FR”.

Furthermore, the mix of processes assumed for biodiesel production for the s-LCA inventory are shown in Table 30, in light of the considerations that a certain proportion of biodiesel feedstocks are imported (Transport and Environment, 2017).

A common assumption for both eLCA and sLCA is that these inventories are relevant for all scenarios. This is judged to be a reasonable assumption in light of the significant uncertainty about the future development of biodiesel production pathways and the relatively small shares for biodiesel in any of the scenarios considered (see also Figure 7). The consequences of these assumptions are further addressed in discussion of the sLCA results.

Table 30: Shares of pathways for biodiesel production used for social LCI. The processes given below are those used as custom inputs into the original ecoinvent/SOCA background process "market for vegetable oil methyl ester | second screening| cut-off, U – GLO". The process represents 1 kg "vegetable oil methyl ester"

Amount	Unit	Original ecoinvent/SOCA background to this process	Notes
0.27	kg	esterification of palm oil | vegetable oil methyl ester | cut-off, U - RoW	Based on the current import of palm oil for biodiesel production (Transport and Environment, 2017)
0.15	kg	treatment of waste cooking oil, purified, esterification | vegetable oil methyl ester | cut-off, U - FR	Based on data on the potential for biodiesel production from used cooking oil (Baker et al., 2017) and (Transport and Environment, 2017)
0.58	kg	esterification of rape oil | vegetable oil methyl ester | cut-off, U - Europe without Switzerland	In this model, the process for rape oil production has been changed compared to the original to reflect data for current feedstock origins given in (Baker et al., 2017). See also Table 31

Table 31: Region-specific shares and background processes used to model rape seed production for social LCI and used as custom input to original background process "rape oil mill operation | rape oil, crude | cut-off, U – Europe without Switzerland". In turn this process is used as a custom input to the original background process "esterification of rape oil | vegetable oil methyl ester | cut-off, U - Europe without Switzerland" shown in Table 30.

Proportion of total rape seed input	Original background process	Notes
67%	rape seed production | rape seed | cut-off, U - DE	The activity variable and risk profile are changed from the German original to reflect average European conditions. This is in the ISIC sector 0111 - Growing of cereals, leguminous crops and oil seeds
33%	rape seed production | rape seed | cut-off, U - RoW	This process is not changed from the original for the model developed

2.3.3.4 Biokerosene

In aviation, only high quality paraffinic biofuels can be adopted. Camelina oil is regarded as the best available sustainable feedstock that can be easily produced in order to meet expected demand for jet biofuel. Considering the data availability, jatropha, a plant with similar characteristic with camelina oil (Campbell, 2018; Heinrich, 2018) is chosen as the feedstock to model biokerosene production for all scenarios. Biomass must be converted through advanced processes into pure hydrocarbon fuels (Chiaramonti, Prussi, Buffi, & Tacconi, 2014). Esterification is still considered the effective conversion process. In light of this, biokerosene production is modelled using processes originally for biodiesel production due to lack of any related process. For the e-LCI, these are adapted in terms of feedstock production and feedstock input, with data from (Hou, Zhang, Yuan, & Zheng, 2011). Specifically, the Ecoinvent process "esterification of soybean oil | vegetable oil methyl ester | cut-off, U – B" is selected to represent the background data for 1 kg biokerosene production. The upstream feedstock i.e. soybean oil production is removed and replaced by jatropha oil production (1 kg of biokerosene requires 1.108 kg of jatropha oil). Additionally, to produce 1 kg of jatropha oil, 3.33 kg of jatropha seed is required.

Similarly, the LCI of biokerosene production for s-LCA assessment is summarized in Table 32. First, a global process is considered to model jatropha production, which is considered appropriate in light of the uncertainty about the future production chain for biokerosene. Secondly, it is assumed that the seed is then processed into oil, assuming the same milling process as for rape seed and according to conditions for ecoinvent's "rest of world" category. This is based on the assumption that crude oil will be produced from the jatropha outside of Europe. The quantity of jatropha seed input for each kg of oil produced is based on Hou et al. (2011). Finally, the oil undergoes an esterification process that is assumed to take place at European conditions.

Table 32: Summary of key processes for sLCI used to model biokerosene production for all future scenarios

Row number	Process to be modelled	Name of original ecoinvent background process	
1	Jatropha seed production	market for jatropha seed | jatropha seed | cut-off, U – GLO	No change from original
2	Oil production from Jatropha seed	rape oil mill operation | rape oil, crude | cut-off, U – Europe Rest of World	Jatropha seed substituted for rape seed, see row 1, this table and Hou et al. (2011)
3	Biokerosene production from Jatropha oil	esterification of rape oil | vegetable oil methyl ester | cut-off, U – Europe without Switzerland	Assume oil production from process in row 2, this table

Since no industrial-scale process for biokerosene production exists, the process here is largely based on general considerations of technical potential according to the perspectives for creating future LCI presented in the REFLEX SELES framework.

2.3.3.5 Natural gas in the transport sector

It is assumed that all types of gas used in the transport sector (compressed natural gas, liquefied natural gas) can be modelled using the same LCI processes as for gas supply for electricity production, see section 2.3.2.3.

2.3.3.6 Electricity demand in the transport sector

For electricity demand in the transport sector, the scenario-based electricity mix shown in Figure 6 is used.

2.3.3.7 Hydrogen production in the transport sector

Amongst the sectors considered in the assessment, the transport sector has the highest demand for hydrogen as an energy carrier across the scenarios considered (see Figure 7).

Modelling hydrogen for the assessment takes as a starting point the assumption that all hydrogen is produced by electrolysis. The modelling focusses on three stages for hydrogen production: Firstly, LCI for the electrolysis plant, secondly the production and compression of hydrogen ready for transport by pipeline or direct use and thirdly, hydrogen transport by pipeline.

Data for the electrolysis plant (the capital in the process) is taken from an eLCA study of 1 MW polymer electrolyte membrane-based plant, cf. Bareiss, de la Rua, Mockl, and Hamacher (2019). Data for material input for the plant, considering the material demand and plant lifetime is taken directly from

Bareiss et al. (2019). To model the construction of the electrolysis plant itself from the raw material input, cost for an electrolysis plant were based on a recent expert elicitation study on future costs for such plants (Schmidt et al., 2017). It was then assumed that the construction was performed in the ISIC sector “4290: Construction of other civil engineering products” and was carried out according to European average conditions. Based on these assumptions, the activity variable (in worker hours) and the social risk profile for the process of plant construction was produced from relevant data in the SOCA add-on.

Foreground input data for plant operation is also based on Bareiss et al. (2019). These data together with the LCI background processes used in conjunction with them to model hydrogen production are given in Table 33 below. In order to establish a social profile for hydrogen production, the cost of the production was first estimated to be 6.85 Euro/kg H_2 based on data presented in Bareiss et al. (2019) and Schmidt et al. (2017). It was further assumed that the hydrogen production process itself was carried out according to European average conditions and with the same risk profile as the ISIC sector “3510 - Electric power generation, transmission and distribution”. This was considered appropriate given that electrolysis is essentially a backwards electricity generation process. Based on these assumptions, the activity variable (in worker hours) could further be calculated from existing data in the SOCA add-on.

Table 33: Summary of LCI input data for operation of electrolysis plant for hydrogen production in the assessment. The data is given for the quantitative reference of 1 kg compressed hydrogen.

	Amount	Unit	Notes	LCI process
Electricity demand	55	kWh	Quantity based on Bareiss et al. (2019).	Average scenario-based electricity mix including 10 % losses for distribution (see Figure 6 and section 2.3.2)
Capital plant	9.26e-7	Item(s)	Based on plant lifetime given in (Bareiss et al. 2019)	New process, described in text in this section
Water	9	kg	Based on (Bareiss et al. 2019)	Water demand for operation
Social profile for hydrogen production and compression – see text in this section				

In addition, it is assumed that after production hydrogen is transported by pipeline on average 1,000 km, which is our own judgement in light of the size of the European continent. For the social assessment this is modelled by an ecoinvent/SOCA process for natural gas transportation, “transport, pipeline, long distance, natural gas | transport, pipeline, long distance, natural gas | cut-off, U - RER w/o DE+NL+NO”. To reflect the fact that hydrogen transportation is more economically and labour intensive than transportation of natural gas, it is assumed for the purposes of the social assessment that hydrogen transportation is five times more expensive than transportation of natural gas. This is in order to provide a conservative assumption for the process. Therefore transporting 1 kg compressed hydrogen 1,000 km requires a quantity of 5 tkm of the background process “transport, pipeline, long distance, natural gas | transport, pipeline, long distance, natural gas | cut-off, U - RER w/o DE+NL+NO”.

In modelling hydrogen production, a technical potential perspective is applied when developing future LCI according to the discussion in developing the REFLEX SELES framework.

2.3.4 Residential and tertiary sectors

Foreground data in terms of the final energy demand in the residential and tertiary sectors for the EU for the temporal cases considered are shown in Figure 8 below. The data is based on the output from the Forecast model in the REFLEX consortium.

The data as shown in Figure 8 were produced from the original Forecast data received by reassigning certain categories. In particular, the original Forecast output data indicated a certain level of demand in each scenario (up to about 15 % of the total final energy demand for a given scenario) for district heating. No data on the energy carriers used for district heating were available for the assessment however. Therefore, the district heating demand as modelled in Forecast was reassigned to the other energy carriers in the system in proportion to their original proportion in the mix less district heating.

As discussed earlier, eLCA for the residential and tertiary sectors as with other end-use sectors focuses on the production of upstream energy carriers to be used, with no consideration of energy conversion process taking place in end-use sectors.

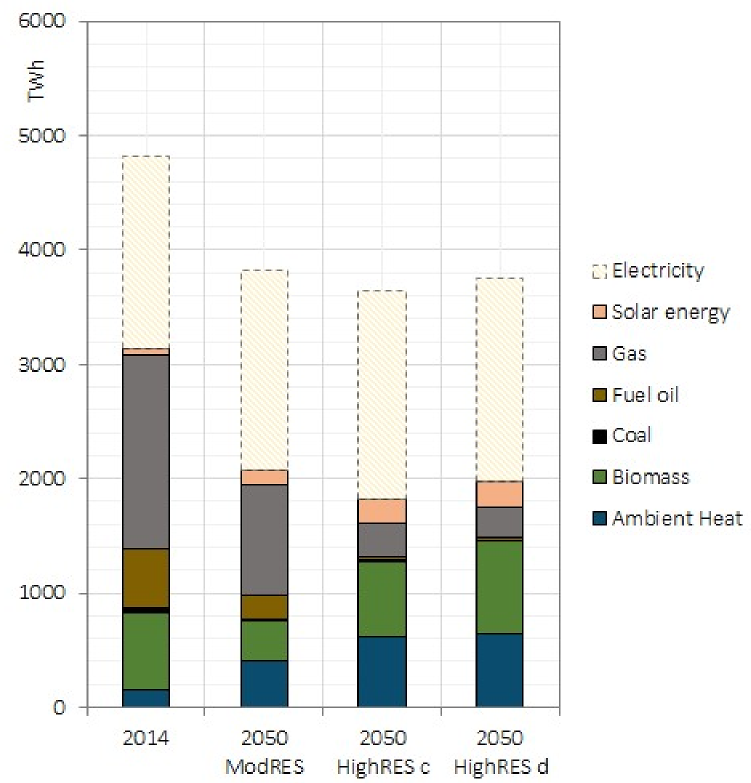

Figure 8: Energy demand in base year and all scenarios for EU in residential and tertiary sectors

Social LCI

The background processes used for social LCI for each energy carrier in the sector are shown in Table 34. The table highlights how changes were made to the original ecoinvent processes for the LCI model used in this study. Processes with the geographical scope covering “Europe without Switzerland” were chosen as the most appropriate to model average European conditions from a social perspective. The main amendment to the original background processes is to use supply mixes for fossil fuels in the sector based on the countries of origin according to Eurostat (see Table 21, Table 22 and Table 27 for gas, oil and coal respectively) and also shown in the table. For biomass the fuel supply in the original process was already based on average European conditions therefore no change was necessary to the background process chosen.

In the case of ambient heat, the original background process shown in Table 34 represents heat production from a heat pump. Since the purpose of the process in this study is only to represent the ambient heat part, this original process was amended by reducing the electricity input (which in this study is covered in the electricity demand in the different scenarios, see Figure 6) to zero, and then by reducing the amount of heat in the process output by the same amount of energy. As shown in the table, the heat output of the process is therefore reduced to 0.65 MJ.

Table 34: Background ecoinvent processes used for modelling supply chains for energy carriers in the residential and tertiary sectors. These background processes are used in all scenarios.

	Original background processes	Amendments made to original background process
Ambient heat	heat production, air-water heat pump 10kW | heat, air-water heat pump 10kW | cut-off, U – Europe without Switzerland	Electricity input reduced to zero (see accompanying text for explanation). Output of process changed to 0.65 MJ of heat (instead of the previous 1 MJ)
Coal	heat production, hard coal briquette, stove 5-15kW | heat, central or small-scale, other than natural gas | cut-off, U – Europe without Switzerland	Coal supply mix based on countries of origin as in Table 22
Fuel oil	heat production, light fuel oil, at boiler 10kW condensing, non-modulating | heat, central or small-scale, other than natural gas | cut-off, U – Europe without Switzerland	Fuel oil supply mix based on countries of origin as shown in Table 27
Biomass	heat production, wood pellet, at furnace 9kW, state-of-the-art 2014 | heat, central or small-scale, other than natural gas | cut-off, U – Europe without Switzerland	No changes necessary – fuel supply already based on average European conditions
Natural gas	heat production, natural gas, at boiler fan burner non-modulating <100kW | heat, central or small-scale, natural gas | cut-off, U – Europe without Switzerland	Natural gas supply mix based on countries of origin as shown in Table 21
Electricity	Electricity mix in residential and tertiary sectors according to electricity production for each scenario. See Figure 6.	

Environmental LCI

As only upstream production processes to produce energy carriers are considered, renewables used in industry e.g. ambient heat, solar energy, the cradle to gate upstream emissions are assumed as zero. Table 35 shows the processes used in all scenarios. Note that from an environmental perspective, district heating is considered and based on a background ecoinvent process, assuming natural gas as the fuel used for heat production.

Table 35: Ecoinvent processes used for modelling supply chains for energy carriers in the residential and tertiary sectors for eLCI.

Type of energy carriers	Name of process used in modelling
Biomass	Market for wood chips, wet, measured as dry mass, Europe without Switzerland (50%) Market for wood pellet, measured as dry mass, Europe without Switzerland (50%)
Coal	Market for hard coal | hard coal | cut-off, U, WEU
Electricity	According to electricity production for each scenario. See Figure 6
Fuel oil	market for heavy fuel oil | heavy fuel oil | cut-off, U, Europe without Switzerland
Natural gas	market group for natural gas, high pressure | natural gas, high pressure | cut-off, Europe without Switzerland
Ambient heat	Excluded from the assessment

Conversion of energy carriers is made according to their lower calorific values (see Table 36).

Table 36: Conversion factors for energy carriers used for eLCI for assessment of the residential and tertiary sectors.

Type of energy carriers	Unit	Conversion factors
Biomass	MJ/kg	4.3
Coal	MJ/kg	30
District heating	MJ	1
Electricity	MJ/kWh	3.6
Fuel oil	MJ/kg	43.8
Natural gas	MJ/kg	53.2

For residential and tertiary sectors a principally technical preserving perspective is used when establishing future LCI, according to the approaches discussed in the REFLEX SELES framework.

2.3.5 Industry Sector

Foreground data for the assessment in terms of the final energy demand disaggregated by energy carrier for all scenarios in the industry sector are shown in Figure 9. The data is based on the output from the Forecast model in the REFLEX consortium.

The data as shown in Figure 9 was produced from the original Forecast data received by reassigning certain categories. In particular, the original Forecast output data indicated a certain level of demand in each scenario (up to about 10 % of the total final energy demand for a given scenario) for district heating. No data on the energy carriers used for district heating was available for the assessment. Therefore, the district heating demand as modelled in Forecast was reassigned to the other energy carriers in the system in proportion to their original proportion in the mix less district heating.

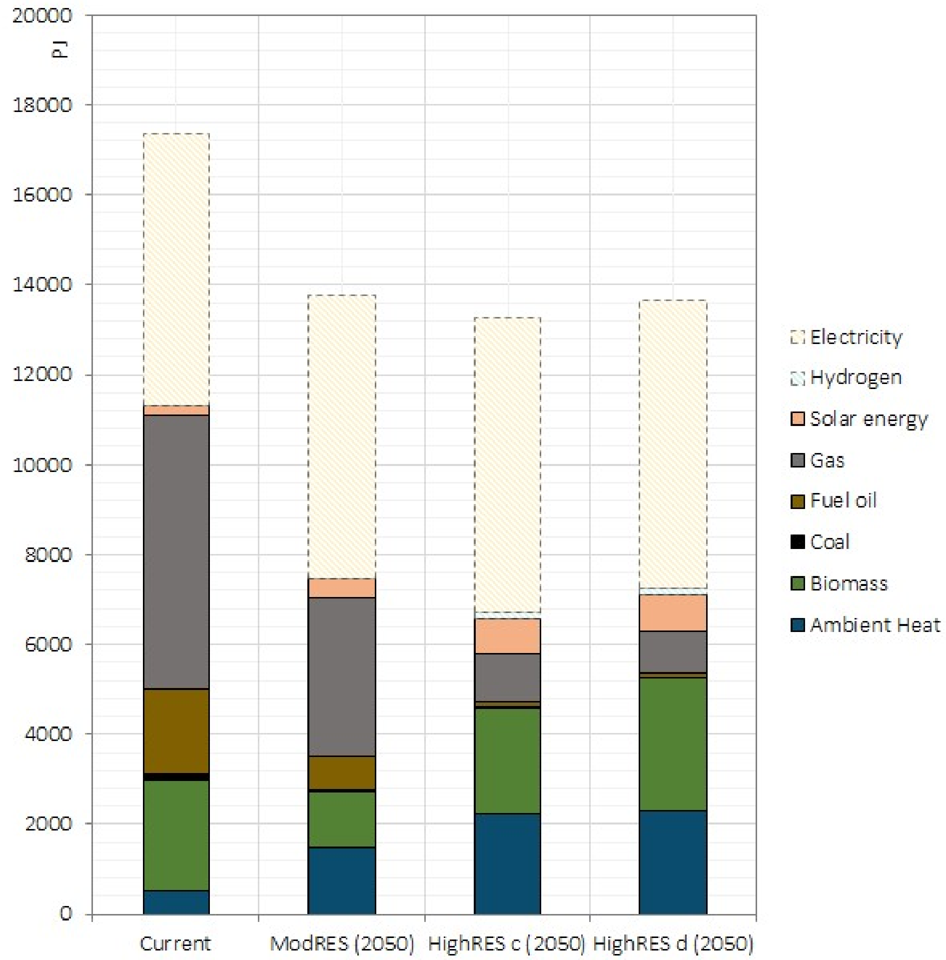

Figure 9: Final energy demand in the industry sector for all scenarios. Based on output from the Forecast model in the REFLEX consortium.

Social LCI

In light of the broad scope of the study, LCI in the industry sector is simplified. The background processes used for social LCA for each energy carrier in the sector are shown in Table 37. In selecting these background processes it is noted for the solar thermal that a process representing Europe was not directly available. A process representing Switzerland was nonetheless deemed appropriate for this energy carrier in light of the relatively small contribution it makes in the overall energy mix for the sector (see Figure 9). In the case of biomass, a Swiss process was chosen for the final conversion in view of the lack of a process more representative for European conditions.

Table 37: Background Ecoinvent processes used for modelling supply chains for energy carriers (except hydrogen) in the industrial sector. These background processes are used in all scenarios.

Energy carrier	Original background process	Amendments made to original background process
Coal	heat production, at hard coal industrial furnace 1-10MW | heat, district or industrial, other than natural gas | cut-off, U – Europe without Switzerland	Coal supply mix based on countries of origin as in Table 22
Fuel oil	heat production, heavy fuel oil, at industrial furnace 1MW | heat, district or industrial, other than natural gas | cut-off, U - Europe without Switzerland	Fuel oil supply mix based on countries of origin as shown in Table 27
Natural gas	heat production, natural gas, at industrial furnace low-NOx >100kW | heat, district or industrial, natural gas | cut-off, U – Europe without Switzerland	Natural gas supply mix based on countries of origin as shown in Table 21
Biomass	hardwood chips from forest, at furnace 5000kW, state-of-the-art 2014 | heat, district or industrial, other than natural gas | cut-off, U - CH	Wood chips supplied from European market to better represent European conditions
Solar thermal	operation, solar collector system, Cu flat plate collector, multiple dwelling, for hot water | heat, central or small-scale, other than natural gas | cut-off, U- CH	
Electricity	Electricity mix in industrial sector according to electricity production for each scenario. See Figure 6.	
Hydrogen	As for transport sector (see next section)	

In order to make supply chains as representative as possible for energy carriers in the sector, countries of origin for the fossil fuels listed in Table 37 are based on those used for other sectors (see Table 21, Table 22 and Table 27 for gas, oil and coal respectively). In the case of biomass, it was assumed for the social LCI that the wood chip fuel is produced on the European market.

Environmental LCI

Similar to the residential and tertiary sector, the ecoinvent processes used to model environmental LCI are shown in Table 38.

Table 38: Background ecoinvent processes used for modelling supply chains for energy carriers (except hydrogen) in the industrial sector for environmental LCI. These background processes are used in all scenarios.

Type of energy carrier	Name of process used in modelling
Biomass	Market for wood chips, wet, measured as dry mass, Europe without Switzerland (50%) Market for wood pellet, measured as dry mass, Europe without Switzerland (50%)
Coal	Market for hard coal | hard coal | cut-off, U, WEU
Electricity	According to electricity production for each scenario. See Figure 6.
Fuel oil	Market for heavy fuel oil | heavy fuel oil | cut-off, U, Europe without Switzerland
Natural gas	market group for natural gas, high pressure | natural gas, high pressure | cut-off, Europe without Switzerland
Ambient heat	Not considered as giving rise to environmental impacts in supply

In light of the special consideration of hydrogen designed for the centralized and decentralized world, hydrogen transport is included in the assessment, along with the hydrogen production, the LCI of which is assumed the same as the transport sector (see section 2.3.3).

There are three possible supply chains for hydrogen transport, i.e. pipelines, gas truck transport as well as liquid organic hydrogen carriers (LOHCs). An investigation performed by Wulf et al. (2018) that shows that pipeline has the lowest life cycle environmental impacts for most of the cases compared to the other transport solutions. In light of this, pipeline is chosen as the transport option for all scenarios, but with different daily hydrogen transport amount and transport distances assumption (see Table 39).

Table 39: Transport quantities and distances for hydrogen for future scenarios, used in eLCI.

Scenarios	Daily amount (t)	Distances (km)	Considerations
Mod-RES 2050	10	400	the hydrogen demand in mod-res scenario is rather low compared to both High-RES scenarios
High-RES Central	80	400	A longer distance need for centralized world
High-RES Decen.	40	100	a shorter distance considering that the plants are near-site; a lower demand, as smaller capacity plants are designed for

The LCI of hydrogen pipeline transport is based on the work of Wulf et al. (2018). The construction of these pipelines is considered similar to that of natural gas pipelines. The main changes are the diameters and, by then, the thickness of the pipeline. Therefore, the ecoinvent process for natural gas pipelines (transport, pipeline, long distance, natural gas | transport, pipeline, long distance, natural gas | cut-off, U) is referred to and adapted for hydrogen in terms of the special coating used to prevent hydrogen diffusion. The coating called GALVALUME is an alloy that consists of aluminium, zinc and silicon (Krieg, 2012). The LCI for GALVALUME is from Wulf et al. (2018).

3 METHODS: SPATIALLY DISAGGREGATED IMPACT PATHWAY ANALYSIS OF DIRECT EMISSIONS

The approach to calculate the external costs of direct pollutant emissions is based on the Driver-Pressure-State-Impact-Response (DPSIR) framework. Based on the chain of causality human caused drivers (use of primary energy sources) are linked to pressures on the environment (emissions), changes of environmental states (air quality, human health) and eventually responses to correct the situation (constraints imposed on energy scenarios). "Drivers", "Pressures" and "Responses" are addressed with the "REFLEX energy modelling system" whereas "States", including the level of ambient air concentration and deposition of pollutants, are covered by Polyphemus - which is a full system for air quality modelling. Health impacts are limited to people's long-term exposure to fine particulate air pollution.

