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A life cycle perspective on the benefits of renewable electricity generation

Authors:
Evert A. Bouman (Norwegian Institute for Air Research – NILU)

ETC/CME consortium partners: *AETHER*, Interprofessional Technical Centre for Studies on Air Pollution (*CITEPA*), Czech Hydrometeorological Institute (*CHMI*), Energy and Environmental Studies and Software Development (*EMISIA)*, Institute for Applied Ecology (*ÖKO-INSTITUT*), *ÖKO-RECHERCHE*, Norwegian Institute for Air Research (*NILU*), Netherlands Environmental Assessment Agency (*PBL*), National Institute for Public Health and the Environment (*RIVM*), Environment Agency Austria (*UBA*), Flemish Institute for Technological Research (*VITO*)

European Topic Centre on Climate
change mitigation and energy
Boeretang 200
B-2400 Mol, Belgium
Tel.: +32 14 33 59 77
Web: www.eionet.europa.eu/etcs/etc-cme
Email: etccme@vito.be

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Executive Summary

Introduction

The generation of electricity and heat contributes significantly to annual anthropogenic greenhouse gas (GHG) emissions of the European Union (EU). The transformation of the energy system towards the use of clean technologies is a key part of climate change mitigation strategies. Despite multiple benefits for human health and the environment associated with the reduction in fossil fuel use for energy, the increased use of RES is not impact free and may come at a cost to the environment. In this report, the benefits of the use of RES to produce electricity are investigated from a life cycle perspective.

Approach

A bottom-up approach was taken to calculate the gross avoided potential environmental impacts due to increased use of RES in the electricity production mix. A collection of life cycle inventories (LCIs) describing archetypical electricity generation processes using main energy sources was assembled building on the work of the UN International Resource Panel (IRP) on co-benefits of increased renewable electricity generation (UNEP, 2016). Using available national statistical data on fuel consumption, fuel characteristics, and gross electricity production, these LCIs were adapted to create an LCI specific to an energy source, year, and Member State. These specific LCIs were then used to calculate potential impact intensities for electricity generation by source in a Member State, for any given year in the period 2005-2018. Six different impact indicators for the production of electricity are estimated for all Member States in the period 2005 to 2018 for a total of sixteen different renewable and non-renewable energy sources. Finally, an estimate is given on gross avoided life-cycle impact by comparing historic values to a counterfactual scenario where the level of electricity production from RES is frozen at the 2005 level.

Main results

Life cycle impact intensities for electricity production were found to differ considerably across energy conversion and between Member States and years, driven by differences in fuel conversion efficiency and capacity utilization. Impact intensities are driven by a wide range of processes and emissions to the environment, but opportunities exist to decrease impact intensities for singular processes, either by focusing efforts to increase efficiency, or to implement emission mitigation technology.

The increased use of RES has led to an absolute decrease in potential impacts in the period 2005-2018 for most impact indicators investigated in this study. Gross avoided impacts are driven by the increased production of onshore wind power and solar photovoltaic power, followed by electricity production from bioenergy sources biogas and solid biomass. The increased use of RES comes at a cost in terms of freshwater ecotoxic impacts (related to solar PV and combustion of renewable wastes) and land occupation impacts (related to combustion of solid biomass). These costs are partially compensated for through the use of other RES to produce electricity. Lifetime extension may be an option to mitigate negative consequences from the increased use of non-combustion RES.

Uncertainty remains with respect to the source data in the life cycle inventories and in individual cases results are sensitive to single environmental emissions in the LCI. In addition, the study does not include impact indicators, such as a water or material footprint which may obscure relevant results. It is recommended to expand future work across more impact indicators as well as to continue efforts to update, improve and harmonize life cycle inventories. Furthermore, it is recommended to support this study with other more specific studies addressing in more detail the potential impacts for which life cycle impact assessment methods are known to be uncertain.

1 Introduction

The generation of electricity and heat contributes significantly to annual anthropogenic greenhouse gas (GHG) emissions of the European Union (EU) and energy system transformation towards the use of renewable and low-carbon energy sources is a key part of climate change mitigation strategies. For the EU, this is reflected by the headline targets for climate change mitigation, energy efficiency and renewable energy for 2020 and 2030 in the Energy