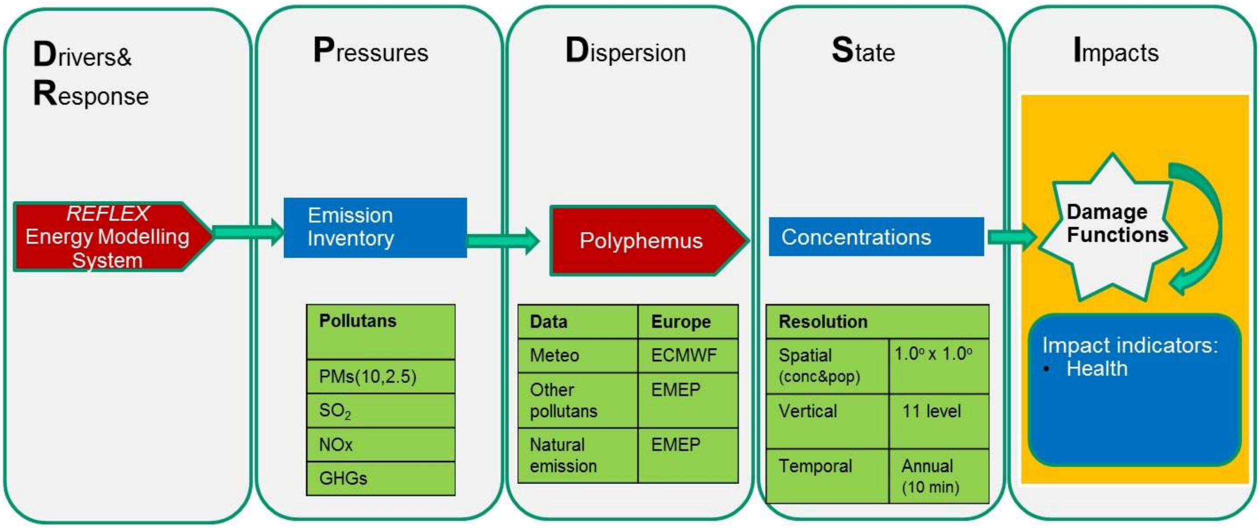

Figure 10: The steps of analysis of external costs of direct emissions.

3.1 Goal and Scope of the Analysis

The main goal of the Impact Pathway Analysis was to estimate health impacts and external costs of direct emissions in the REFLEX scenarios. The analysis was performed for a domain covering Europe with a starting point from 12.0°W longitude and 35.0°N latitude and consists of 40 x 34 cells with a horizontal resolution of 1.0° x 1.0° (along longitude and latitude respectively, see Figure 11). The following simulation cases were considered: (i) anthropogenic emissions based on EMEP (European monitoring and evaluation program) emission data from 2015 and on REFLEX emission data for 2015 for SNAP1* (SNAP – selected nomenclature for sources of air pollution) and SNAP7* (current situation) and (ii) based on REFLEX emission data (all scenarios) for 2050 for SNAP1* and SNAP7* (remaining emissions as in (i)).

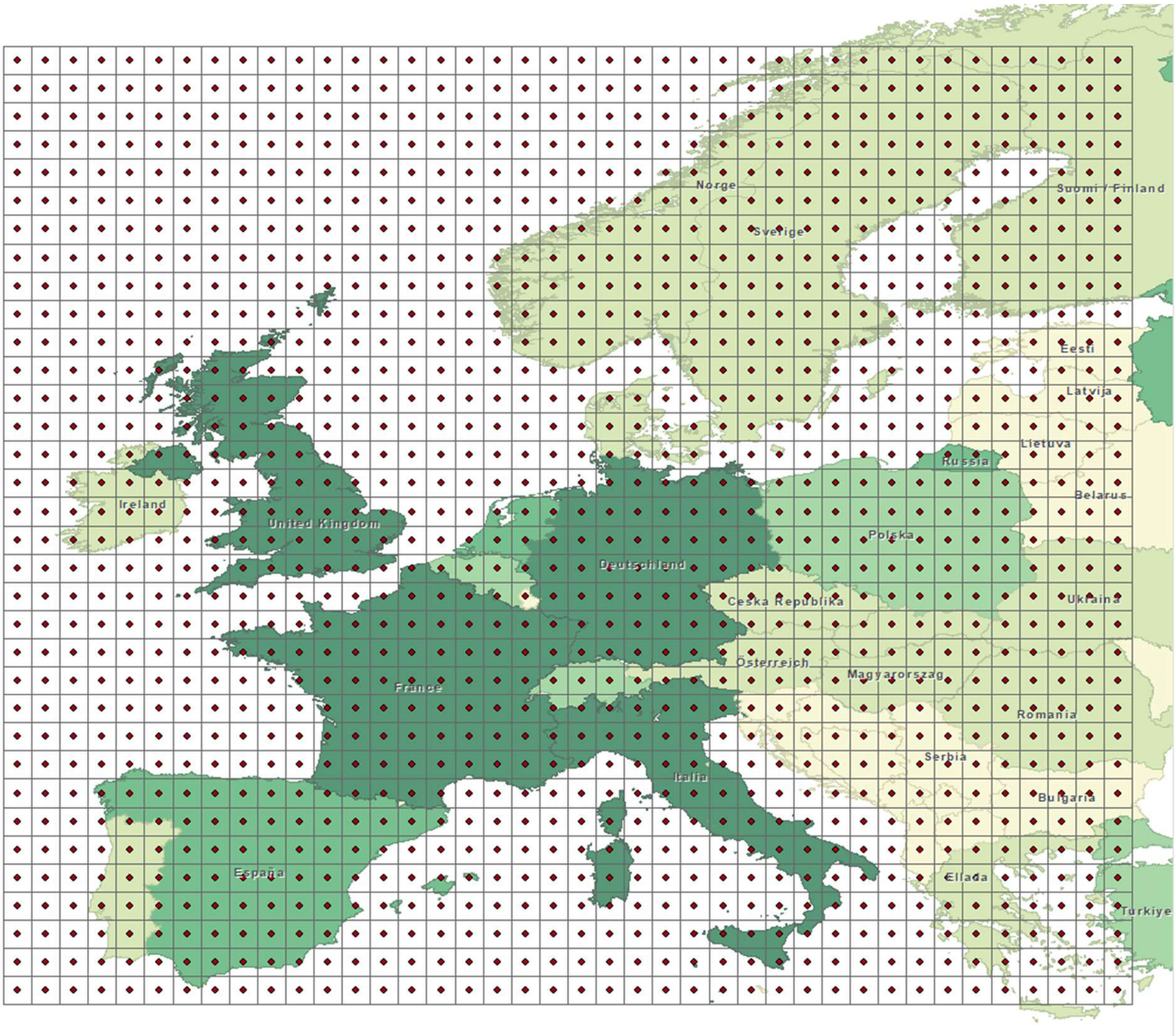

Figure 11: Modelling domain for estimation of health impacts and external costs.

3.2 Description of methodology and tools

3.2.1 Emissions scenarios

Emissions scenarios were prepared based on the results of the ELTRAMOD, TIMES-HEAT-EU and ASTRA models for different REFLEX scenarios including consumption of fuels (so called activity) in power and district heat generation. Subsequently, emission factors (only for direct emissions) of different pollutants were applied for the activity data to derive the emission scenarios. For instance, the TIMES-HEAT-EU uses the emission factors provided by the European Environment Agency (2016) and the applied emission factors (for PM2.5 only) are presented in Table 40.

Table 40. PM2.5 emission factors applied in TIMES-HEAT-EU model

Technology	Value	Lower	Upper	Unit	Table*	Page*
Hard coal	3.4	0.9	90.0	g/GJ	3.2	16
Brown coal	3.2	1.0	32.0	g/GJ	3.3	17
Gas	0.9	0.4	1.3	g/GJ	3.4	18
Heavy oil	19.3	0.9	90.0	g/GJ	3.5	19
Fuel oil	0.8	0.3	2.5	g/GJ	3.6	20
Biomass	133.0	66.0	266.0	g/GJ	3.7	20
Wet bottom Boiler - hard coal	3.1	3.0	12.0	g/GJ	3.14	29
Fluid bed boilers using brown coal	5.2	3.0	12.0	g/GJ	3.15	30
Fluid bed boilers using hard coal	2.8	0.9	8.4	g/GJ	3.16	31
Gas turbine - gaseous fuels	0.2	0.1	0.8	g/GJ	3.17	33
Gas turbine - gas oil	2.0	0.7	5.9	g/GJ	3.18	33
Reciprocating engine - natural gas	21.7	10.8	43.4	g/GJ	3.19	35
Reciprocating engine - gas oil	2.0	1.0	3.0	g/GJ	3.20	36

*In the European Environment Agency (2016)

In the case of ELTRAMOD emissions were calculated based on the power production level by each technology and emission factors provided by the LCA team in this work package. These emission factors covered only direct emissions from operation of power generation technologies. They were based on the ECOINVENT database with updated efficiency of power generation technologies according to the ELTRAMOD assumptions.

With reference to the transport sector, the results of the ASTRA model have been used: results of the REFLEX scenarios in terms of Tank to Wheel yearly emissions of air pollutant (CO, NOx, VOC, PM2.5) and CO_2 were provided by TRT. Emissions were related to land modes (road, rail, inland waterways) for both passenger and freight transport demand, as well as air passenger mode and freight maritime ship mode. Emissions from air mode were treated by separating the contribution of the LTO cycle (Landing and Take-Off) and the cruise phase, because the vertical level of these emissions is different (i.e. they are released at different heights which influences their atmospheric dispersion). The outputs in terms of emissions at country level have been further elaborated with exogenous procedures and data assumptions in order to estimate the time profile (over a typical working day, a typical non-working day, and during the months of the year) and were spatially-distributed based on data from EMEP and the Centre on Emission Inventories and Projections (EMEP/CEIP, 2019).

Exemplary pollutants emissions levels from power and district heat generation for the Mod-Res scenario are presented in Table 41 and Table 42 for 2015 and 2050, respectively.

Table 41. Total pollutants emissions in 2015 from ELTRAMOD and TIMES-HEAT-EU, Mod-Res.

Country	Pollutant emission [t]				
	NO_x	NMVOC	$SO_2(SO_x)$	PM10	PM2.5
AT	17655.42	705.8705	15481.26	9603.674	8176.672
BE	20802.35	717.3335	5878.368	8928.68	7675.167
BG	14716.48	98.94921	58732.62	1137.424	863.3864
CH	1.822792	0	0.018228	0.018228	0.018228
CY	1642.096	1.00043	194.6493	26.34033	24.9737
CZ	38010.85	533.5722	304898.5	7516.767	5862.295
DE	270301.4	4592.588	330033.2	72940.52	62475.24
DK	21676.25	680.9811	45716.64	11493.23	9696.146
EE	6010.219	138.9628	13596.67	2381.177	2032.31
ES	53109.1	834.9857	32160.28	6691.62	5786.843
FI	41493.19	2264.039	124940.9	38362.92	32607.91
FR	26400.06	915.2249	21751.69	10351.43	8809.057
GB	106690.5	725.8427	76213.94	7186.275	6307.892
GR	24328.8	50.82626	22029.26	2018.828	1769.814
HR	2531.635	34.17282	2682.859	174.264	151.0985
HU	12324	236.8374	10672.77	1647.289	1415.993
IE	9865.809	95.79512	4741.797	396.7724	356.2198
IT	137454.1	2228.382	56074.92	18285.47	15818.71
LT	6526.314	268.1187	1258.785	4326.008	3709.397
LU	481.629	13.07734	1.753174	4.81629	4.81629
LV	5997.445	195.2453	363.9016	2726.424	2345.479
MT	893.2698	0	653.4124	51.36207	45.95064
NL	59975.56	1096.614	25505.24	8165.402	7019.463
NO	88.45155	11.79363	147.4193	0	0
PL	142232.6	895.5883	478088.6	16037.36	12696.48
PT	14124.16	461.2654	5897.517	6968.207	5986.041
RO	18389.35	273.8858	60266.58	2241.5	1839.63
SE	26281.13	2176.341	25805.7	41327.68	35391.45
SI	5062.295	57.43448	17274.02	1024.179	858.0139
SK	13583.24	596.506	92848.09	10371.92	8670.885

Table 42. Total pollutants emissions in 2050 from ELTRAMOD and TIMES-HEAT-EU, Mod-RES.

Country	Pollutant emission [t]				
	NO_x	NMVOC	$SO2(SO_x)$	PM10	PM2.5
AT	24522.58	1149.641	2431.929	23650.57	20324.65
BE	21445.73	737.3326	1508.914	11542.61	9937.138
BG	6003.293	179.3549	299.6225	1448.953	1250.948
CH	444.7816	0	11.97247	11.41897	11.41897
CY	223.9753	0.918211	58.77438	7.955482	7.595311
CZ	15641.33	960.2315	6358.831	17439.76	14959.31
DE	119953.9	4538.213	28331.64	80393.94	68963.49
DK	21819.65	786.4118	1512.69	14828.21	12733.74
EE	12882.48	187.5987	8220.73	4690.096	4054.197
ES	27538.33	1007.935	1032.606	13572.13	11669.42
FI	37372.84	2567.633	6773.199	49084.38	42119.38
FR	39950.41	1666.201	3268.602	35230.49	30286.66
GB	27283.41	1141.541	4882.459	8158.782	7042.411
GR	1728.648	87.39669	128.6097	881.0036	758.6637
HR	1788.126	66.04909	102.7326	1206.644	1038.338
HU	8070.291	517.6166	744.8045	9282.359	7972.208
IE	4453.114	157.3882	637.3176	1966.244	1696.685
IT	75110.73	2224.604	3771.004	38857.07	33398.54
LT	4775.887	360.8754	577.8947	7592.716	6515.657
LU	1195.634	30.16099	63.13329	634.9436	547.6036
LV	3908.117	260.6847	395.8012	5528.188	4744
MT	354.0919	0	255.8806	23.34416	21.19965
NL	41507.82	1243.078	2497.673	13587.84	11719.56
NO	169.7036	22.62731	282.8393	0	0
PL	72685.9	1642.351	3947.169	27430.82	23575.73
PT	9099.898	676.875	1072.751	14152.09	12144.7
RO	7993.874	407.2296	689.7969	3258.749	2809.531
SE	26402.22	1885.548	4918.634	36146.08	31016.3
SI	1865.162	91.26578	180.3004	1579.712	1358.989
SK	13315.35	279.8384	362.5939	1328.301	1156.875

Table 43 and Table 44 show pollutants emissions from the transport sector.

Table 43. PM2.5 emission from transport in 2015, Mod-Res

Country	PM2.5 emission [1000 t]					
	Road Passenger	Road Freight	Railways	Shipping	Airplane	Inland Water Ways
AT	1.21373	0.732257	0.34227	0	0.342718	0.037637
BE	1.9042	0.726062	0.18244	0.243666	0.395693	0.175845
DK	0.360511	0.370686	0.15764	0.079516	0.378328	0
ES	5.13519	3.41002	0.730063	0.441575	3.04207	0
FI	0.770875	0.472829	0.200328	0.257994	0.298702	0.002392
FR	12.3656	5.28291	1.456	0.594818	2.39312	0.141515
UK	4.85323	3.91734	1.25138	0.761616	3.51227	0.00316
DE	11.143	8.06894	2.41944	0.298293	2.71087	1.1187
GR	0.397249	0.550112	0.040635	0.169778	0.818264	0
IE	0.405574	0.253919	0.039468	0.067041	0.482738	0
IT	9.02856	3.67434	0.88517	0.620852	1.92561	0.00196
NL	1.18771	1.288	0.231316	0.414742	0.747337	0.756301
PT	1.64563	0.538728	0.069521	0.103512	0.521791	0
SE	1.12099	0.760796	0.298658	0.270356	0.657213	0
BG	0.405324	0.255674	0.107451	0.040689	0.154768	0.062221
CH	0.772688	0.553667	0.34057	0	0.616428	0.000638
CY	0.02362	0.039623	9.43E-07	0.019741	0.841558	0
CZ	0.422514	0.701759	0.459934	0	0.312405	0.00125
EE	0.073336	0.071062	0.044552	0.087542	0.025625	0
HU	0.27935	0.513211	0.28143	0.002276	0.15542	0.042712
LV	0.08237	0.126854	0.107591	0.309462	0.050549	0
LT	0.188704	0.158049	0.091797	0.043962	0.046138	4.4E-05
MT	0.016806	0.010258	2.95E-07	0.029223	0.154036	0
NO	0.674655	0.43969	0.10847	0.359067	0.700031	0
PL	1.23855	3.01493	0.770254	0.141659	0.371466	0.004174
RO	0.520586	0.434111	0.409878	0.053799	0.166166	0.183329
SI	0.20075	0.237038	0.068974	0.021166	0.026622	0
SK	0.290948	0.339811	0.160042	0	0.04768	0.028057
LU	0.107182	0.063343	0.012242	7.78E-05	0.033156	0.004535
HR	0.239572	0.188694	0.084194	0.35443	0.118192	0.01553

Table 44. PM2.5 emission from transport in 2050, Mod-Res.

Country	PM2.5 emission [1000 t]					
	RoadPass	RoadFre	Railways	Shipping	Airplane	Inland Water Ways
AT	0.5	0.9	0.4	0.0	0.4	0.0
BE	1.0	1.0	0.3	0.3	0.5	0.2
DK	0.2	0.4	0.1	0.1	0.6	0.0
ES	2.9	3.7	0.8	0.9	4.9	0.0
FI	0.3	0.5	0.2	0.2	0.4	0.0
FR	5.2	6.4	1.9	0.4	2.9	0.2
UK	3.8	3.5	0.8	1.0	3.5	0.0
DE	4.2	7.1	2.6	0.2	3.5	1.4
GR	0.2	0.6	0.0	0.1	1.0	0.0
IE	0.4	0.4	0.0	0.1	0.6	0.0
IT	4.4	3.4	1.0	0.4	2.2	0.0
NL	0.4	1.1	0.2	0.4	0.8	1.1
PT	0.5	0.6	0.1	0.1	0.6	0.0
SE	0.3	0.8	0.4	0.3	0.8	0.0
BG	0.3	0.3	0.1	0.0	0.2	0.1
CH	0.4	0.6	0.4	0.0	0.5	0.0
CY	0.0	0.0	0.0	0.0	0.7	0.0
CZ	0.4	0.8	0.4	0.0	0.5	0.0
EE	0.1	0.1	0.0	0.1	0.1	0.0
HU	0.2	0.5	0.3	0.0	0.2	0.0
LV	0.1	0.1	0.1	0.3	0.1	0.0
LT	0.1	0.2	0.1	0.0	0.1	0.0
MT	0.0	0.0	0.0	0.0	0.1	0.0
NO	0.3	0.5	0.1	0.4	0.6	0.0
PL	1.4	3.6	0.9	0.4	0.9	0.0
RO	0.4	0.6	0.4	0.1	0.4	0.3
SI	0.1	0.3	0.1	0.0	0.0	0.0
SK	0.2	0.5	0.2	0.0	0.1	0.0
LU	0.1	0.1	0.0	0.0	0.0	0.0
HR	0.1	0.3	0.1	0.6	0.1	0.0

It is important to note that emissions of particulate matter from district heat generation are increasing in 2050 as compared to status quo in all REFLEX scenarios. This is due to the fact that the emission factor for PMs for the biomass based CHPs is very high (Table 40) and biomass (assumed to have zero direct CO_2 emissions) is widely used for district heat generation in all the REFLEX scenarios. This will obviously have implications for the health impact analysis in which people's exposure to PM concentration plays a crucial role. The resulting emission scenarios were then used as the input data for the Polyphemus model for air quality.

3.2.2 AIR QUALITY MODELLING

For each emissions scenario ambient concentration of air pollutants was calculated with the use of Polyphemus. Polyphemus is a complex modelling system for air quality (Mallet et al., 2007). It contains three types of dispersion models: Gaussion, Eulerian and Lagrangian. In this modelling exercise an Eulerian chemistry-transport-model called Polair3D is used for both gaseous and aerosol species. Polair3D tracks multiphase chemistry: (i) gas, (ii) water and (iii) aerosols. The transport driven by wind is approached with the third order direct space time (DST3) and the piecewise parabolic method (PPM). Gas-phase chemical scheme is RACM (also other chemical schemes e.g. CB05, RADM 2, Melchior are available). Aerosol chemistry is treated depending on the cloud liquid water content. Inside clouds, aqueous-phase chemical reactions are modelled using the Variable Size-Resolution Model (VSRM). Outside clouds, a size-resolved aerosol model (SIREAM) treats the effects of condensation/evaporation, coagulation and nucleation upon the particle size distribution. The ISORROPIA module is used for inorganic aerosol thermodynamics.

The main equation for the chemistry-transport that Polair3D solves numerically is presented below (Boutahar et al., 2004):

$$\frac{\partial c_i}{\partial t} = \underbrace{-\mathrm{div}\left(\vec{V} c_i\right)}_{\text{advection}} + \underbrace{\mathrm{div}\left(\rho K \nabla \frac{c_i}{\rho}\right)}_{\text{diffusion}} + \underbrace{\aleph_i(c)}_{\text{chemistry}} + S_i - L_i \qquad \text{Equation 5}$$

which is satisfied by all involved chemical compounds.

The concentration of the *i*-th species is c_i. The transport driven by wind $\vec{V}$ is represented by the advection term. The diffusion term $\mathrm{div}(\rho K \nabla (c_i/\rho))$ essentially accounts for turbulent mixing in the vertical layer. Chemical production and losses of the *i*-th species are introduced with $\aleph_i(c)$. Additional sources (S_i, emissions) and losses (L_i, wet and dry deposition) are also taken into account (Boutahar et al., 2004).

A typical simulation of atmospheric dispersion with Polyphemus consists of three following steps:

- Preparation of i.e. databases: meteorological fields, emission databases, land use coverage (and miscellaneous data associated with land categories), pollutant concentrations at higher scales (e.g. global concentrations, which constitute the boundary conditions for continental simulations), and physical parameters associated with chemical species.
- Generation of the inputs for Polair3D from these databases: some fields need to be adapted to the simulation characteristics (domain, time step, species). Some other fields such as vertical diffusion coefficients need to be computed on the basis of physical parameterisations. All these fields are strongly linked to the raw data (contained in the previously mentioned databases) since they use these data as input values. This step is achieved by using a set of programs that make calls to functions available in AtmoData.
- Run of Polair3D: the chemistry-transport model is the last step in the simulation process. From the generated input fields, it computes the evolution of the pollutant concentrations.

The air quality modelling domain starts from 12.0°W longitude and 35.0°N latitude and consists of 40 x 34 cells with a horizontal resolution of 1.0° x 1.0° (along longitude and latitude respectively). The meteorological parameters were taken from the European Centre for Medium-Range Weather Forecasts (ECMWF) meteorological data for 2008. The ECMWF data are provided with a resolution of 0.25° on 54 vertical levels every 3 hours. Polyphemus accounts for the transport (wind advection and turbulent diffusion), the chemical reactions (which depend on the target application) and the additional fluxes such as the boundary conditions, the emissions and the deposition fluxes. Running the simulation required also: (i) calculation of biological and sea salt emission, (ii) preparation of the ground, (iii) generation of the meteorological fields, (iv) generation of the initial and boundary conditions, (v) calculation of the dry deposition velocity.

3.2.3 External Costs calculation

According to ExternE, PMs (primary and secondary) are responsible for the most significant impact on human health. The prevailing health damages caused by PMs are: reduced life expectancy (85%), chronic bronchitis (10%) and restricted activity days (4%) (Bickel & Friedrich, 2005). These functions are briefly described below, and only these were taken into consideration in the model.

Chronic mortality (Years of Life Lost - YOLL)

Air pollution does not directly cause individual deaths (unlike accidents or heart attacks), therefore it is not correct to use the number of fatal cases as an indicator of air pollution. Air pollution is only one of the parameters that have an impact on health condition, and as such, its influence is not simply additive with other causes of mortality. It is reasonable, therefore, to consider air pollution in terms of loss of life expectancy, which can be expressed in years of life lost (YOLL). In such context, YOLL is additive and impact of pollution can be separated from other factors leading to health damage.

Chronic bronchitis (CB)

This function corresponds to newly developed cases of chronic bronchitis. It is important to emphasize that it refers only to newly observed cases, but not to change in the prevalence illness rate among adults. In evaluating the unit cost of CB, all medical treatment expenses over the patient’s lifetime are considered.

Restricted Activity Days (RAD)

This function corresponds to days when an individual’s routine activities are disrupted. Cost of illness, loss of productivity and welfare loss (i.e. someone’s unadjusted willingness to pay to avoid the pain and suffering and loss of personal work time due to illness) are included in unit cost for RADs.

The monetary values and S_{CRF}s used in the study which have been derived from results of ExternE (Bickel & Friedrich, 2005) and netcen database (Holland & Watkiss, 2002) are presented in Table 45.

Table 45: Slopes and unit values of considered CRFs for PM2.5.

Concentrated response function (CRF) function (Effects)	CRF [Cases/(year·person·µg/m³)]	Unit value [EUR/case*]
$PM_{2.5}$ - Mortality YOLL	3,42E-04	50 000
$PM_{2.5}$ - Chronic Bronchitis	3,90E-05	169 330
$PM_{2.5}$ - Restricted activity days	4,20E-02	110

* Case means: YOLL,RAD,CB

The following equation was used to calculate the external costs in each grid cell:

$$C_i^{EXT,Eff} = Pop_i \cdot Con_i^{PM_{2.5}} \cdot CRF^{Eff} \cdot Val^{Eff}$$

Equation 6

where

$C_i^{EXT,Eff}$ - external costs due to effect such as YOLL, CB or RAD [EUR/yr],

i - grid-cell number,

Pop_i - population in cell i,

$Con_i^{PM_{2.5}}$ - $PM_{2.5}$ concentration in cell i,

CRF^{Eff} - Concentration-Response Function for a given effect,

Val^{Eff} - Unit external cost of the effect.

In order to make calculations according to Equation 6, it was required to put together information about population density distribution and $PM_{2.5}$ concentrations. For this purpose the GEOSTAT 2011 grid dataset for population distribution with 1 km x 1 km spatial resolution (European Commission, 2019) was used as depicted in Figure 12.

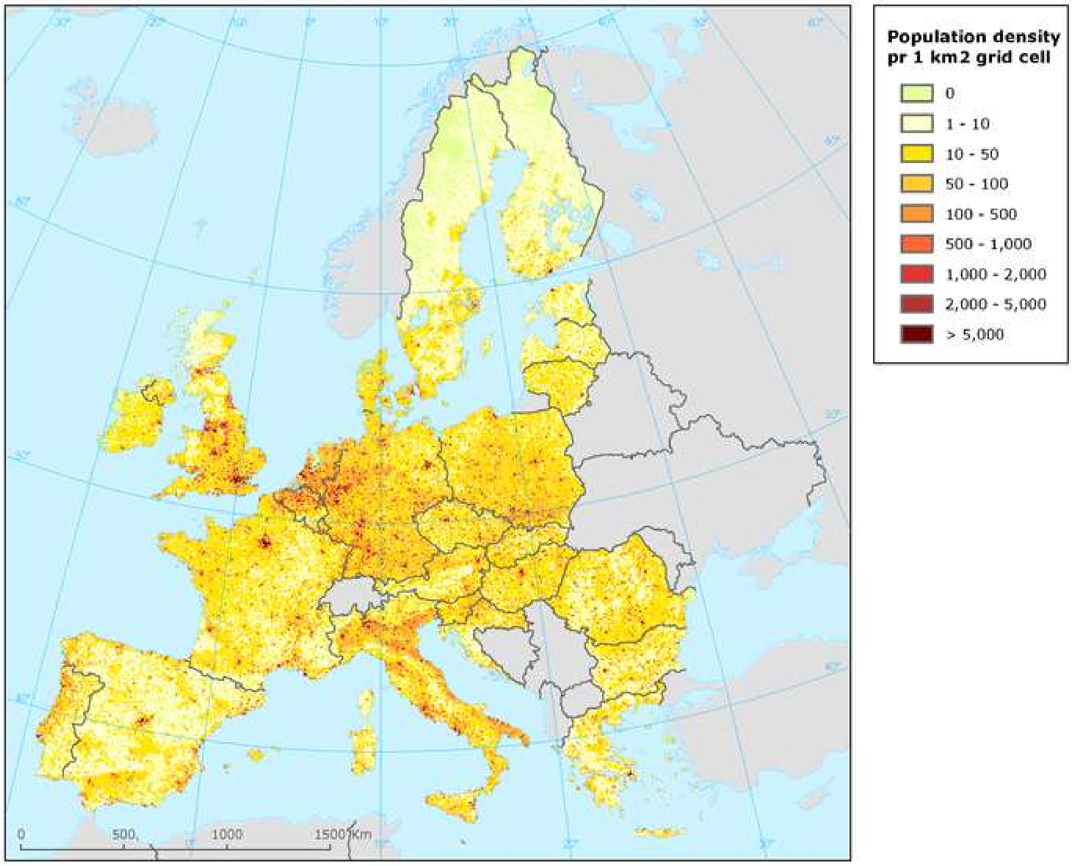

Figure 12: Population distribution according to the GEOSTAT dataset.

Because of the different spatial resolution it was necessary to geo-process both gridded datasets in order to assign relevant $PM_{2.5}$ concentration to each population grid-cell. The match of the two datasets is presented in Figure 13.

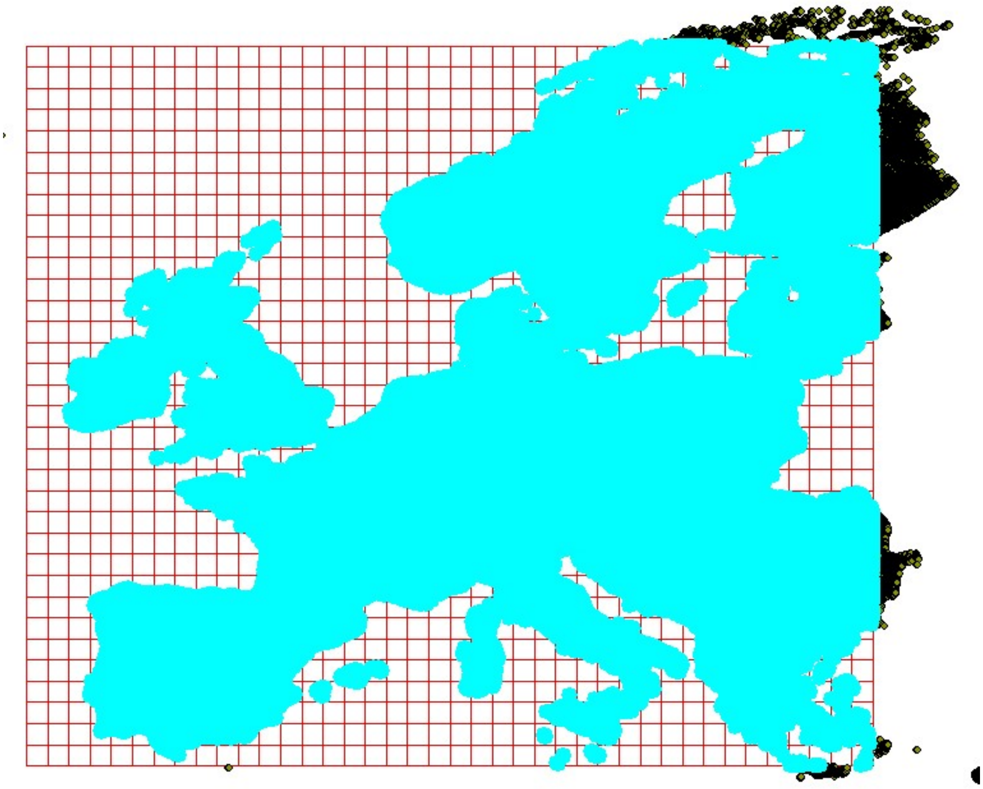

Figure 13: Coverage of PM2.5 concentration and population domains. The common part of both datasets is marked in blue.

The calculations were done in the PostgreSQL database environment.

4 RESULTS OF LIFE CYCLE BASED ASSESSMENT

4.1 ELECTRICITY SECTOR

4.1.1 SOCIAL RISK PROFILE

Overall normalised results for social risk for workers due to electricity production for all scenarios are shown in Figure 14 below. The results show that in general, levels of risk increase from the current case through the future scenarios. Further figures below demonstrate the underlying reasons for the observed increases. Firstly, the total number of worker hours required in the system increases by up to about 12 % in the High-RES cases as shown in Figure 15. Note that the number of worker hours is the same irrespective of which impact category is considered. Meanwhile, as shown in Figure 16, a more significant contributor to the observed increases is the increase in the average risk factor (i.e. the risk level according to the impact assessment scheme used) which increases by almost 40 % for certain impact categories in High-RES scenarios.

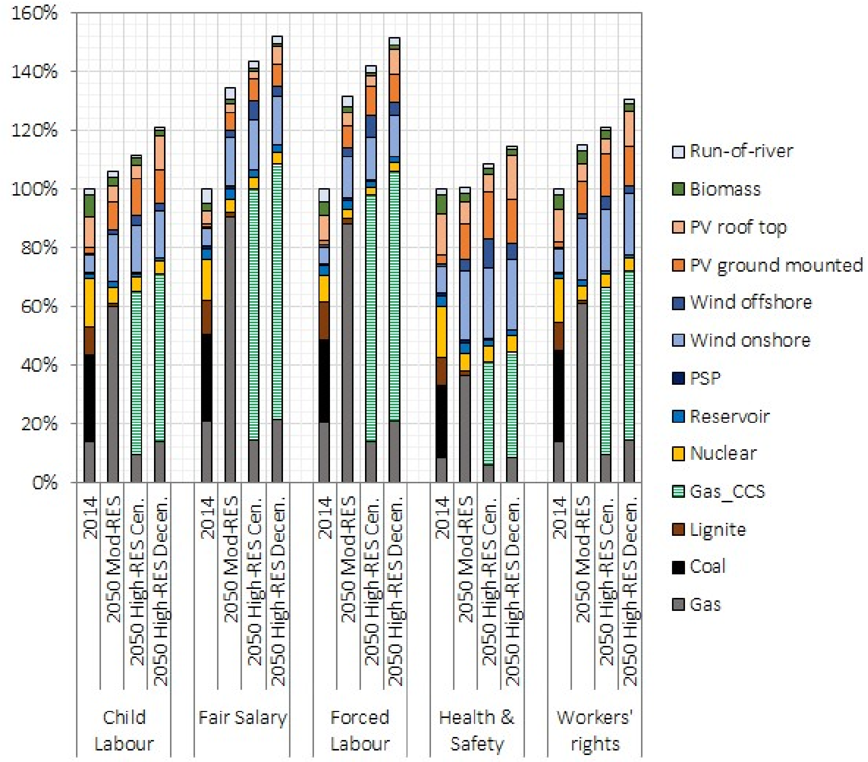

Figure 14: A normalised comparison of the weighted worker hours required to produce 1 kWh of European electricity in the current (2014) and the 2050 scenarios (i.e. Mod-RES, High-RES centralized and decentralized).

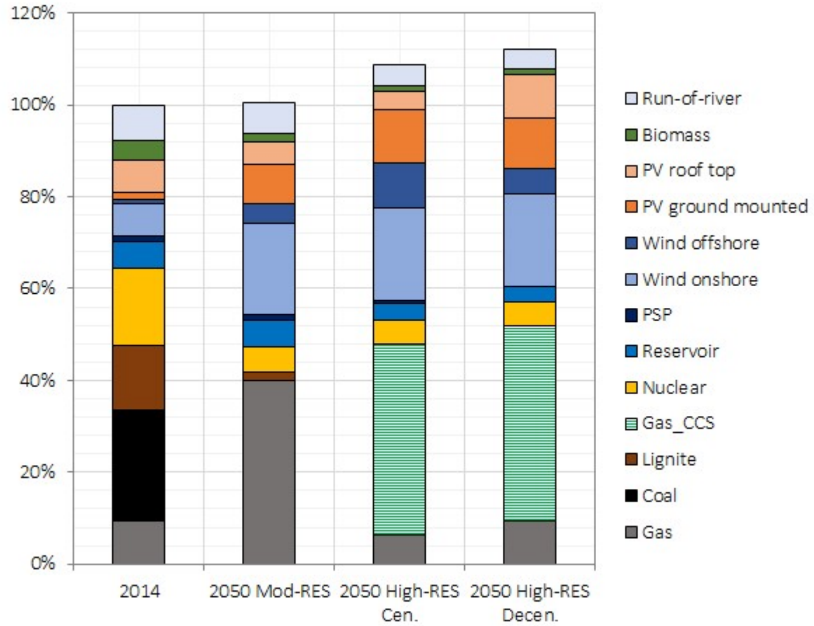

Figure 15: A normalized comparison of the estimated worker hours required to produce 1 kWh of European electricity in the current (2014) and the 2050 scenarios (i.e. Mod-RES, High-RES centralised and decentralised).

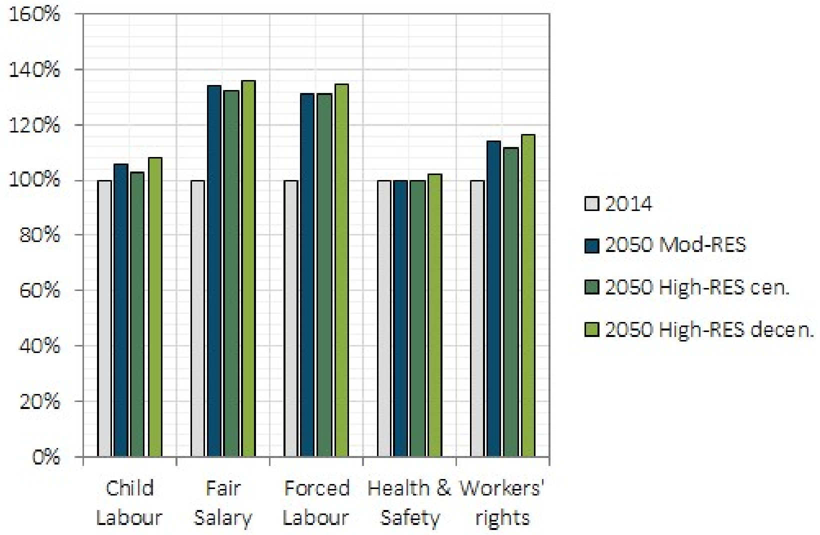

Figure 16: A normalized comparison of the average risk factors (calculated as the ratio of risk-assessed worker hours/non risk-assessed worker hours) assigned to each worker hour across the five social impact categories for all scenarios

In the current case, fossil-based technologies and nuclear power largely dominate social risk in all categories. For coal, over 70 % of the total social risk arises as a result of the coal supply. Within this, the analysis further shows that for fair salary and forced labour, most of this risk arises from coal supply from Russia (which is a large coal supplier to the EU). Meanwhile, considering child labour, health and safety and workers' rights, risks are more spread out amongst other supply countries, including Russia, Latin America, South Africa and Poland. The fuel supply chain is also the significant factor for gas-based electricity production. For child labour and workers' rights, gas import from Algeria is the single most significant risk-contributing process. Meanwhile, for fair salary and forced labour, it is the supply from Russia that is the most significant process from a risk perspective. Finally, for health and safety imports from Russia and Algeria are both highly significant from a risk perspective. For nuclear power, SOCA's default global process for nuclear fuel is assumed, which is also responsible for a large proportion of total social risk for the technology for all categories considered. The assumption of this global process is a simplification here, but it seems relevant in light of the fact that uranium is currently imported from a diverse group of countries as Canada, Russia, Kazakhstan, Niger and Australia (World Nuclear Association, 2019).

As also shown in Figure 14, gas-fired generation (with and without Carbon Capture and Storage (CCS) technology) is a dominant contributor in all categories in all future scenarios, especially Forced Labour and Fair Salary. Although CCS improves the performance of gas from an environmental point of view (i.e. decreasing CO_2 emissions), it provides no particular benefit in any of the considered social impact categories. This is because the largest contributions from this technology arise from the supply chain for natural gas, as for the current situation. In particular, gas from Russia (~30% of imports) and Algeria (~10% of imports) is a significant driver, associated with high levels of risk related to workers. For instance, gas procurement from Russia constitutes 55 % of its contribution to the Fair Salary-category and 80% of the contribution to the Forced Labour-category. Gas imported from Algeria is a key driver of the contribution in the categories Child Labour (40% of the contribution) and Workers' rights (50% of the contribution).

Also shown in Figure 14, wind (onshore and offshore) and solar photovoltaics (PV) technologies have noteworthy contributions in the 2050 scenarios. For PV, the panel production is a key driver of its contribution, accounting for ~60% in all but one category, Health & Safety (~35%). In this category, the installation/construction of PV systems is also a significant driver, ~25% of the contribution. For wind, plant construction is also a large driver in the Health & Safety category (~50%). This is due to a high accident risk associated with the EU construction industry.

The hotspots for social risk identified in the assessment are shown in Table 46.

Table 46: Social hotspots identified for all future scenarios according to the assessment method applied.

	Child Labour	Fair Salary	Forced Labour	Health & Safety	Workers' rights
Key contributors	- Gas supply chain, especially from Algeria - PV panel production - Materials for wind plants (esp. metals supply chain)	- EU plant construction and operation - Gas supply chain, especially Russia	- Gas supply chain, especially Russia	- Plant construction (EU) - PV panel production (GLO)	- Power plant operation in EU - Gas supply chain, especially from Algeria

Finally, it should be noted again that, according to Figure 15 the total number of worker hours required for electricity production actually increases in all future scenarios. The increasing shares of Solar-, Wind- and Natural gas (with and without Carbon Capture and Storage (CCS)) technologies in the electricity production mix are driving this trend. The potential for job creation through energy transition has been noted elsewhere (IRENA, 2018a), and it is of course positive from socioeconomic perspective. On the other hand, as shown in Figure 14 and Figure 16 this increase in labour intensity comes with increased social risk in the supply chain, as judged by SOCA.

4.1.1.1 Sensitivity analysis

The results of the sensitivity analysis assuming social conditions for gas production based on typical Western European conditions are shown in Figure 17 below.

It is not intended that such a measure is practically applied in the future development of the energy systems, rather the analysis offers insight into the extent to which the methodology employed may be able to capture significant changes in social performance. As Figure 17 shows, there are significant decreases in impacts in all categories, therefore showing the sensitivity of the method to the change. Particularly significant decreases are noted for the areas fair salary and forced labour.

On the other hand, the method still shows the risk of child labour in gas supply (see Figure 17), in spite of the absence of risk in this category under European conditions. Rather the judgement that a risk for child labour exists in the supply chain suggests that such risks occur elsewhere in the supply chain. In light of this finding, further investigation of the modelled supply chain is necessary.

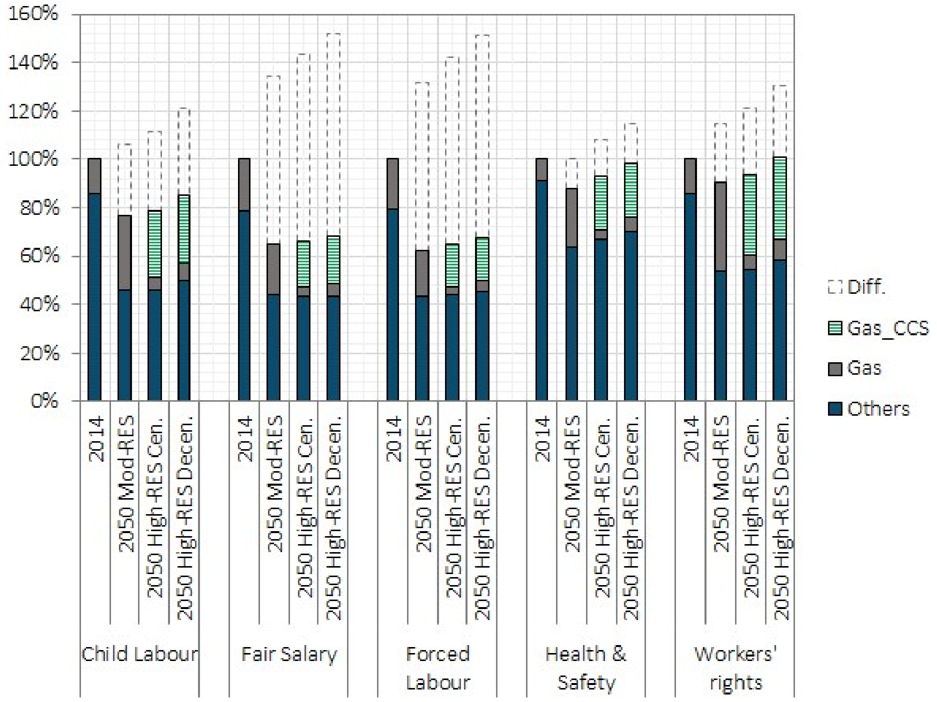

Figure 17: Normalised social risk for the production of 1 kWh electricity in the current case and all REFLEX future scenarios, assuming gas supply with Norwegian social conditions in future scenarios. The bars with dotted lines represent the risk level according to the standard assumptions for gas supply (see also Figure 14). Diff. – difference between the assessment with sensitivity analyses applied and without.

4.1.2 Environmental impacts

Figure 18 shows that there are significant advantages from an environmental perspective beyond climate change for freshwater eutrophication and agricultural land occupation. Meanwhile in the categories particulate matter formation and ozone depletion there is no significant change in normalised impacts, while metal depletion and urban land occupation are classified as categories with significant disadvantages.

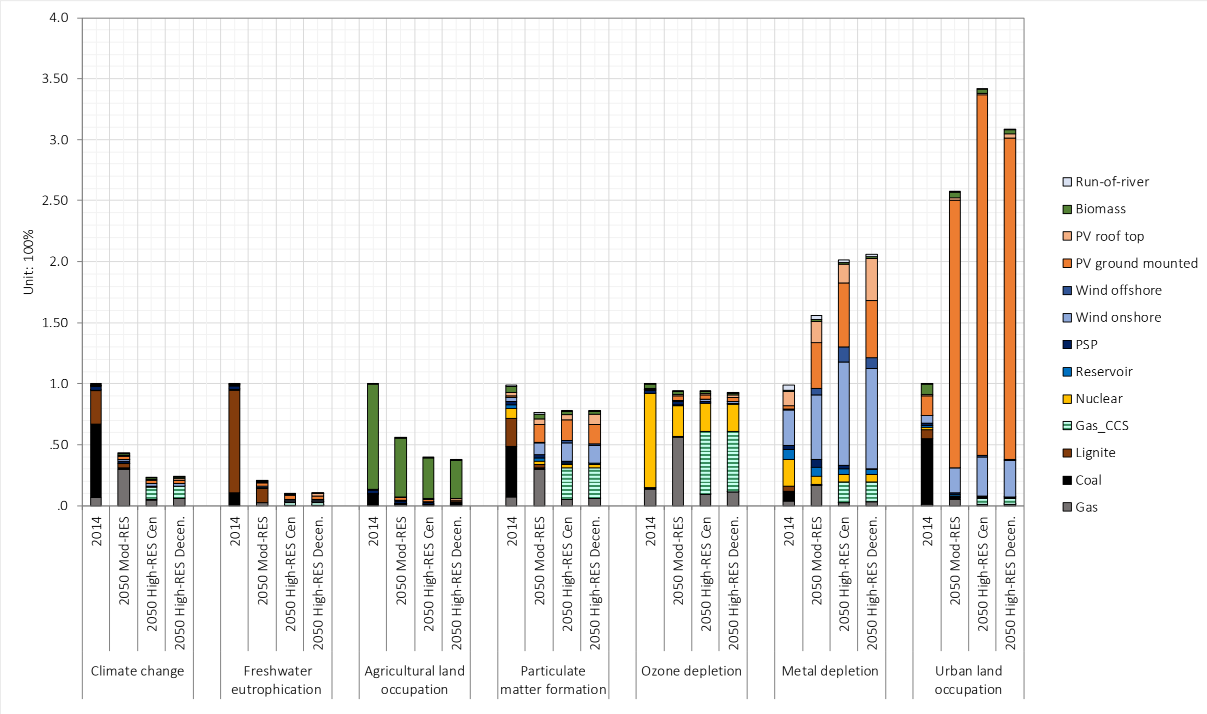

Figure 18: The normalised environmental impacts for 1 kWh of European electricity generation for Mod-RES and both High-RES centralised and decentralised 2050 compared to the current situation

Considering in more depth categories showing significant advantages from an environmental perspective in Figure 18, life cycle climate change impacts decrease from 2014 to 2050 in all scenarios, which is in line with the decarbonisation targets of the REFLEX scenarios. Climate change impacts in Mod-RES 2050 are 44% compared to the 2014, while it decreases to only 23% in both High-RES central and decentral scenarios for 2050. The most important reason of the decreasing trend to 2050 is the technological change from high carbon technologies (lignite and coal) to low carbon technologies (gas, gas CCS and renewables).

Over 98% of total GHG emissions in lignite are from the direct emissions i.e., the emissions associated with lignite combustion, while the remaining 2% are from the upstream processes (the largest contribution is from the process for SOx retained in lignite flue gas desulfurisation which accounts for about 0.74%). The direct emissions from coal combustion account for over 95% of the total life cycle GWP and upstream processes covered around 5% (amongst, 4.22% are from the ecoinvent process of market for hard coal).

The proportion of GWP arising from direct emissions for gas (without CCS) is around 85% of total GHG emissions and the use of CCS technology lowers it to 37%. For the emissions from upstream processes, the greatest contribution is from the process of market for natural gas (around 60% for Gas with CCS and 15% for Gas without). Natural gas pipeline transport processes play an important role here. For example, around 30% of natural gas is assumed from Russia, and in the Russian natural gas market, 76% of GHG emissions are from the process of long distance pipeline transport of natural gas, while only around 30% of the emissions are from the process of natural gas production.

Along with the decrease of climate change impacts up to 2050, freshwater eutrophication also decreases, showing a significant co-benefit. This is mainly due to the decrease in the share of lignite. Compared to other technologies, lignite-based electricity dominates the emissions associated with freshwater eutrophication. With only 1.3% of the electricity mix in 2014, lignite contributes up to 83.98% of the life cycle freshwater eutrophication. In particular spoil treatment in the upstream lignite mining processes plays a major role: the process of treatment of spoil from lignite mining accounts for around 99% of total freshwater eutrophication impacts.

Similar to freshwater eutrophication, agricultural land occupation shows another significant advantage from an environmental perspective for the transition to a low carbon energy system. Looking at the contributions of the technologies on agricultural land occupation, biomass plays a major role for all scenarios, with a moderate decreasing trend from 2014 to Mod-RES 2050 and a sharp decreasing trend from 2014 to both High-RES 2050. The decrease of this impact from 2014 to 2050 is due to the assumptions with regard to the choice of feedstock for biomass. As presented in the method section, less wood fuel and more biogas from bio-waste, manure, industrial and agricultural residues, etc. are expected to be used for biomass in 2050 for all the three scenarios compared to 2014. The decreasing wood consumption (69% in 2014 and 40% in 2050) leads to lower land occupation impacts from forest. With the same feedstocks assumption for all of the scenarios, the different moderate and sharp decreasing rates in Mod-RES and both High-RES 2050 are due to the contribution differences of biomass on electricity mix production. The share of biomass in Mod-RES 2050 (1.70%) is slightly higher than those in both High-RES scenarios (1.17% in High-RES central 2050 and 1.10% in High-RES decentral 2050).

Particulate matter formation shows a slight reduction trend from 2014 to 2050. The impacts in 2050 for the three scenarios are about the same. Coal (42%), lignite (23%), nuclear (8%) and gas (7%) are the main contributors in the category in 2014, while in future scenarios, the contributions are from a combination of low carbon technologies, i.e., gas (38%, 6% and 8% for Mod-RES, High-RES central and decentral scenarios, respectively, here after), Gas CCS (0%, 33% and 32%), wind onshore (12%, 19% and 18%), PV rooftop (6%, 5% and 11%) and PV ground mounted (19%, 22% and 20%). Figure 18 demonstrates the significance of the phase out of coal and lignite in the reduction of these impacts from 2014 to 2050.

Emissions for particulate matter formation from coal and lignite are mainly a result of fuel combustion (86% for coal and 76% for lignite). The processes of coal and lignite flue desulphurisation are the main contributors of the upstream emissions for both coal and lignite technologies (accounting for 6% and 16%, respectively). In contrast, impacts for other production technologies mainly arise due to the upstream processes: natural gas production and transportation processes for gas and Gas CCS (79% and 85%, respectively), uranium fuel element production (86%) for nuclear, resources and metal demand (nearly 100%) for the construction of wind and PV plants. Figure 18 shows the percentages of upstream and direct emissions for 2014 and High-RES central 2050 (a representative for future scenarios), which implies that with the implementation of carbon reduction measures, the contribution of direct emissions for particulate matter formation is lessened from 2014 to 2050 (from 38% to 3%), while upstream emissions become dominant (97% in 2050).

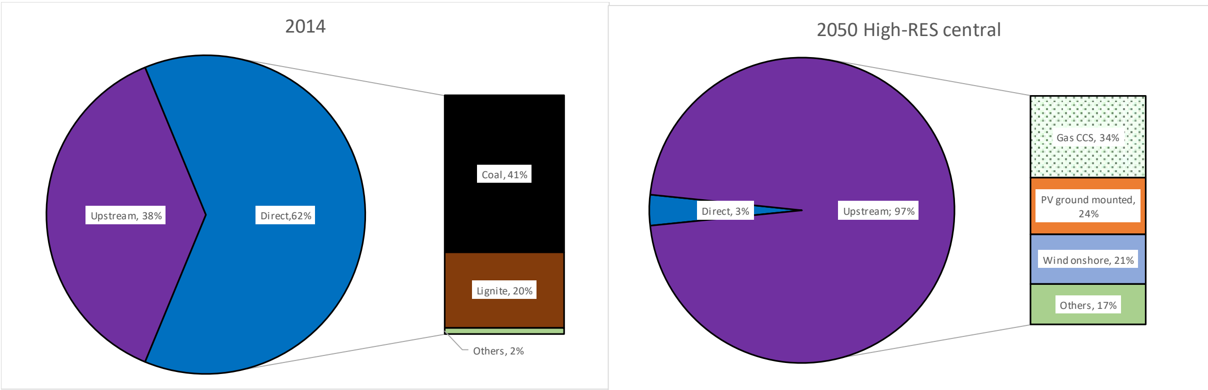

Figure 19: Contributions of direct and upstream emissions on particulate matter formation in 2014 and High-RES central 2050

Ozone depletion remains nearly constant between all temporal cases, with only slight reduction in future scenarios. As shown in Figure 18 gas, nuclear and gas CCS are the main contributors to ozone depletion, accounting for around 90% of total emissions for status quo (13%, 77% and 0%) and all the three future scenarios (60%, 28% and 0% for Mod-RES 2050, 10%, 25% and 55% for High-RES central, 13%, 24% and 54% High-RES decentral). The partial replacement of nuclear by gas in the Mod-RES scenario and by gas CCS in both High-RES scenarios causes the variations from 2014 to the future cases, as nuclear causes larger impacts per unit electricity compared to gas and gas CCS. Ozone depletion-related emissions from gas, gas CCS and nuclear generation technologies are due to the contributions from upstream processes, for example, the supply of natural gas (including gas production and transport) for gas and gas CCS (both over 99%) generation, and uranium fuel element production for nuclear (direct emissions of uranium production represent around 99%).

Metal depletion is one of the environmental impact categories where an increase is observed from 2014 up to 2050. This is mainly due to the intensive deployment of renewable technologies. For example, wind onshore (42%) and offshore (6%), PV rooftop (8%) and ground mounted (26%) require over 80% of the overall metal required to produce these technologies for High-RES central 2050. From a life cycle perspective, these are mainly due to, respectively, the steel production (accounting for around 90% of total metal depletion) used for the towers, rotors and nacelles of wind power plants and PV cell production (nearly 100%) for photovoltaic plant production. Although a breakdown of technologies is made in LCI analysis in terms of wind and PV technologies, the critical metals taken into account contributed insignificantly regarding the metal depletion. For example, the SG-PM wind technologies use a new gearbox with requiring rare earth materials such as neodymium. The gearbox represent only 0.25% of total metal depletion for these technologies. In an in-depth analysis, it was identified that ReCiPe (the chosen life cycle assessment method) does not include the mines and commodities related to many rare earth materials. For this study, ReCiPe does not have data for the commodities related to monazite and bastnaesite, the ores of neodymium and many other rare earth metals.

In terms of urban land occupation, coal contributes to over 50% of the overall urban land occupation in 2014, while for the three future scenarios, PV ground mounted technologies substitute coal and become the largest contributor (over 80% of total urban land occupation, with only around 10% in electricity mix), supplemented by wind onshore technologies (8%, 9% and 10% for Mod-RES, High-RES central and High-RES decentral scenarios). Other technologies only have minor contributions. PV ground mounted technologies' impacts in this category are mainly due to the reality that the plants require large amounts of land (over 99% of total urban land occupation).

4.2 END-USE SECTORS

4.2.1 TRANSPORT SECTOR

4.2.1.1 Social risks

Figure 20, Figure 21, Figure 22 and Figure 23 each show results for the assessment of social risk for energy supply to the transport sector in the current case and in future scenarios. It is interesting to note firstly that the total number of worker hours (see Figure 21) increases significantly for both High-RES cases, but stays the same as the current case for the Mod-RES. The underlying reason for this is that biofuel, electricity and hydrogen production are significantly more labour intensive than producing fossil fuels. From a job creation perspective this factor can be considered positive.

Meanwhile, by comparison, the risk factors (see Figure 22 and Figure 23) either decrease significantly (e.g. health and safety or child labour) or stay approximately the same (consider e.g. forced labour or workers' rights). It is the combination of increases in worker hours and changes in risk factors that cause the overall normalised risk to change as seen in Figure 20. It is interesting to note according to average risk factors that the factors for workers' rights and forced labour all lie around 1, indicating a preponderance of low to medium risk hours in the category. Meanwhile, in other categories, risk factor varies between 7 and 18, indicating the presence of high risk and very high risk hours in those categories. It is of course an ethical question as to what level of risk is satisfactory.

As shown in Figure 20 only one (Health & Safety) of the considered social impact categories shows a decreasing trend for all 2050 scenarios. It is increasing shares of electricity and hydrogen in the mix that contributes to the significant decrease in the category. The large increases in forced labour and workers' rights can be attributed to the demand for biofuels in future scenarios, particularly biokerosene. However, it should also be remembered that there is a relatively low risk factor for these impact category (see Figure 23). The noted increase in impacts in the category fair salary is essentially due to the increase in worker hours noted in Figure 21 and further to using biofuels to a greater extent in High-RES 2050 than in the current case or Mod-RES.

Meanwhile, for child labour a counterbalancing effect is observed. Electricity and by extension hydrogen made from electrolysis have relative lower risks in the category than fossil fuels, which in turn have relatively lower risk than biofuels. Thus by using electricity and biofuels to substitute in the mix, the use of the one cancels out the use of the other.

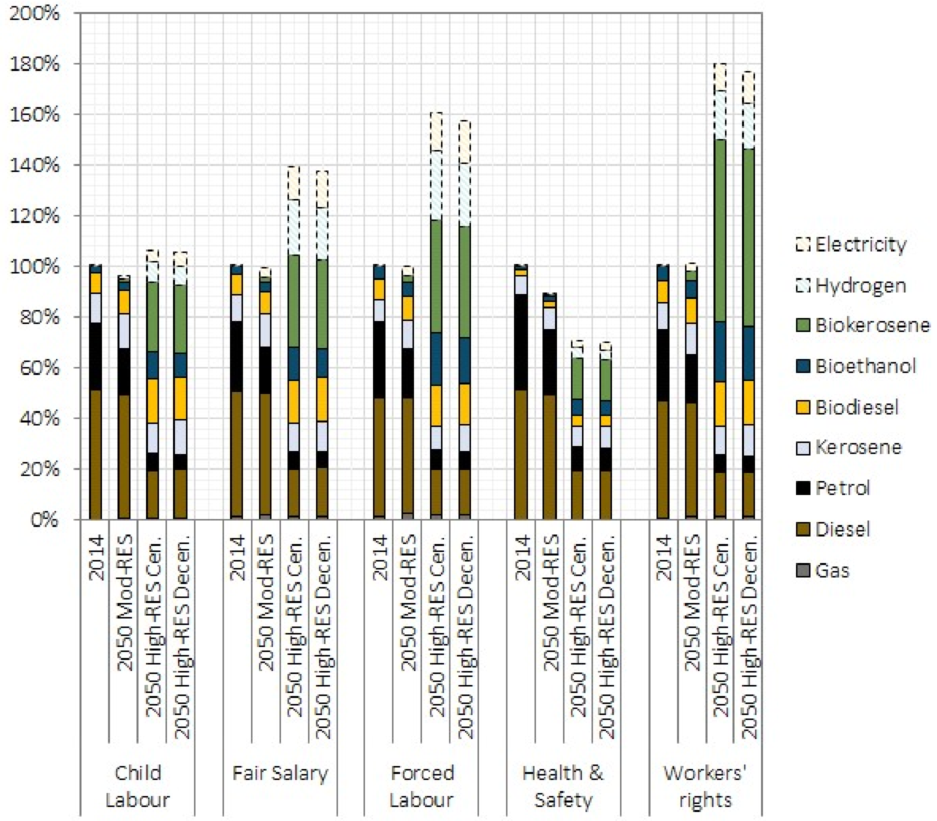

Figure 20: Contribution of different energy carriers to normalised social risk for energy supply to the transport sector in the EU for the current case and all REFLEX scenarios.

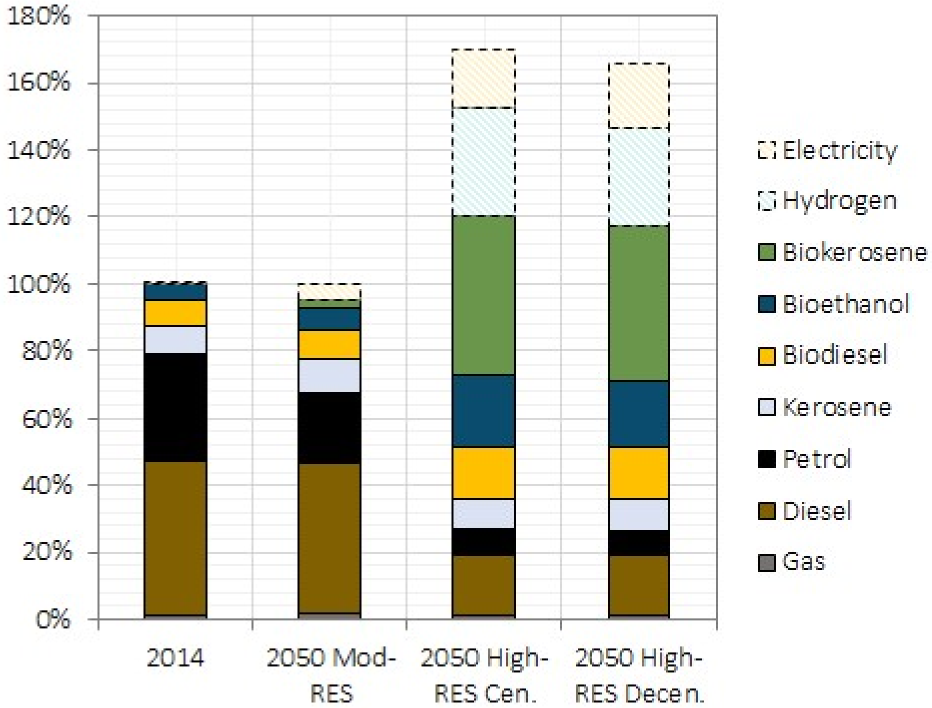

Figure 21: Contribution of different energy carriers to normalised total worker hours for energy supply to the transport sector in the EU for the current case and all REFLEX scenarios

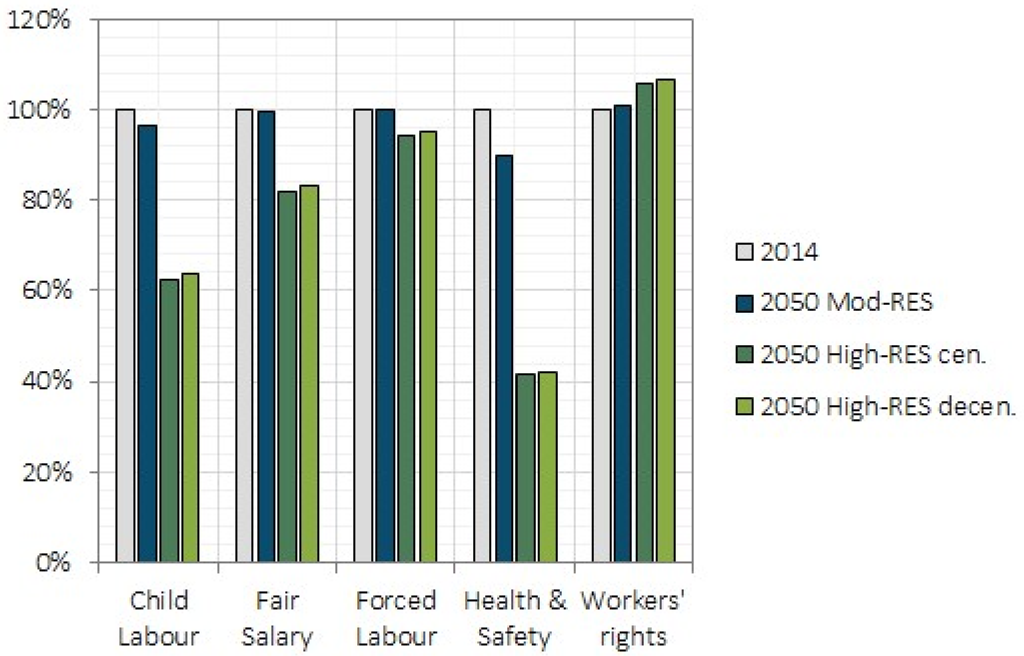

Figure 22: Normalised social risk factor for energy supply to the transport sector in the EU for the current case and all REFLEX scenarios

Figure 23: Absolute social risk factor for energy supply to the transport sector in the EU for the current case and all REFLEX scenarios

4.2.1.2 Upstream environmental impacts

As discussed in the method, the mix of energy carriers in the transport sector is transformed from conventional fossil fuels in the current situation to "greener" ones in future scenarios. Specifically, the energy carrier mix in 2014 is dominated by diesel (55.73%), petrol (25.43%) and kerosene (12.30%) and a partial replacement of diesel and gasoline by electricity and hydrogen is observed in 2050 for all scenarios, especially for both High-RES scenarios. Additionally, biofuels (biodiesel, bioethanol, biokerosene and biomethane) shows an increase in the mix in 2050.

Figure 24 demonstrates the reductions in upstream impacts from conventional fossil fuels that can be achieved by reducing the quantities of said fossil fuels in the mix. However, the demand increase for e.g. electricity, hydrogen and biokerosene in the mix causes overall increases in upstream environmental impacts as calculated in the assessment As shown in Figure 24, considering all energy carriers, ozone depletion is the only one to show an overall decrease. Other impacts increase dramatically from 2014 to 2050, implying significant disadvantages from an environmental perspective according to the system boundary used.

As the only impact category showing a significant environmental benefit for upstream environmental impacts from energy demand in transport, ozone depletion is dominated by diesel (59%) and petrol (27%) in 2014. In the future scenarios, diesel continues to make a significant contribution in this category, accounting for 59% in Mod-RES 2050 and 32% for both High-RES scenarios. This is mainly due to the process of the petroleum and gas production, which contribute to over 90% of total emissions with regard to ozone depletion for diesel production.

- *Disadvantage for the environment:*

Climate change, freshwater eutrophication, particulate matter formation, metal depletion as well as both urban and agricultural land occupation show significant increases in upstream environmental impacts (see Figure 20). The upstream environmental impacts for due to electricity, hydrogen and biokerosene demand in the sector play a significant role here. The following text therefore presents a detailed analysis of their contributions from the perspective of the High-RES central scenario (which is considered representative of the future cases).

Electricity contributes to 24% of climate change, 18% of freshwater eutrophication, 11% of particulate matter formation, 33% of metal depletion, 42% of urban and 2% of agricultural land occupation. For a full contribution analysis of the role of electricity production in these impact categories please see the previous section. In summary, climate change is mainly due to the fossil fuel combustion process occurred in the conventional generation technologies (lignite and coal). Freshwater eutrophication is mainly due to the spoil treatment occurred in the lignite mining processes for lignite. In terms of particulate matter formation, there is a combined contribution from fuel combustion-based technologies (mainly due to direct emissions) and renewable technologies (due to upstream emissions). Metal depletion is due amongst other things to the high metal requirements during the production and manufacturing processes of wind turbines and solar panels. With regard to land occupation, the installation of the PV mounting system is the main source for urban land occupation, and biomass from wood dominates urban land occupation.

Hydrogen as an energy carrier in the model is converted from electricity and thus subject to conversion losses. The conversion efficiencies from electricity to hydrogen are assumed to be 74% and 80% for 2014 and 2050 (all scenarios), respectively. There is thus no doubt that hydrogen production has a worse environmental performance for all environmental impacts than electricity. Electricity used in hydrogen production plays a major role for all impacts (over 95%) from a life cycle perspective, which implies that the environmental performance of electricity production has a direct and significant positive or negative effect on the environmental performance of hydrogen.

Biokerosene gives rise to negative impacts for these significantly increased upstream environmental impacts, especially in terms of agricultural land occupation. The upstream process of jatropha oil production is the largest contributor for biokerosene for all the upstream environmental impacts: 90%

of climate change, 89% of freshwater eutrophication, 94% of particulate matter formation, 85% of metal depletion, 58% of urban land and 99% of agricultural land occupation. It is clear that jatropha oil production (including upstream agricultural activities) should have an effect on freshwater eutrophication and agricultural land occupation. It is nevertheless potentially more challenging to understand the impact of jatropha oil production on e.g. urban land occupation. To understand how agricultural production could contribute to urban land occupation, it is necessary to realise that all the upstream processes have their own upstream processes. For example, phosphate fertiliser is needed to produce jatropha oil which in turn requires chemical plants which occupy urban land.

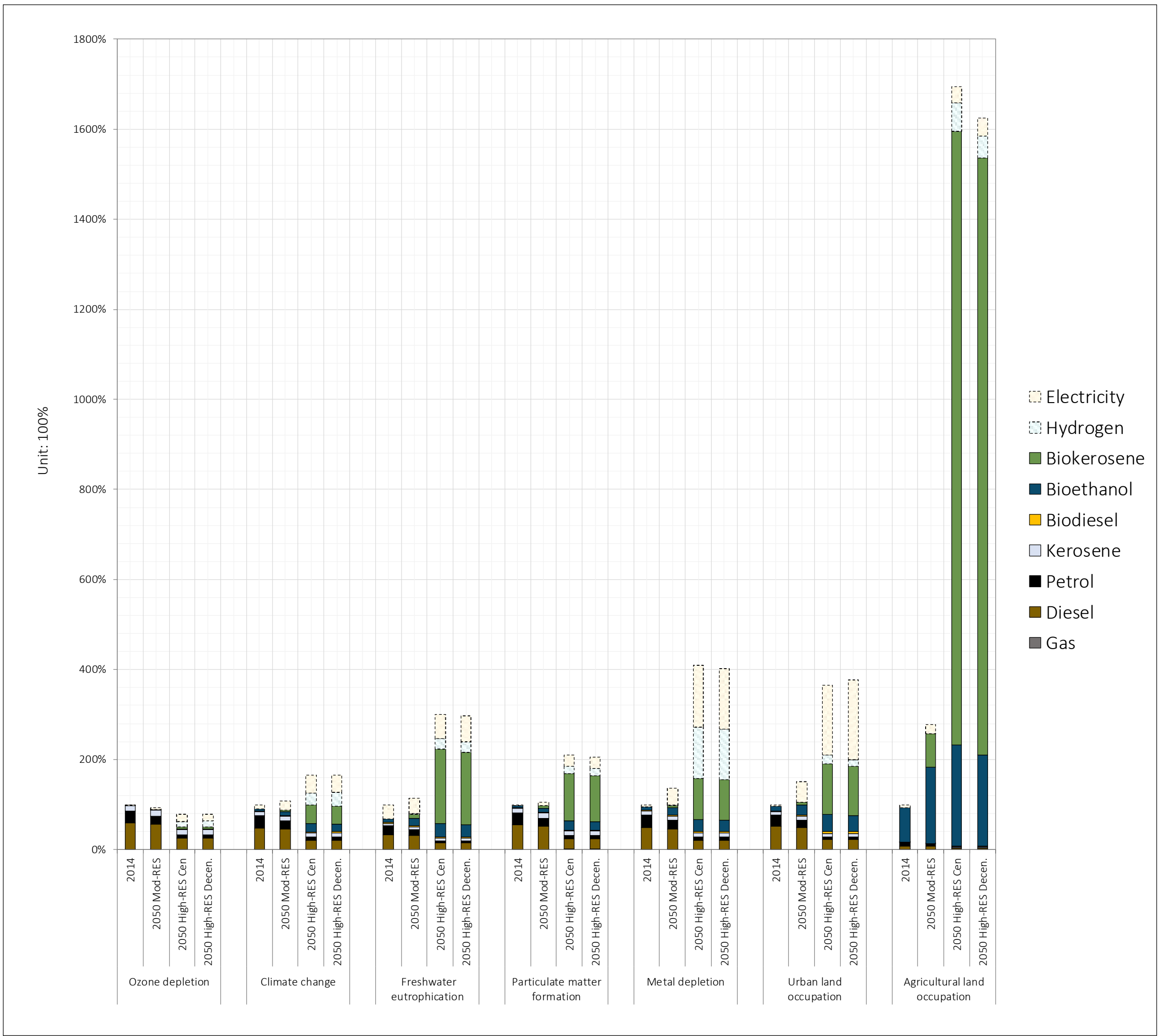

Figure 24: The normalised environmental impacts of fuels production per unit energy for Mod-RES and both High-RES centralised and decentralised 2050 compared to 2014.

4.2.2 *INDUSTRY SECTOR*

4.2.2.1 Social Risks

Figure 25, Figure 26, Figure 27 and Figure 28 each show results for the assessment of social risk for energy supply to the industry sector in the current case and in future scenarios. Firstly it can be noted the total number of worker hours increases only slightly between the current case and future scenarios, in spite of significant differences between the energy mix in each temporal case. Ultimately this depends on the fact that electricity and gas which together amount to about 70 % of the total energy supply in all cases have relatively similar labour intensities. Meanwhile, coal which has a relatively low labour intensity and is used to a certain extent in the current situation is replaced by biomass and ambient heat in future situations, which have similar labour intensities to that of coal.

According to Figure 28, absolute social risk factor varies significantly between different categories. For child labour and fair salary, the data shows that many processes are included with at least a high risk according to the scale used by SOCA. Meanwhile, for forced labour, most processes are carried out at a medium risk level according to the SOCA scale. For health and safety there are some processes carried out at a high level of risk but also others carried out at medium and low risk levels.

Figure 25 shows that from a risk perspective, gas, oil and electricity dominate in the current case. The contributions for electricity production are discussed in more detail in the results section for electricity production above. Meanwhile, for fuel oil, risk hotspots in all categories occur for oil production in Russia and other countries outside of Europe. Risk hotspots for gas delivery are also principally due to the gas supply chain from Russia and Algeria, as discussed previously in relation to electricity production above.

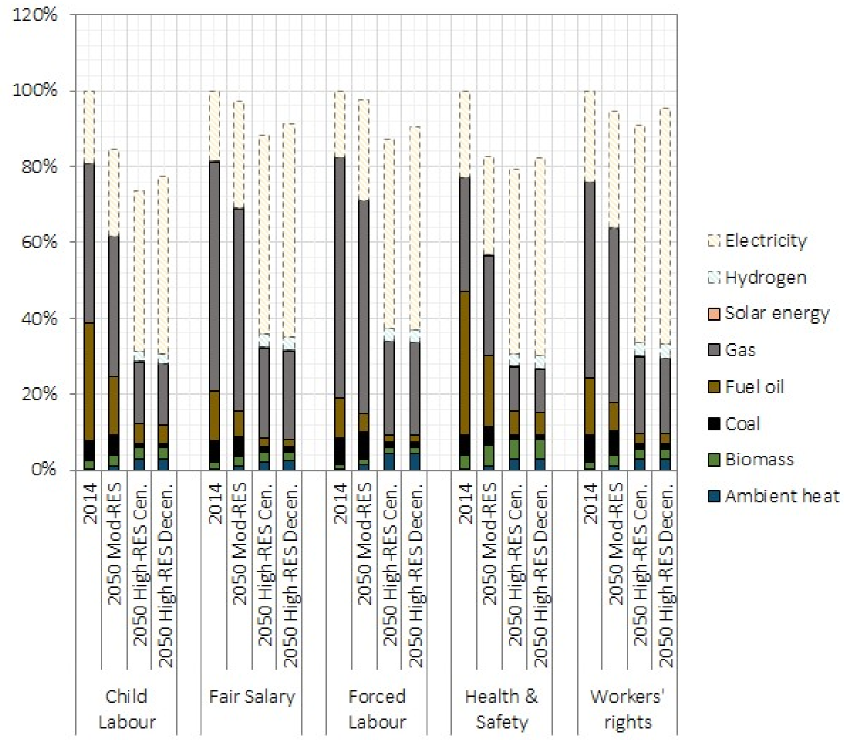

Figure 25: Contribution of different energy carriers to normalised social risk for energy supply to the industry sector in the EU for the current case and all REFLEX scenarios.

Considering the change in the overall impacts shown in Figure 25, the small variations in social risk seen between the current case and future situations arises in a similar way to the observed changes in worker hours in Figure 26. Coal demand with relatively low risk is reduced significantly in the High-RES and replaced by biomass and ambient heat also with low social risk. Meanwhile, gas demand also reduces in the High-RES, whilst electricity demand increases. Electricity has a slightly lower social risk than gas for most indicators, and significantly lower than oil, therefore contributing to small reductions for future scenarios noted in Figure 25.

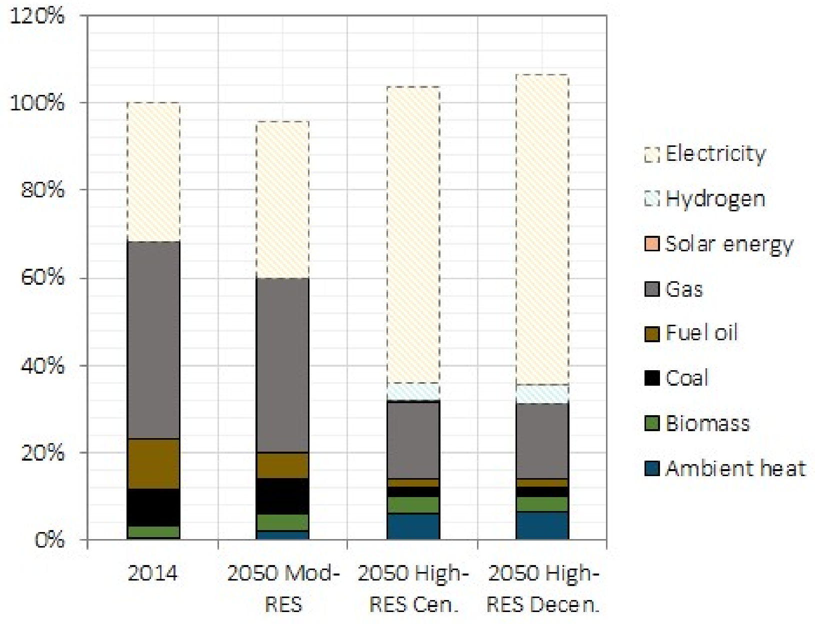

Figure 26: Contribution of different energy carriers to normalised total worker hours for energy supply to the industry sector in the EU for the current case and all REFLEX scenarios

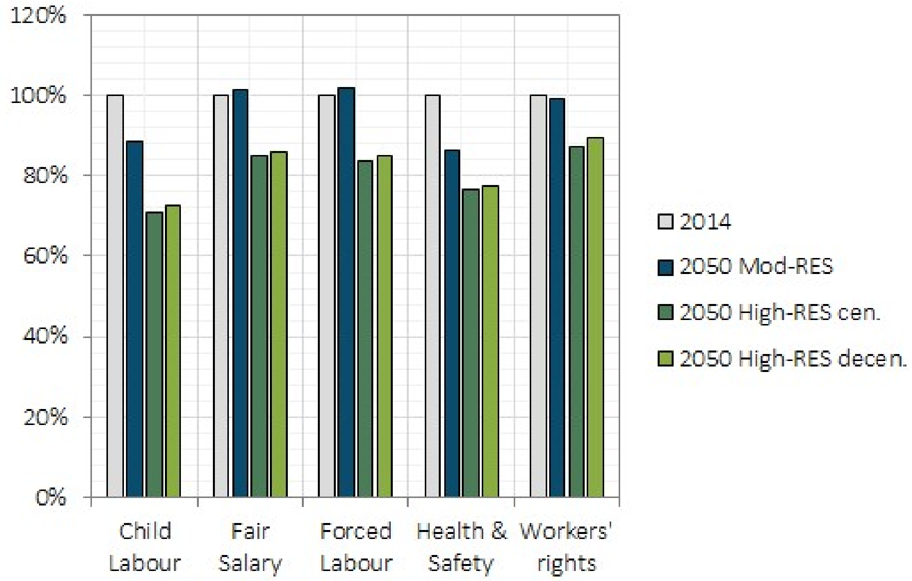

Figure 27: Normalised social risk factor for energy supply to the industry sector in the EU for the current case and all REFLEX scenarios

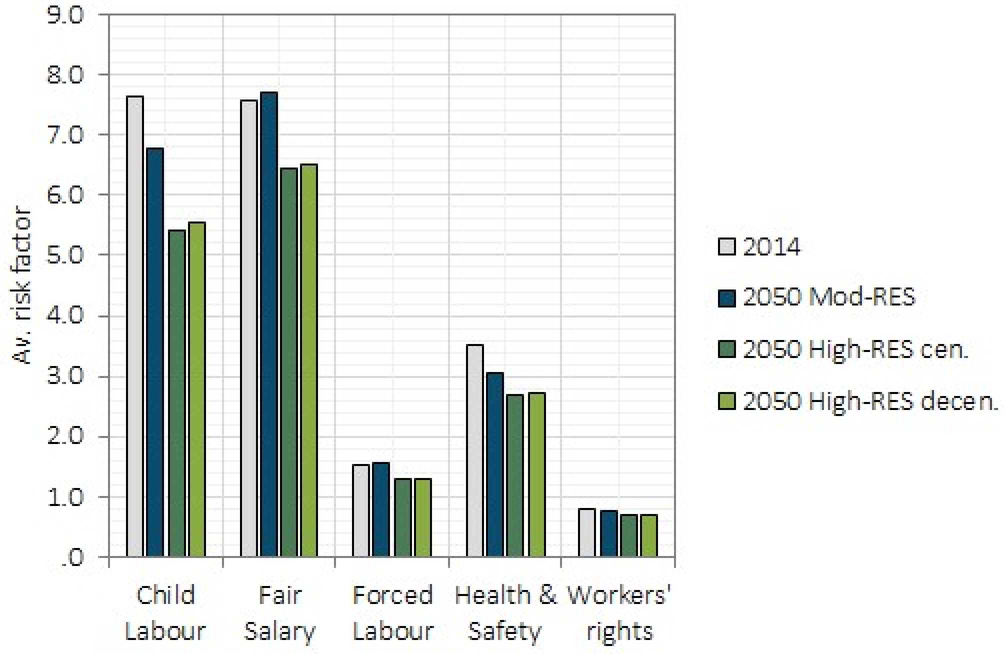

Figure 28: Absolute social risk factor for energy supply to the industry sector in the EU for the current case and all REFLEX scenarios

4.2.2.2 Upstream environmental impacts

Electricity plays an increasingly important role on the industry sector from 2014 (20%) to 2050 (32% for Mod-RES and 56% for both High-RES scenarios) (see LCI section for industry earlier in this report). Meanwhile, the electricity-intensive fuel hydrogen is also expected to be used in the industry sector in 2050 (from 0% in 2014 to 1.6% for both High-RES scenarios 2050) as one from the broad range of mitigation options. Correspondingly, with future higher demand of electricity and hydrogen, the upstream environmental impacts for energy supply to industry follow to a great extent the environmental impact profile for electricity production (see Figure 29, the dashed yellow and green bars, and Figure 18).

Electricity's contribution to upstream environmental impacts in the industrial sector are significant from a life cycle perspective both positively and negatively. A detailed analysis of electricity's environmental performance in the scenarios considered has been presented in Section 4.1.2 and supplemented in Section 4.2.1.2.

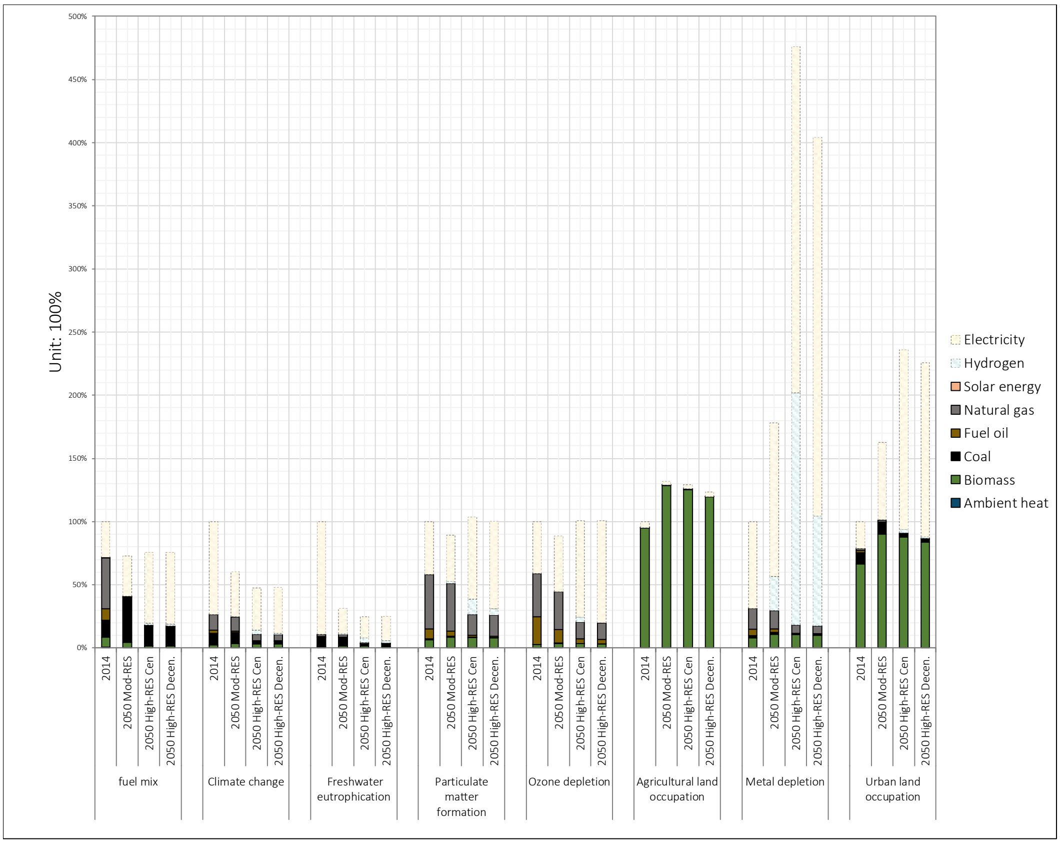

Figure 29: The normalised upstream environmental impacts for energy carrier production per unit energy delivered for Mod-RES and both High-RES Centralised and Decentralised 2050 compared to 2014.

A significant improvement in upstream environmental performance is shown in terms of climate change and freshwater eutrophication due to the transformation of the electricity system in the defined specific scenarios.

No absolute changes in the normalised upstream environmental impacts are observed for particulate matter formation and ozone depletion which both follow the impact profile for the electricity sector (see analysis earlier in the results section). No change in normalised upstream environmental impact is observed for agricultural land occupation either, though this is not only a result of changes in electricity production for the scenarios in question. Rather the reductions observed in the electricity section in this category (see analysis earlier in the results section) are counteracted by an increased demand for woody biomass in the industry sector.

In contrast, metal depletion and urban land occupation show a significantly increasing trend for upstream environmental impacts from 2014 to 2050. Apart from electricity, hydrogen makes a considerable contribution to metal depletion, with a higher impact on High-RES central 2050 (38%) than the decentral 2050 (22%). This stems from the higher transport distance requirement of hydrogen from production plants to the factory in the centralised world. Urban land occupation is mainly due to the contributions biomass besides electricity. These contributions from the woody biomass are a result of occupation of traffic area (99%) for the sustainable forest management.

4.2.3 RESIDENTIAL AND TERTIARY SECTORS

4.2.3.1 Social Risks

Figure 30, Figure 31, Figure 32 and Figure 33 each show results for the assessment of social risk for energy supply to the residential and tertiary sectors in the current case and in future scenarios. Firstly it can be noted that the total number of worker hours actually decreases by up to 20 % for future scenarios (Figure 31). A significant driving force for this reduction is the increased share of biomass and ambient heat in the supply mix in future scenarios, that are considered according to the assessment to require fewer worker hours compared to other carriers.

As also shown in Figure 32 and Figure 33, the risk factors decrease for future scenarios compared to the current case also. This is largely due the use of solid biomass and ambient heat in future scenario more than in the current case that are less risky compared to prevalent energy carriers in the current case.

The result of the decrease in worker hours and the decrease in risk factors shown is that overall risk, as shown in Figure 30 decreases in future scenarios, particularly in the High-RES scenarios.

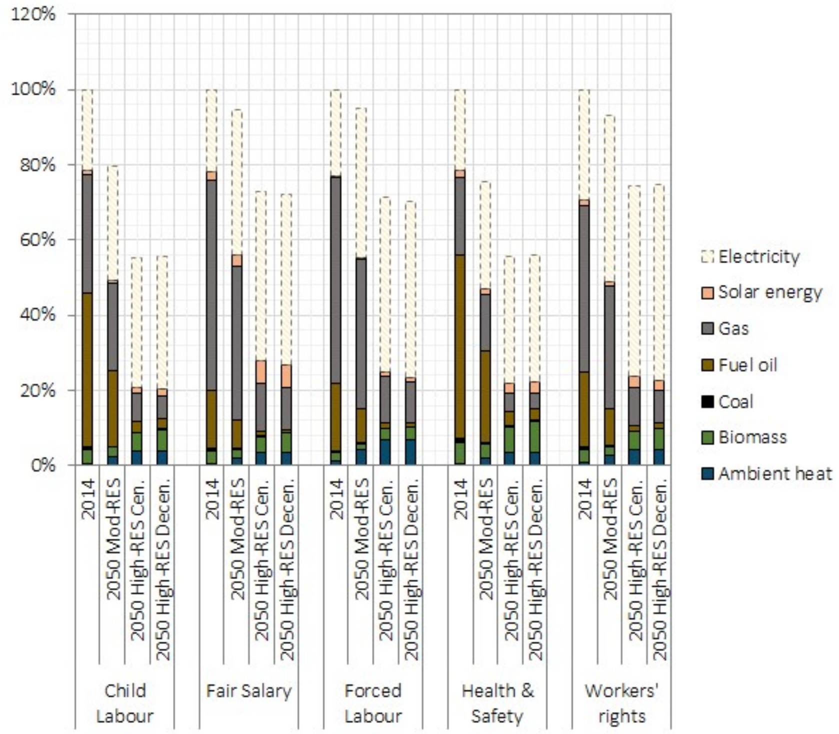

Figure 30: Contribution of different energy carriers to normalised social risk for energy supply to the residential and tertiary sectors in the EU for the current case and all REFLEX scenarios.

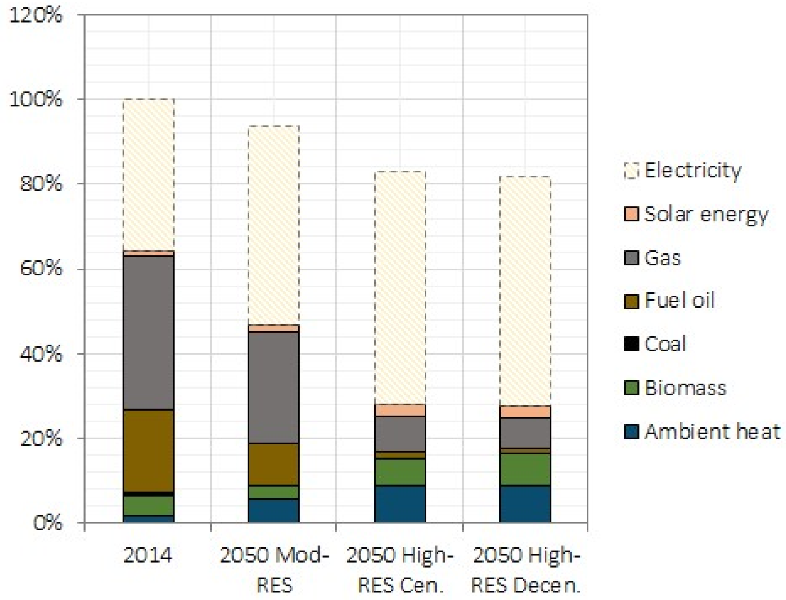

Figure 31: Contribution of different energy carriers to normalised total worker hours for energy supply to the residential and tertiary sectors in the EU for the current case and all REFLEX scenarios

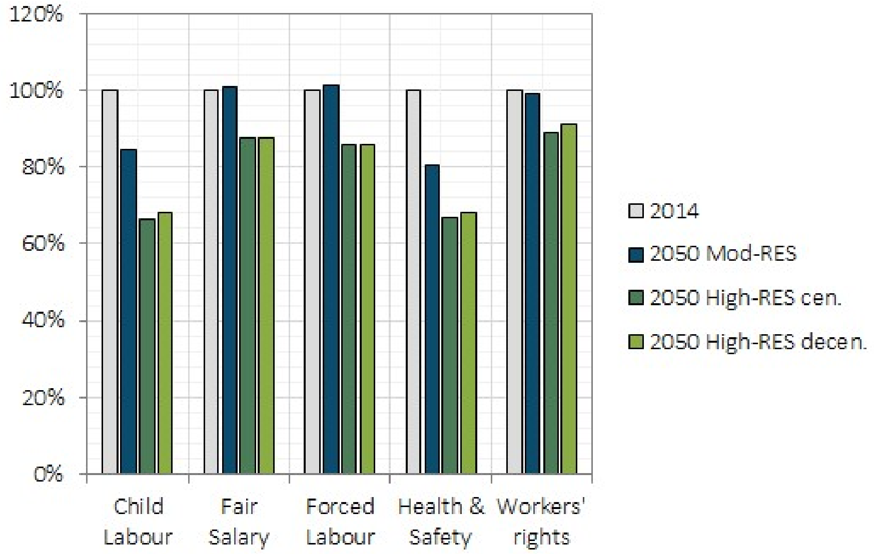

Figure 32: Normalised social risk factor for energy supply to the residential and tertiary sectors in the EU for the current case and all REFLEX scenarios

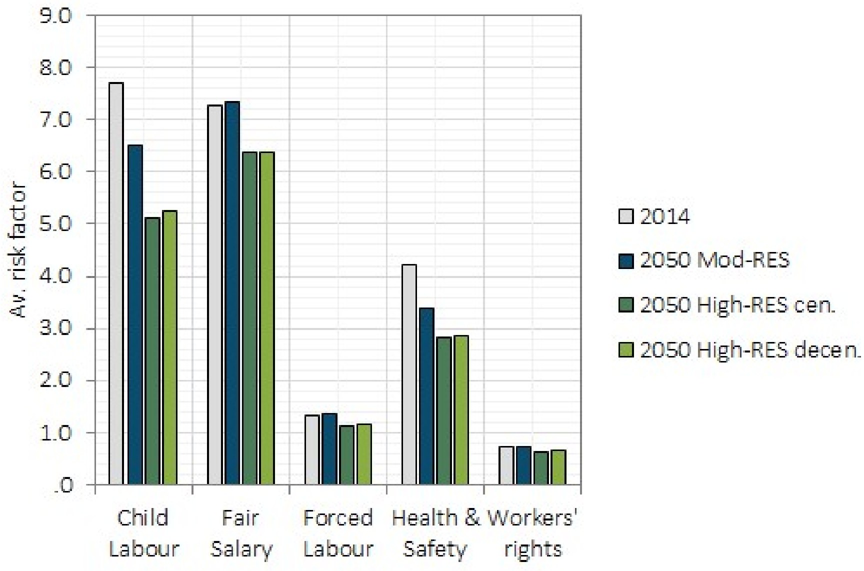

Figure 33: Absolute social risk factor for energy supply to the residential and tertiary sectors in the EU for the current case and all REFLEX scenarios

4.2.3.2 Upstream environmental impacts

Similar upstream environmental impacts are seen for the residential and tertiary sectors compared to the industry sector, see Figure 34. This confirms the significant environmental benefits of increased electricity share in the sector on climate change and freshwater eutrophication.

Figure 34 also demonstrates that there is no significant change in the normalised environmental impacts as calculated for particulate matter formation and ozone depletion, also following trends for the electricity sector. Figure 34 also shows significant increases in upstream environmental impacts in metal depletion and urban land occupation categories, also following previously discussed trends for electricity production. Finally, biomass demand in the residential and tertiary sectors makes a dominant contribution to the sector's upstream environmental impacts for agricultural land occupation, due to the demand for woody biomass in the sector. Biomass causes significant upstream impacts in terms of urban land occupation as well, alongside significant upstream impacts in the category arising due to electricity production (see Figure 34).

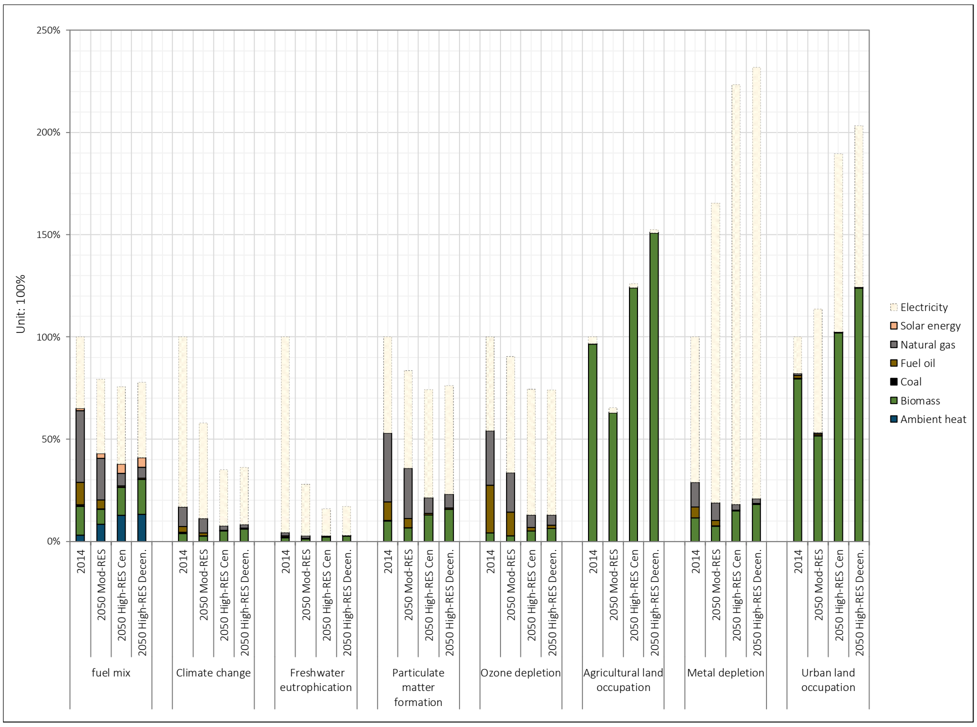

Figure 34: The normalised environmental impacts of energy carriers production for the residential and tertiary sectors in the EU for Mod-RES and both High-RES Centralised and Decentralised 2050 compared to 2014

4.3 External Costs due to Environmental Impacts

Figure 35, Figure 36 and Figure 37 each show the external costs due to calculated life cycle environmental impacts for electricity production in all scenarios. Comparing the figures, it can be seen that three impact categories together give rise to a significant proportion of total external costs so calculated – Climate change, particulate matter formation and freshwater eutrophication. Having said that, because of the uncertainty in the damage costs associated with climate change in particular (see the method section in this report), the actual damages due to climate change vary dependent on which end of the range of damage values in EcoValue12 are considered. For maximum and average values (Figure 35 and Figure 36), climate change is the dominant impact from the external cost perspective. For the minimum damage values considered (see Figure 37), the external cost due to climate change is still significant in the current case, but is very low compared to other impact categories for each future scenario.

Considering further assessment with the average damage values from EcoValue12 (see Figure 36) it is clear that coal and lignite are major contributors to total external costs for the current case, largely through the mechanism of climate change. To a lesser extent, external costs also arise due to lignite-based production through freshwater eutrophication (as a result of leaching from lignite spoil).

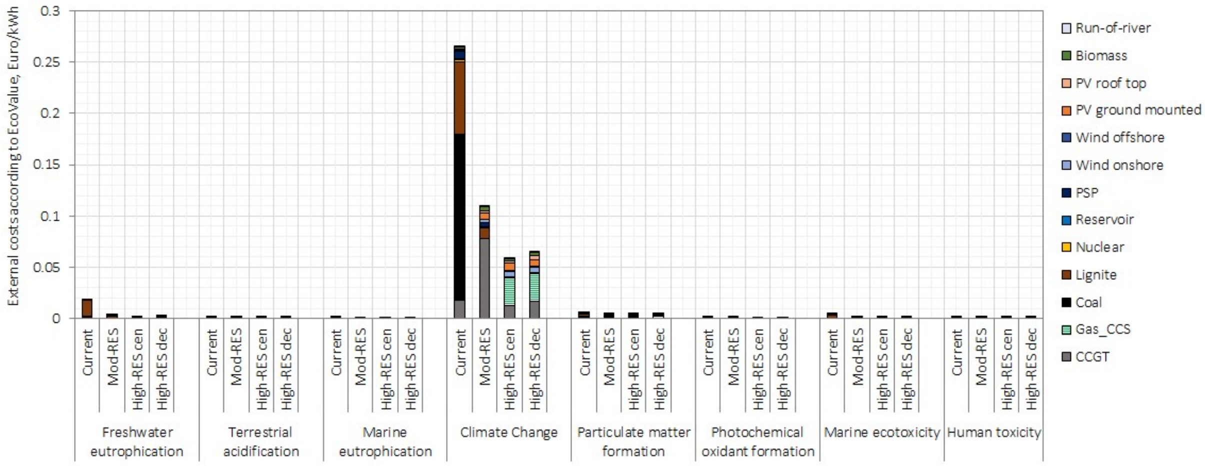

Figure 35: External costs in Euro/kWh due to life cycle environmental impacts for electricity production for all scenarios according to maximum damage values stated by the EcoValue12 tool

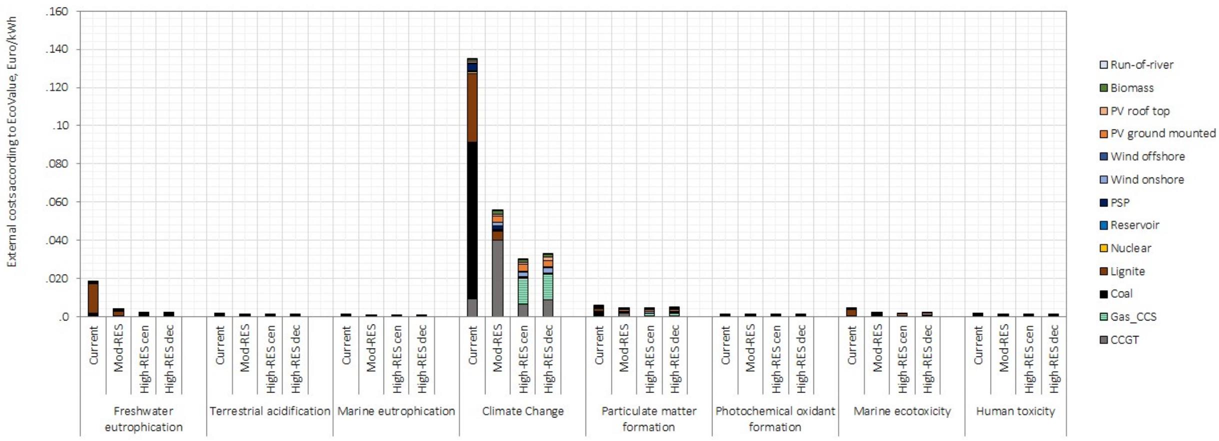

Figure 36: External costs in Euro/kWh due to life cycle environmental impacts for electricity production for all scenarios according to average damage values stated by the EcoValue12 tool

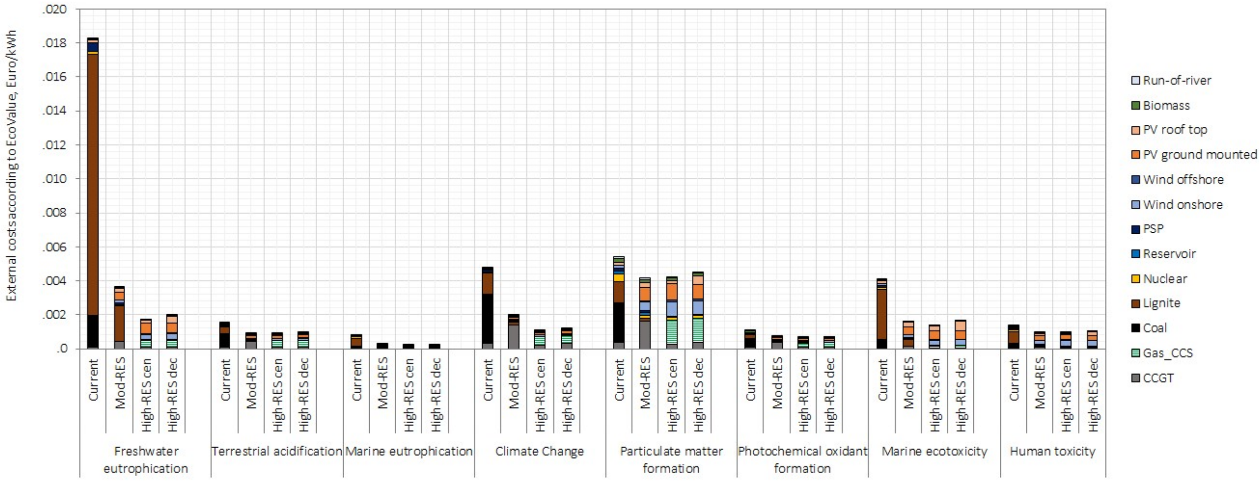

Figure 37: External costs in Euro/kWh due to life cycle environmental impacts for electricity production for all scenarios according to minimum damage values stated by the EcoValue12 tool

Figure 38, Figure 39 and Figure 40 each show an assessment of the total production cost for 1 kWh electricity, using the maximum, average and minimum average damage values from EcoValue 2012.

For maximum and average values in the current case, the external cost is a few times greater than the indicative production costs. The main contributor to the relatively high external cost in this case (see earlier discussion) is due to coal and lignite through the mechanism of climate change. Even when assuming minimum damage values (see Figure 40) the external cost in the current case constitutes a significant part of the total cost, where freshwater eutrophication due to the lignite production cycle is the major contributor.

Interesting to note is that irrespective of the damage values used, the total costs calculated for all future scenarios are lower than the respective total cost for the current case. In fact, only for the assumption of minimum damage values is the total cost greater in ambitious High-RES scenarios than in the Mod-RES (and the increase between Mod-RES and High-RES is small). Meanwhile, the indicative production costs used for comparison increase between the current case and the future scenarios. Therefore, in light of damage values due to environmental impacts considered in this assessment, the economic performance of future electricity production is better than for the current system. Indeed, the future economic performance of ambitious climate mitigation policies is at least as good as (and possibly better) than less ambitious scenarios according to this analysis.

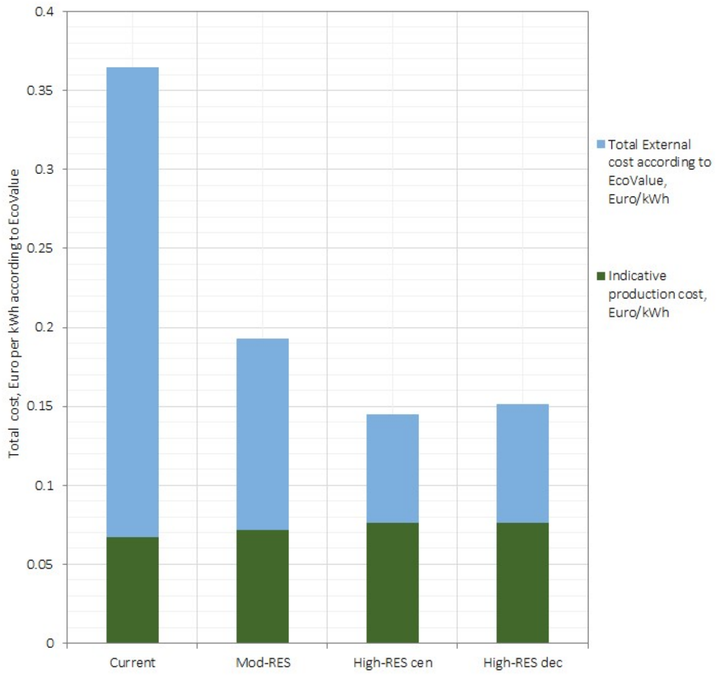

Figure 38: Total cost for production of 1 kWh electricity, including external costs due to life cycle environmental impacts calculated according to maximum damage values according to the EcoValue12 tool and indicative production costs.

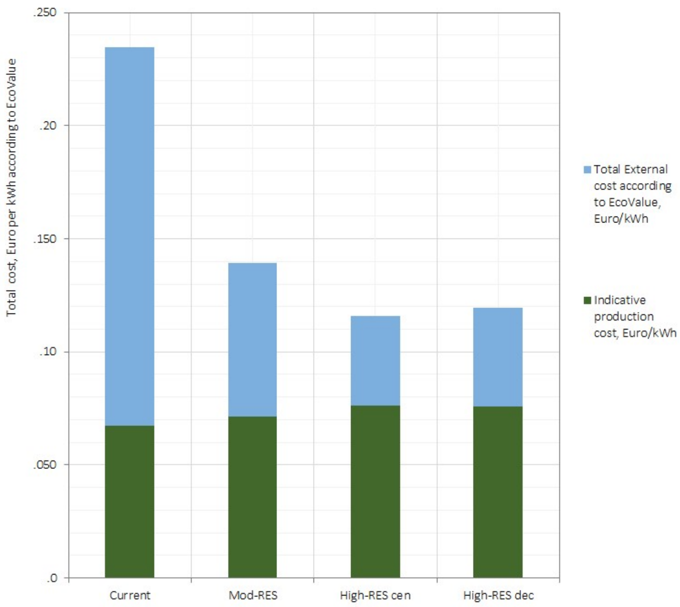

Figure 39: Total cost for production of 1 kWh electricity, including external costs due to life cycle environmental impacts calculated according to average damage values according to the EcoValue12 tool and indicative production costs.

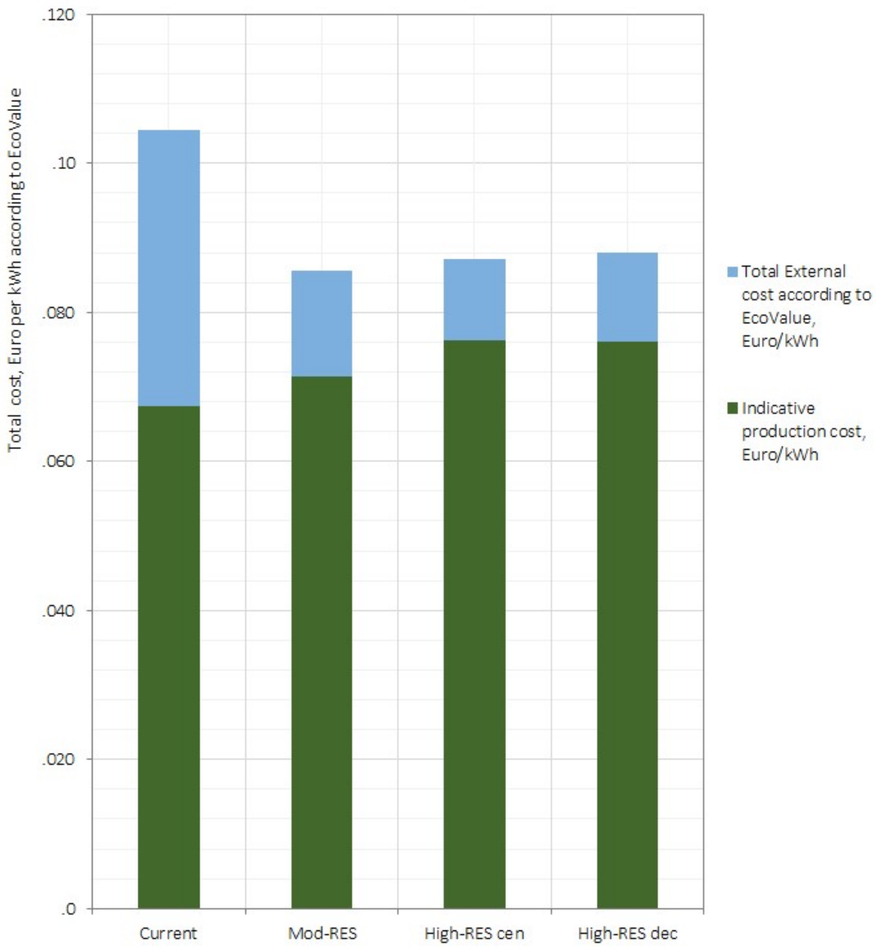

Figure 40: Total cost for production of 1 kWh electricity, including external costs due to life cycle environmental impacts calculated according to minimum damage values according to the EcoValue12 tool and indicative production costs.

Figure 41 and Figure 42 show that external costs for industry and the residential and tertiary sectors are dominated in the current case by those arising from electricity production in the category climate change. The figures also show that external costs decrease significantly in future scenarios. Contribution analysis shows that this is mostly due to reduction of the carbon intensity in electricity generation. Note that the environmental assessment only includes upstream impacts.

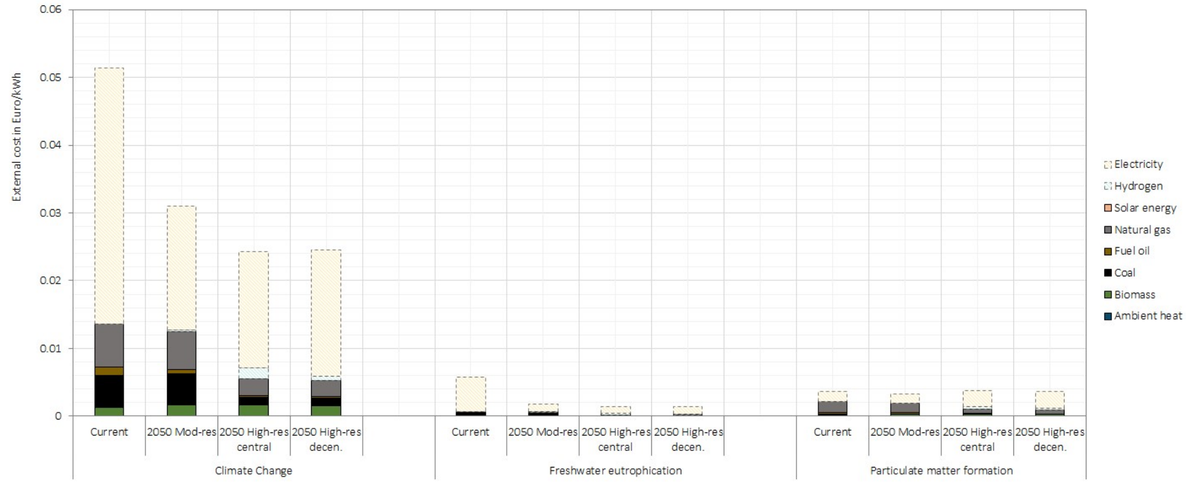

Figure 41: Total external costs in Euro/kWh due to upstream environmental impacts for the industrial sector for all scenarios according to average damage values stated by the EcoValue12 tool.

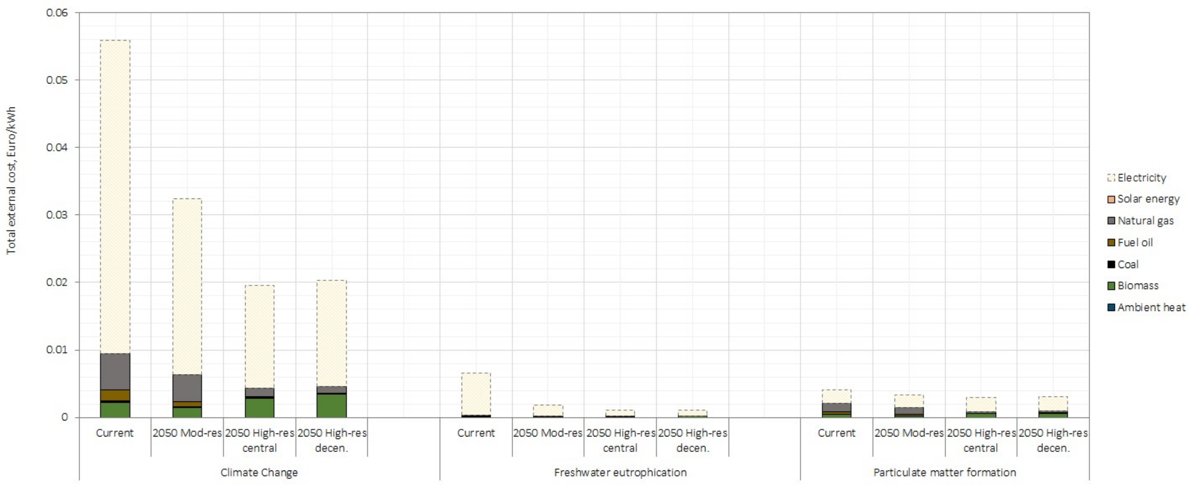

Figure 42: Total external costs in Euro/kWh due to upstream environmental impacts for the residential and tertiary sectors for all scenarios according to average damage values stated by the EcoValue12 tool.

Figure 43 shows that external costs due to climate change are the dominant factor in total external cost in the transport sector. Figure 43 also shows that the external costs according to the assessment are lower for the transport sector in the current case compared to the same case for the industry and residential and tertiary sectors (see Figure 41 and Figure 42). One significant reason for this of course is the fact that the environmental assessment here is considering specifically upstream environmental impacts. Meanwhile, Figure 43 also shows that on aggregate calculated external costs increase in future scenarios, particularly for High-RES cases. This increase is largely due to the larger upstream impacts associated with the production of biofuels, particularly biokerosene. Meanwhile, the decreasing demand for fossil fuels causes upstream external costs to decrease in future scenarios.

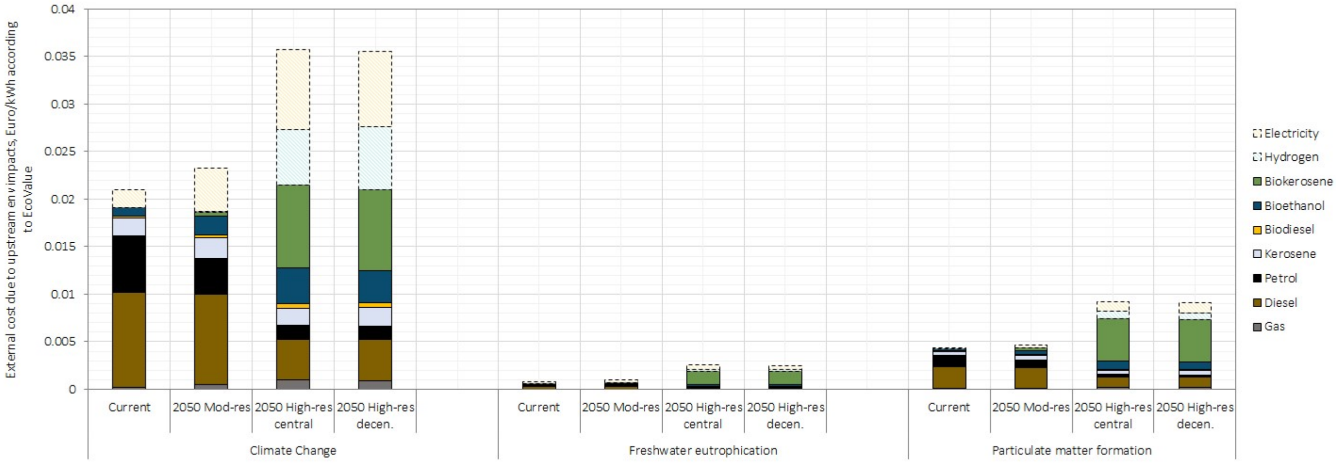

Figure 43: Total external costs in Euro/kWh due to upstream environmental impacts for the transport sector for all scenarios according to average damage values stated by the EcoValue12 tool.

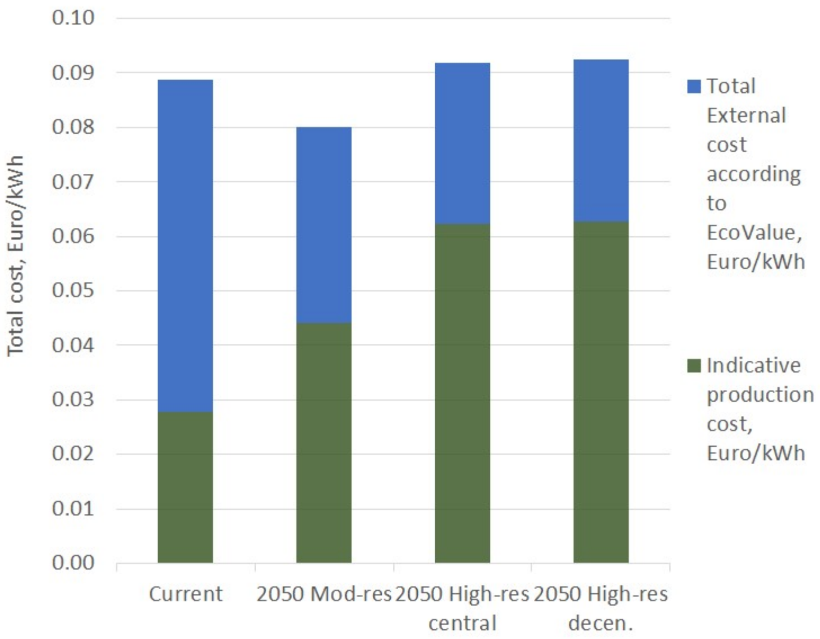

Figure 44: Total average energy cost for 1 kWh delivered energy in the industrial sector, including external costs due to upstream environmental impacts calculated according to average damage values according to the EcoValue12 tool and indicative production costs.

Figure 44, Figure 45 and Figure 46 show that even only accounting for upstream impacts, external costs are of a similar order of magnitude as indicative production costs in end use sectors. Figure 44 and Figure 45 also show that there is little variation in the total energy cost as assessed between the current case and future scenarios for the industrial and residential and tertiary sectors. The decrease in external costs makes a significant contribution to this trend in light of the fact that they decrease significantly in future scenarios compared to the current case, whereas the indicative production costs increase in future scenarios.

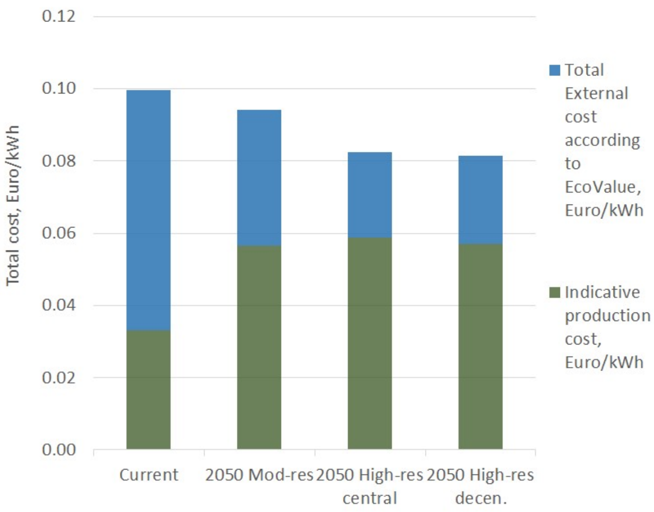

Figure 45: Total average energy cost for 1 kWh delivered energy in the residential and tertiary sectors, including external costs due to upstream environmental impacts calculated according to average damage values according to the EcoValue12 tool and indicative production costs.

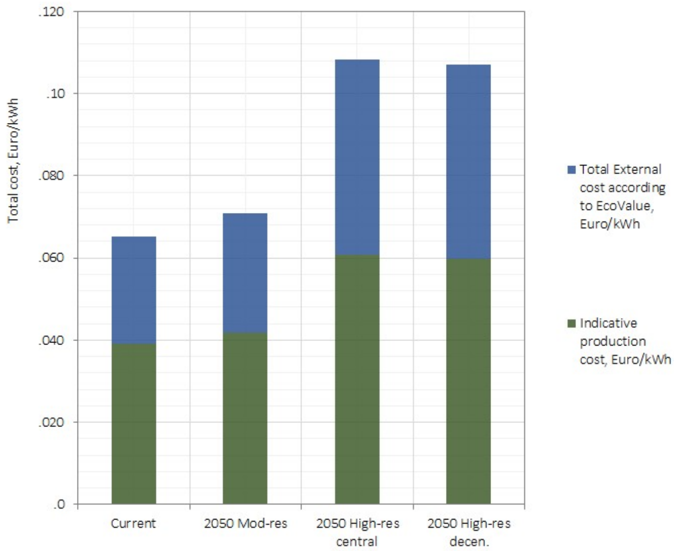

Figure 46: Total average energy cost for 1 kWh delivered energy in the transport sector, including external costs due to upstream environmental impacts calculated according to average damage values according to the EcoValue12 tool and indicative production costs.

Finally, Figure 46 shows that the total costs for energy supply in the transport sector actually increase significantly in future scenarios compared to the current case. This is due to the increase in external costs for upstream environmental impacts and increase indicative production costs. It is important to point out that a different cost profile may arise when external costs due to combustion impacts are considered.

5 Results: Spatially disaggregated Impact Pathway Analysis of direct emissions

5.1 Atmospheric concentration of pollutants

Results of modelled ambient $PM_{2.5}$ concentrations for different scenarios and years are presented in Figure 47 - Figure 54. That the figures appear so similar is because the aggregate emissions in each of the temporal cases is roughly similar. This is because though combustion of fossil fuels decreases in the future scenarios, the combustion of biomass increases, therefore leading to no aggregate change in emissions.

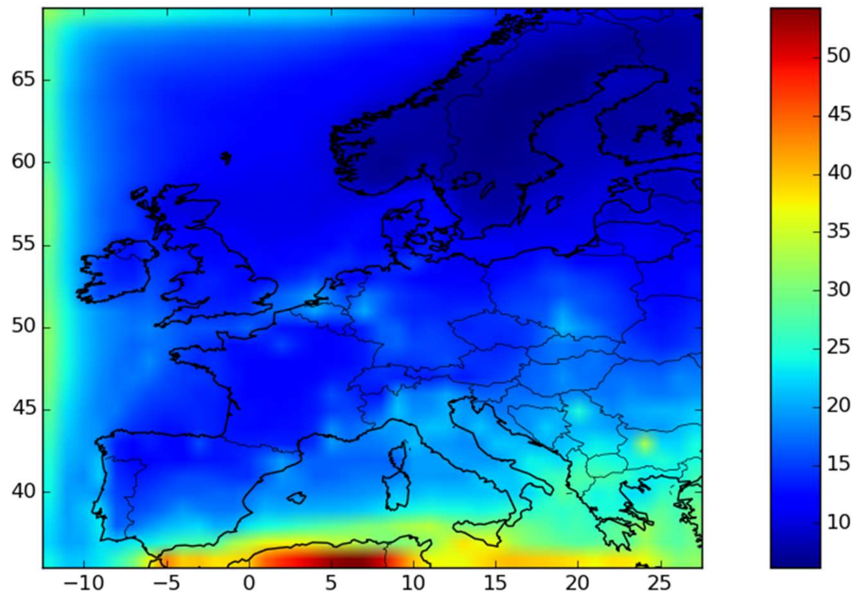

Figure 47: Modelled ambient PM_{10} concentrations in 2015 [µm/m³].

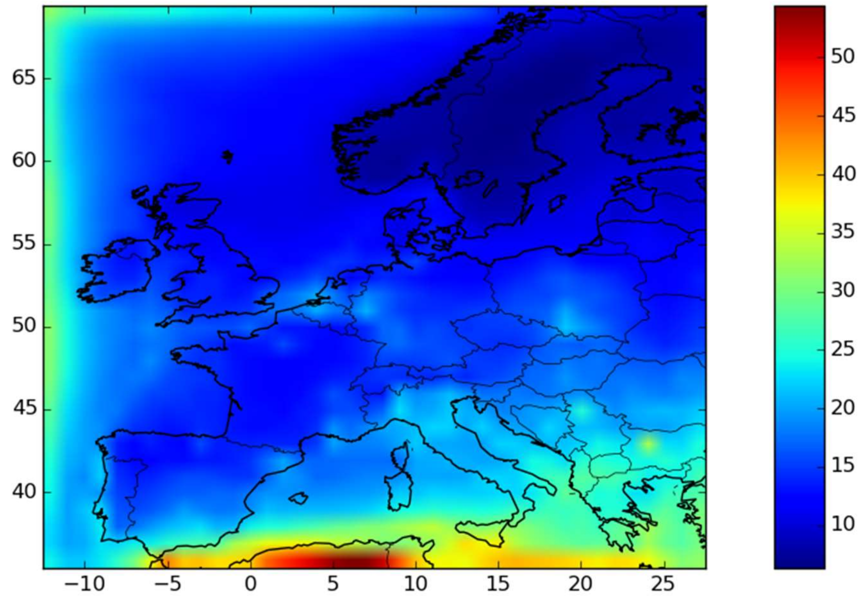

Figure 48: Modelled ambient PM_{10} concentration in 2050 for Mod-Res scenario [µm/m^3].

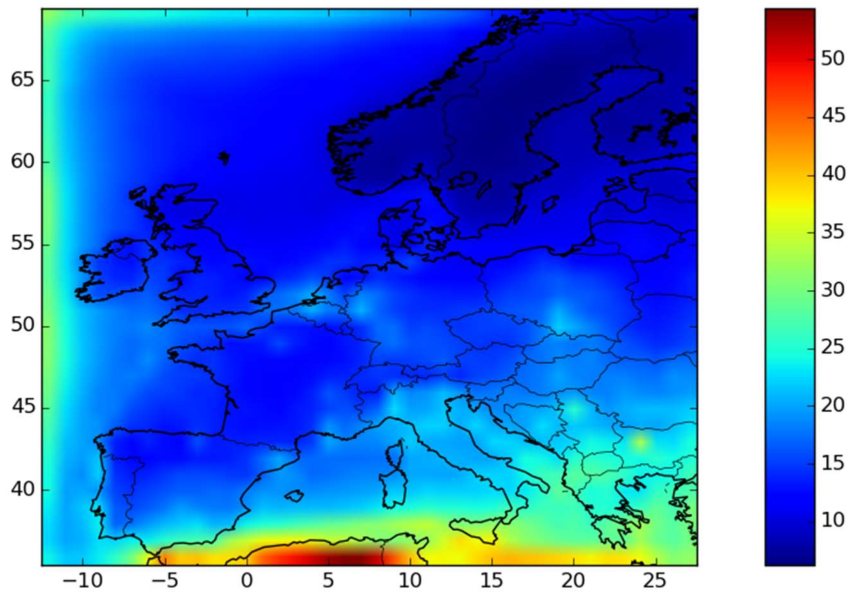

Figure 49: Modelled ambient PM_{10} concentration in 2050 for High-Res decentralized scenario [µm/m^3].

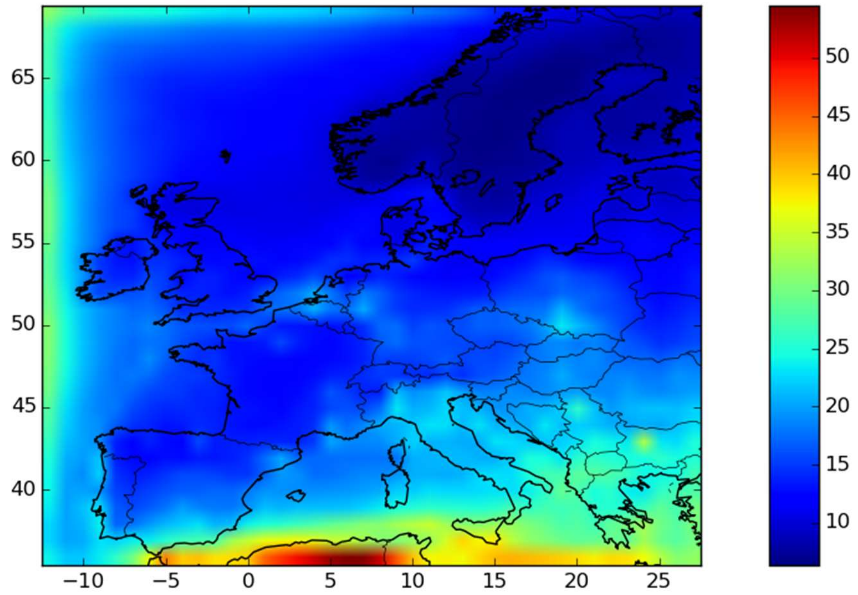

Figure 50: Modelled ambient PM_{10} concentration in 2050 for High-Res centralized scenario [µm/m^3].

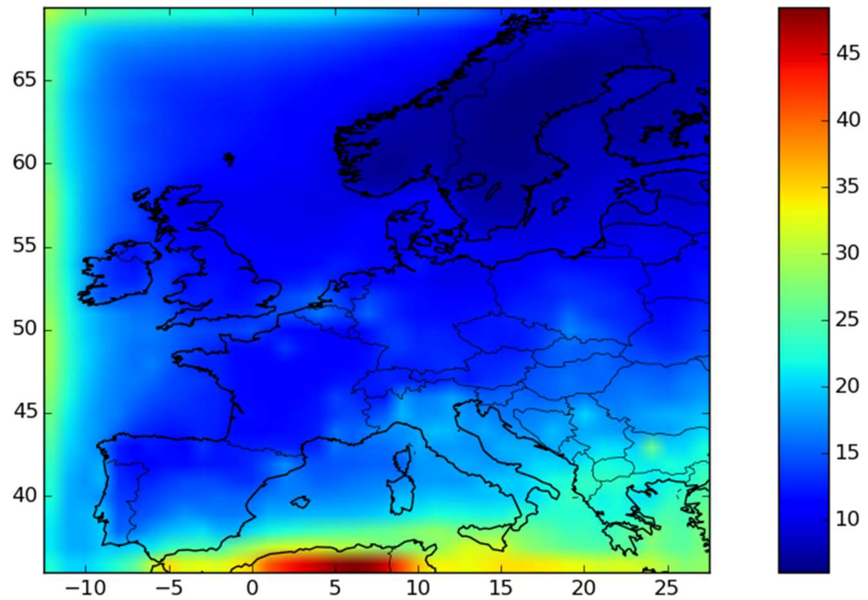

Figure 51: Modelled ambient $PM_{2.5}$ concentrations in 2015 [µm/m^3].

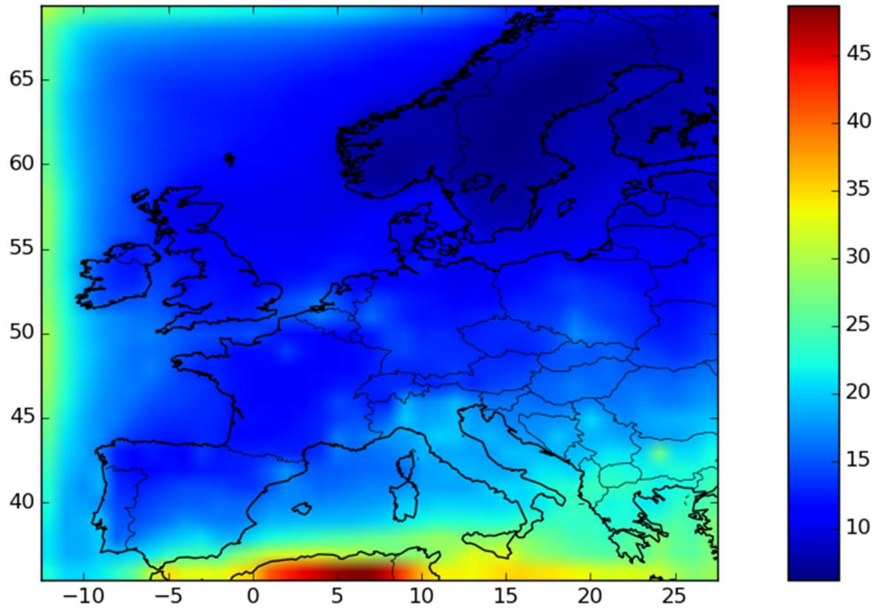

Figure 52: Modelled ambient $PM_{2.5}$ concentration in 2050 for Mod-Res scenario [µm/m^3].

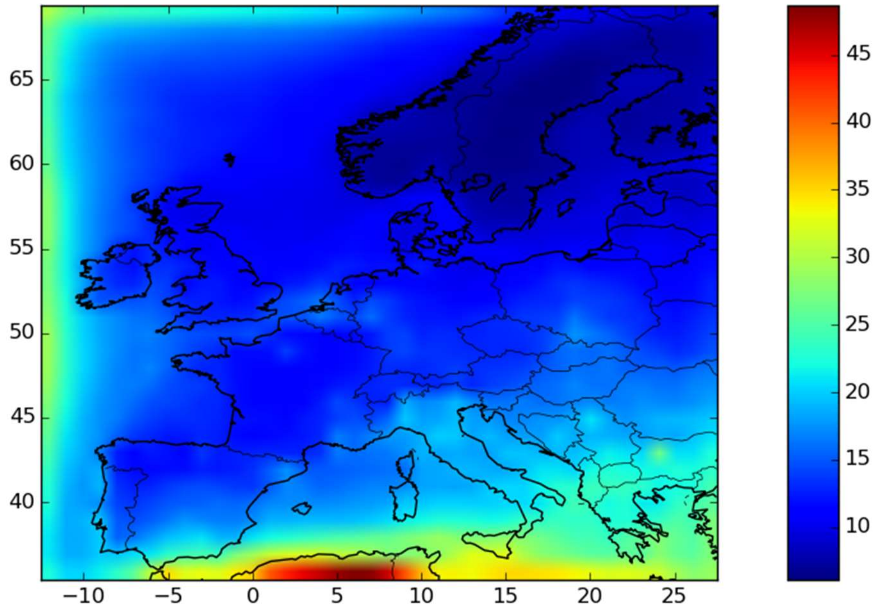

Figure 53: Modelled ambient $PM_{2.5}$ concentration in 2050 for High-Res decentralized scenario [µm/m^3].

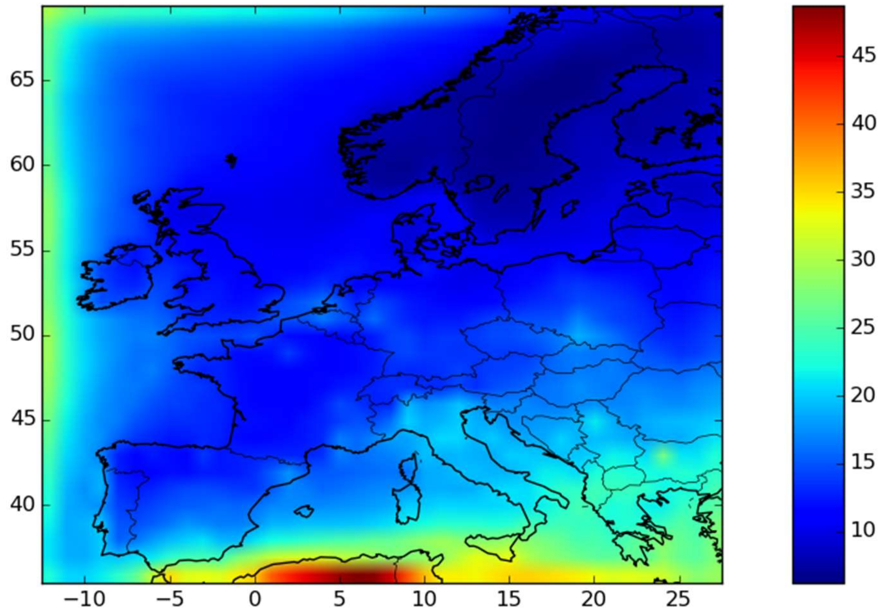

Figure 54: Modelled ambient $PM_{2.5}$ concentration in 2050 for High-Res centralized scenario [µm/m³].

5.2 Health Impacts

Calculated health effects for the Mod-Res scenario in 2015 and 2050 are presented in Table 47-Table 49. These health effects are almost the same for the High-RES centralized and de-centralized scenarios due to similar PM emissions levels.

Table 47: YOLL for 2015 and for the Mod-Res 2050.

Country	YOLL - 2015 [YOLLs.year-1]	YOLL - Mod-Res 2050 [YOLLs.year-1]
AL	21914.3	22315.8
AT	38020.8	39664.8
BE	56416.4	57828.6
BG	48036.3	48876.1
CH	35016.4	36332.6
CZ	45911.7	48194.1
DE	348689.9	361119.0
DK	19127.4	19551.8
EE	3710.5	3829.8
EL	85659.4	86790.9
ES	252830.8	256379.3
FI	13199.3	13655.0
FR	275801.4	282632.7
HR	24198.6	25063.4
HU	52611.5	53685.6
IE	21587.8	21826.3
IT	389482.3	404907.6
LI	155.2	162.4
LT	10563.3	10894.9
LV	6646.6	6865.5
MT	4864.6	4930.2
NL	77713.1	79911.8
NO	13325.8	13532.9
PL	175146.0	181279.8
PT	59203.2	59592.0
RO	104783.9	106660.1
SE	25641.2	26310.6
SI	10672.0	11201.7
SK	27960.2	28017.8
UK	259058.3	263242.7
Total	**2507948.1**	**2575255.7**

Table 48: RAD for 2015 for 2015 and for the Mod-Res 2050.

Country	CB - 2015 [Cases.year-1]	CB - Mod-Res 2050 [Cases.year-1]
AL	2691226.4	2740531.9
AT	4669217.2	4871116.3
BE	6928328.7	7101763.6
BG	5899192.5	6002326.4
CH	4300261.1	4461898.7
CZ	5638274.5	5918577.3
DE	42821566.6	44347941.7
DK	2348978.1	2401092.4
EE	455680.8	470326.8
EL	10519569.7	10658537.0
ES	31049392.3	31485179.8
FI	1620970.2	1676924.9
FR	33870348.0	34709273.3
HR	2971759.7	3077956.5
HU	6461059.7	6592971.3
IE	2651136.3	2680417.6
IT	47831162.3	49725491.7
LI	19059.4	19939.6
LT	1297244.4	1337964.3
LV	816245.4	843132.9
MT	597403.2	605460.7
NL	9543713.7	9813727.6
NO	1636500.7	1661941.2
PL	21509163.9	22262436.6
PT	7270564.4	7318313.3
RO	12868202.6	13098605.0
SE	3148917.3	3231128.5
SI	1310598.7	1375649.7
SK	3433703.7	3440786.4
UK	31814179.7	32328055.3
Total	**307993621.3**	**316259468.4**

Table 49: CB for 2015 and for the Mod-Res 2050.

Country	CB - 2015 [Cases.year-1]	CB - Mod-Res 2050 [Cases.year-1]
AL	2499.0	2544.8
AT	4335.7	4523.2
BE	6433.4	6594.5
BG	5477.8	5573.6
CH	3993.1	4143.2
CZ	5235.5	5495.8
DE	39762.9	41180.2
DK	2181.2	2229.6
EE	423.1	436.7
EL	9768.2	9897.2
ES	28831.6	29236.2
FI	1505.2	1557.1
FR	31451.0	32230.0
HR	2759.5	2858.1
HU	5999.6	6122.0
IE	2461.8	2489.0
IT	44414.7	46173.7
LI	17.7	18.5
LT	1204.6	1242.4
LV	757.9	782.9
MT	554.7	562.2
NL	8862.0	9112.7
NO	1519.6	1543.2
PL	19972.8	20672.3
PT	6751.2	6795.6
RO	11949.0	12163.0
SE	2924.0	3000.3
SI	1217.0	1277.4
SK	3188.4	3195.0
UK	29541.7	30018.9
Total	**285994.1**	**293669.5**

5.3 SPATIALLY DISAGGREGATED EXTERNAL COSTS

As presented in Table 50 the estimated health related external costs of $PM_{2.5}$ air pollution are about €210 billion per year.

Table 50: Annual external costs associated with PM2.5 for different health effects.

Impact		2015	Mod-Res 2050	Unit value [EUR/case*]	2015 10^6 EUR	Mod-Res 2050 10^6 EUR
YOLL	Overall	2507948.1	2575255.7	50000.0	125397.4	128762.8
CB	Overall	285994.1	293669.5	169330.0	48427.4	49727.1
RAD	Overall	307993621.3	316259468.4	110.0	33879.3	34788.5
Total					**207704.1**	**213278.4**

The external costs for other REFLEX scenarios are very similar to the current situation. As mentioned before, this is mainly due to high PM emissions from the use of biomass for district heat generation.

6 Discussion

6.1 Reflections on methodology for life cycle approach in general

For the social assessment it was assumed that the social risk for any given process was the same in the current case as for the future cases. This was beneficial because it allowed the assessment to identify areas that of potentially greatest significance for improvement in order to reduce social risk. On the other hand, in order to be consistent with the REFLEX scenarios (as discussed in the LCA framework) the risk profiles may have been reduced in the High-RES scenarios, since they assume some improvement in social performance. On the other hand this would have been less interesting since it would not have been so beneficial in terms of providing decision support as the approach used did.

Another reflection is that for most of the energy carriers a principle of technical potential or a technical preserving perspective was applied. Often this was because of a lack of other data or any other such indication as to the future state of the system, e.g. countries of origin for future gas supply. For gas supply this was addressed to a certain extent with the sensitivity analysis for this, but of course there is potential to investigate further in an explorative way. Other areas shown in this assessment could further be investigated in an explorative way.

One particular feature of the investigation was to use a learning curve approach to adjust social LCI for wind turbines and solar PV plant. It was clearly important to do this in light of the fact that these technologies will see significant technological development in the coming decades. One simplification was of course that the same learning rate was used for all future scenarios. It remains therefore for future work to account for the fact that installed capacities will differ for different future scenarios and that therefore there will be different rates of learning. At the same time, it is clear that incorporating learning rates as performed is preferable to having assumed a constant cost profile.

It should be pointed out that though life cycle inventory for social and environmental LCA were not exactly identical in all cases. Such differences were most evident when considering wind power and solar power. From an environmental perspective, developments in wind power and solar PV were considered by considering developments in generator technology and cell technology respectively. Meanwhile, as noted above for a social perspective development in these technologies was considered by applying a learning curve approach. In future work it could therefore be interesting to apply a learning curve approach for the technologies from an environmental perspective. Using an identical modelling approach from an environmental perspective as for a social perspective would make the results more comparable. The learning curve approach in an environmental perspective may also serve to mitigate some of the impacts noted here as increasing in the future, e.g. metal depletion or particulate matter.

It was meanwhile possible to perform the assessment according to the sectoral disaggregation used in the REFLEX models and as is common practice in other energy modelling (see also discussion in REFLEX SELES framework). At the same time, according to the broad scope of the assessment, a finer level of disaggregation was not applied. This is a task that remains for future work.

One feature that could be highlighted based on such a disaggregation is that the system boundaries used for each sector aimed largely to focus on the supply of energy (or the production of electricity). By so doing valuable support has been provided to decision makers. On the other hand, it was not an intention to attempt to assess other features related to the energy system that may also have notable effects. In the first instance it is important that decision makers keep this in mind when interpreting the results presented. On the other hand it is a task for future work to expand the coverage of the assessment.

6.2 METHODOLOGICAL DISCUSSION FOR SOCIAL ASSESSMENT

The underlying approach behind SOCA has for the purposes of this assessment been a valuable one. By connecting ecoinvent data with activity variables and performance data for social assessment it has been possible to assess the modelled energy systems from the perspective of multiple social indicators, connected with valuable, reliable and largely transparent data sources.

Quantitatively, through the use of the SOCA add-on the social impact assessment performed here has considered and compared over thirteen separate supply technologies in the end use sectors transport, residential and tertiary and industry. In addition, thirteen separate supply technologies have been considered in the electricity production sector, yielding twenty-six total energy supply chains considered in the EU context. In addition, each of these separate energy supply chains have been assessed from the perspective of the four different temporal cases considered. Moreover, for each of the twenty-six supply chains for which the SOCA add on was used as a starting point for social inventory, attention was also paid to how the technology may develop between the starting year (status quo) and each 2050 scenario. Having said that, even with the power of the SOCA tool the huge scope of the assessment did not allow a detailed inventory for each energy chain and for every scenario. Nevertheless, thanks to the SOCA add-on this was possible for key technologies in electricity production, in particular wind power and solar power, both of which are key technologies in low carbon futures.

In facilitating the creation of relevant LCI for social assessment for all of the energy supply chains considered, the SOCA add on gave access to social performance data from a huge variety of sources including for example the ILO, the World Bank, Transparency International, the US State Department to name but a few. Therefore the SOCA add on has in a broad sense been hugely important in supporting the successful fulfilment of the original goals of the assessment.

The main reflection in light of using SOCA as a starting point in this study is that had such a tool not been used, it would not have been possible to screen for the amount of indicators and broad system scope that was achieved by using it.

On the other hand, as an innovative approach, the SOCA tool is at an early stage of development, and in light of this one valuable outcome from this study are methodological recommendations for the SOCA tool and approach.

One key issue that has not been addressed in the current version is ultimately the fact that social risk and environmental impacts are driven by different variables in systems' supply chains. Namely whereas an environmental profile is sufficiently representative by considering a representative material flow, a social profile is representative when it is modelled as being performed according to social performance parameters that are relevant for the geographic location of the process. It became clear during the work that while ecoinvent may consider country specific processes for electricity production using a certain technology type, e.g. "electricity production, wind, 1-3MW turbine, onshore | electricity, high voltage | cut-off, U – DE", key technological inputs to this process, such as construction of the wind power plant from manufactured raw materials, i.e. "wind turbine construction, 2MW, onshore | wind turbine, 2MW, onshore | cut-off, U – GLO" are assumed to be carried out according to global conditions. From an environmental perspective this kind of generalizing assumption is potentially sufficiently representative of this technological input, especially since many of the constituent manufactured materials in the turbine (e.g. steel, aluminium, concrete) may be traded on a global market anyway. However, given the geographic specificity of the *construction process* itself for a wind turbine, it is absurd to claim that its construction in Germany is performed according to a global average level of social performance. The fact that this had not been addressed in SOCA/ecoinvent itself meant that significant model development work in this study was directed at ensuring that processes in the model were assigned as being performed in countries and regions that were adequately representative of the reality to be modelled.

The related and converse issue is that for a particular unit process output, e.g. electricity production with a wind turbine, ecoinvent does not give social performance profiles for all potential geographic regions. Specifically in this work it was interesting to model such conditions from average European conditions.

Ultimately, in as good as all cases it was possible to develop representative social performance profiles for processes where the original profiles were not representative, as described in the method section of the report. However in light of this time consuming modelling work and the fact that the background data required to do it are readily available, it seems that SOCA could be further refined. Specifically, it would be a great advantage for a user to be able to choose simply from a dropdown list the country specific sector to be assumed for a given process.

A further issue of interest in the assessment the aim to understand how social performance improvements in certain sectors may contribute to mitigating social risks from the system as a whole. In the current set up, it is certainly possible to change the social performance in a given specific process. However, a further development could be to make it possible to change for an entire country specific sector as well.

6.3 Discussion of environmental impact assessment

Life cycle assessment is conducted for the electricity sector and end-use sectors (mobility, industry, residential and tertiary) to investigate the environmental impacts induced by the low-carbon energy system transformation with focus on flexibility options. The analysis shows that environmental impacts due to the electricity sector decrease notably for the categories climate change, freshwater eutrophication and agricultural land occupation. The analysis further shows that impacts due to particulate matter formation and ozone depletion do not change significantly per unit delivered electricity. Meanwhile impacts in categories metal depletion and urban land occupation increase significantly between the current situation and 2050. The analysis also confirms the significant negative or positive effects of changes in electricity impacts on end-use sectors. Furthermore in end use sectors, the use of biomass in different forms causes increases for agricultural and urban land occupation as calculated.

6.3.1 Climate change

Climate change is a special environmental impact compared to others as climate change mitigation is a key driver for future scenario-based European energy system transformation. For example, according to the sectoral reduction targets proposed by the European Commission, the electricity sector is indicated to have a carbon dioxide emissions reduction by 93 to 99% in 2050 compared to 1990 (European Commission, 2011). From the analysis of ELTRAMOD, the target is fulfilled in both High-RES energy scenarios in 2050, with reduction rates of 96% and 97% for High-RES central and decentral, respectively. Nevertheless, the Mod-RES scenario shows a 91% emissions reduction rate by 2050. From a life cycle perspective, the reduction rates vary to 90%, 88% and 84% for High-RES central, High-RES decentral and Mod-RES scenarios in 2050, respectively, which are lower than the emission target of the electricity sector set by the European Commission. The changes are mainly due to emissions occuring in upstream processes for electricity production, such as the industry sector that are also included in the European low carbon economy framework to reduce GHG emissions by 80-95% by 2050 compared to 1990 commonly. On this basis, it is therefore undeniable that the designed roadmaps towards a decarbonised European energy system are effective even from a life cycle perspective.

6.3.2 Increases in environmental impacts in scenarios

Metal depletion, agricultural and urban land occupation are the environmental impacts that show low advantages in electricity sector and upstream in end-use sectors. From a life-cycle perspective, metal deletion and agricultural land occupation are impacts on a global level, while urban land occupation (due e.g. to the installation of PV mounting systems) is an impact focussed on EU countries. Given such a reality, a primary sustainability challenge in terms of metal depletion and agricultural land occupation is to consider the global scale. Europe is not an isolated region aiming to address the challenges posed by increases in these impact categories. Thus a close collaboration with regions and countries outside of Europe is crucial.

However, it should be noted the LCIA results are dependent on the assumptions made in the LCI analysis. A different result might be achieved if different assumptions are considered, which leads to potential uncertainties and poor robustness of the results. However, as the objective of this work is to provide comparative results for different scenarios, the consistent assumptions seem reasonable and sufficient to fulfill the objective. Nevertheless, exemplary cases of sensitivity analysis are performed to give insights for addressing the challenge of uncertainty, and at the same time, to provide decision support for possible measures to mitigate the negative non-climate associated environmental impacts that increase significantly in future scenarios.

6.3.3 Sensitivity analysis - case 1: steel recycling for wind power technologies

As investigated, wind power is responsible for around 48% (42% for onshore and 6% for offshore) of the metal depletion impacts for the High-RES central scenario 2050. Within this, steel demand (including low-alloyed steel, chromium steel, reinforcing steel and cast iron) accounts for around 90% of total life cycle metal depletion for wind technologies. The results are achieved under a specific assumption that all of the metals are obtained directly from the metal mining activities and no recycling metals are considered. Currently, levels of metal recycling are generally low, but future recycling rates could be higher. In light of this, a scenario is investigated where the required steels for wind power technologies in 2050 are 90% recycled and 10% from primary production. The comparative results based on the High-RES central scenario are shown in Figure 55. The figure shows how recycling activities can relieve the burdens of metal depletion. While metal depletion doubles in the standard High-RES central 2050 compared to 2014, steel recycling activities for wind power technologies mitigate the increasing rate significantly. The recycling activities could occur for other metals such us copper and other technologies like PV, to contribute to constructing a sustainable metal market.

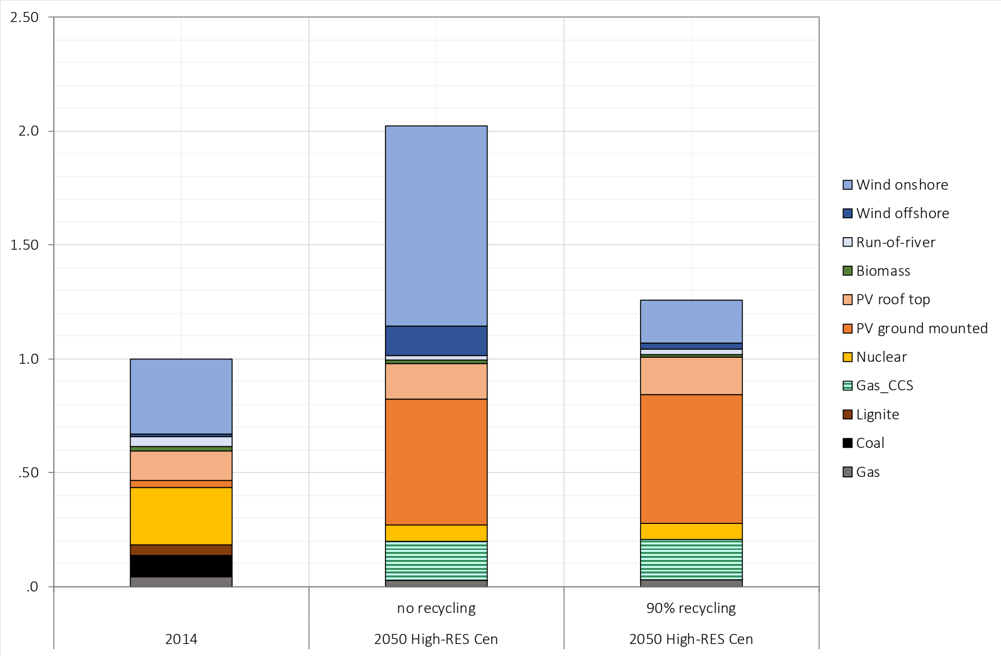

Figure 55: sensitivity analysis between steel recycling for wind technology and environmental impact of metal depletion based on normalized results

6.3.4 Sensitivity analysis - case 2: system boundary for electricity used in end-use sectors

As mentioned in the method section, eLCA of upstream processes of end-use sectors is conducted, aiming to fulfil the system boundary gaps in the model ASTRA (mobility) and Forecast (industry, residential and tertiary) and provide additional knowledge for policy makers and other stakeholders. For example, the system boundary for fuels such as diesel is set from raw materials mining and processing (cradle) to final diesel production. The processes of diesel transportation from plants to fuelling stations and diesel combustion are out of the scope. Similarly, the system boundary for electricity is set from cradle to electricity production.

However, as we know, secondary energy carriers such as electricity and hydrogen are produced from primary energy carriers such as coal, natural gas, nuclear and renewable energy sources (wind, solar, hydropower), and are generally called secondary energy carriers. That means, the identical cradle-to-gate system boundary setting for both primary and secondary energy carriers is to some extent “unfair” for the secondary energy carriers, as energy conversion processes with significant environmental impacts e.g. combustion of primary energy carriers and the required infrastructure that are out of the boundary for primary energy carriers are however included in the boundary for electricity and hydrogen.

If the process of energy conversion and the required infrastructure for electricity and hydrogen are excluded from the life cycle system boundary, the results could be different. As demonstrated in Figure 56, the advantage of using electricity and hydrogen for the industry sector is significant.

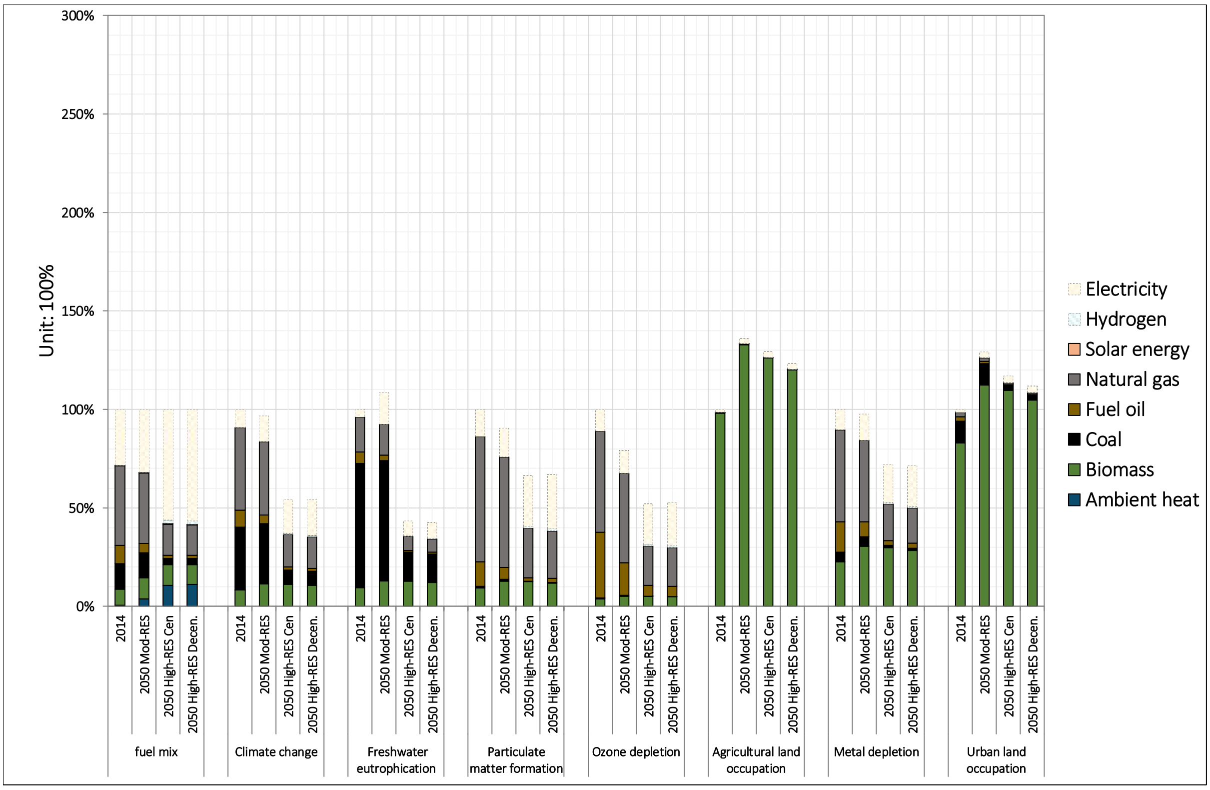

Figure 56: Sensitivity analysis showing environmental impacts for each scenario considering only upstream impacts for all energy carriers (including electricity and hydrogen), based on normalised results of industry sector

The results could also be changed if the energy conversion processes and the associated infrastructure of primary energy carriers are included in the system boundary. These analyses are intended to be performed in our next step of the research.

6.4 DISCUSSION OF EXTERNAL COSTS ESTIMATED WITH THE IMPACT PATHWAY APPROACH

External costs associated with the health effects have been estimated using the Impact Pathway Approach. In our study we followed the consecutive steps of the Driver-Pressure-State-Impact-Response (DPSIR) framework, in which the most demanding one was the modelling of ambient $PM_{2.5}$ concentration for different REFLEX scenarios and years. The main finding of the study is that there are about 2.5 million years of life lost annually in the entire population considered in this study, which are attributed to particulate pollution. The monetary valuation of these impacts gives about €210 billion of health-related external costs per year. The general observation is that there is no big change in the results neither between the modelled scenarios nor between the modelling years. The main reason is that it was possible to take into account only the changes in PM emissions from TIMES-HEAT-EU and ELTRAMOD i.e. energy industries (NFR category 1.A.1) as well as from the transport sector. The change in PM emissions for other emission-intensive sectors such as residential and industry have not been considered due to the time constraint (and they were kept constant at the recent levels). Looking at the elaborated emissions scenarios one can see that the PM emissions are declining in the future in case of the transport as well as power sectors. As indicated in (EEA, 2016) a biomass-based district heat generation is characterised by high PM emission factor. According to the results of the TIMES-HEAT-EU model there is an increase in the biomass use for district heat generation (as also reflected in the inventory used for the life cycle based assessment above) in order to reach necessary CO_2 emission cuts. Consequently, PM emissions are rising from this source which counteracts reductions in PM emissions from other sources. This makes the situation in the future in terms of air quality and health impacts very similar to the current situation. Because biomass, which is CO_2 neutral but PM emission intensive, can play an important role in the EU energy system in the future a special emphasis should be placed not only on sustainable biomass supply solutions but also on the better cleaning of flue-gases to avoid – with increase of biomass use – deterioration of air quality and negative health effects.

7 Conclusion

Social assessment with LCA showed that in the base year, coal, gas and nuclear fuel supply chains contribute significantly to social risk across all subcategories for electricity generation (see Figure 14). Coal and nuclear power each contribute a large portion of total generation, as shown in Figure 6. However, gas has a relatively small proportion of total generation in the base year. In the current situation, wind power and solar photovoltaic (PV) also contribute to social risk, in spite of lower shares in the mix. A significant amount of social risk due to wind power arises due to the global supply chain for steel. Social risk due to solar PV arises to a great extent from the global supply chain and manufacture of solar panels themselves. However, in the health and safety subcategory, social risk due to wind and solar power arises do to onsite construction of the plant themselves. The normalised social risk for electricity generation generally increases in the future scenarios, partly because the number of worker hours increases. It also increases because of the increased proportion of gas-fired generation (with and without CCS) used for EU electricity production. Natural gas supply from Russia is shown to make significant contributions particularly in the subcategories forced labour fair salary. Wind and solar power play a larger role in total generation in all future scenarios (see Figure 6) and consequently make a larger contribution to social risk in the subcategories as shown in Figure 14, though this is mitigated by assumed increases in worker productivity for these technologies between the base year and 2050.

From an environmental perspective, climate change impacts due to electricity production reduce significantly; according to the aim of the scenarios (see Figure 18). In the Mod-RES this is principally due to the elimination of coal and lignite from electricity production and the increase in renewables. Further reduction is achieved in the High-RES scenarios through the widespread deployment of gas CCS. Freshwater eutrophication is also shown to decrease significantly in all future scenarios. This is largely due to the elimination of lignite from the electricity mix in all scenarios compared to the current case. Agricultural land occupation is shown to decrease between the base year and 2050 due to a reduced demand for biomass. Meanwhile, particulate matter formation remains relatively constant between the base year and future scenarios. This is because whilst particulate matter related emissions due to coal and lignite combustion decrease between the base year and 2050, relevant emissions due to the natural gas supply chain and the manufacture of wind and solar plant increase over the same period, causing impacts in the category to remain constant. As further shown in Figure 18, metal depletion impacts increase significantly between the base year and 2050. This is due to increased demand for wind and solar plant, both of which are relatively metal intensive.

Social risk due to energy demand in the transport sector does not change significantly in the impact categories considered between the current case and Mod-RES. This is largely due to continued high demand for fossil liquids in the Mod-RES. However, social risk is shown to increase for the categories forced labour, fair salary and workers' rights for the High-RES compared to the current case. Decreased demand for fossil fuels and increased demand for electricity between the base year and 2050 have the effect of reducing risk in these subcategories. However, the increased demand for hydrogen and biofuels over the same period cause risks to rise overall in the subcategories. Risk decreases however in the health and safety subcategory due to the decreased demand for fossil fuels between the base year and the future scenarios. In order to avoid double counting of direct emissions, the environmental assessment in transport considered only impacts from upstream processes. Since future scenarios for transport consider greater shares of electricity and biofuels, all environmental impacts considered (climate change, freshwater eutrophication, particulate matter, ozone depletion, metal depletion and urban land occupation) increase, significantly so in the case of the High-RES.

From a social perspective social risks change very little between the current case and future cases in the industry sector. This is because risks arising in supply chains for fuel oil, gas and electricity in the current case are variously replaced by risk due to electricity supply and gas supply in all future cases. Again, to avoid double counting only upstream impacts are considered in the environmental assessment of the industry sector. There is a notable decrease in upstream impacts for climate change (up to 50 %) but a large increase in metal depletion. This is largely due to the increased demand for electricity in the sector, unless high recycling rates for steel are assumed.

Social risks in the residential and tertiary sectors decrease in the High-RES compared to the current case. This is because of the increased significance of energy carriers judged to be of lower risk in the High-RES compared to the Mod-RES, in particular EU-produced solid biomass and ambient heat. Finally, the upstream assessment of environmental impacts in the residential and tertiary sectors notably found a decrease in climate change related impacts, but an increase in metal depletion related impacts.

The assessment of external cost based on the environmental impacts assessed by the LCA study showed that external costs are of a similar order of magnitude to indicative production costs considered for all sectors considered. Total external costs for average environmental damage values decreased for the electricity sector and the residential and tertiary sectors, remained the same for the industrial sector and increased slightly for the transport sector between the base year and the future scenarios. It should be noted that for the end use sectors, only upstream environmental impacts were considered. By considering impacts from final combustion in the end use sectors it is likely that external costs will be much higher for all scenarios, but less for High-RES scenarios than for Mod-RES or the base year. The external cost assessment for electricity supports the assertion that the transition to an electricity production system with low GHG emissions is profitable from a societal perspective.

In the spatial assessment, it was shown that health impacts and spatially disaggregated external costs were similar in 2050 scenarios as for the current case. This was considered to be due to the fact that the concentration of particulate matter changed little between the current case and future scenarios. This is because while emissions from the combustion of fossil fuels decreased between 2014 and 2050 according to the scenarios, emissions due to biomass combustion (particularly to provide district heating) increased over the same period.

According to the REFLEX scenarios, electricity becomes an even more important energy carrier in the future compared to today. It also becomes more significant for environmental impacts and social risks. The social assessment demonstrated that gas production in Russia in future scenarios can lead to increased risk in particular for (lack of) fair salary and for forced labour (in the form of risk for trafficking in persons). It was also shown that the steel production supply chain is important when assessing social risk for wind power and that the production of solar panels themselves is important when considering social risk due to solar photovoltaics. From an environmental perspective it was shown that along with significant reductions in global warming potential through 2050, electricity production with low GHG emissions in the scenarios can also reduce freshwater eutrophication and agricultural land occupation. Meanwhile, environmental impacts increased for electricity production in 2050 compared to the base year for in particular metal depletion, due to increased demand for wind and solar power. Beyond this work, it is further interesting to explore different perspectives for the development of new technologies, especially for wind and solar power that are shown to be very important for energy systems with low GHG emissions. This work is also interesting as an application of the SOCA add-on for social assessment. It was shown that with the tool, areas could be identified particularly in the electricity production system where noticeable improvements in social performance can be achieved. To facilitate future studies with the tool, development should be directed towards making it easier to define the geographical location of key processes.

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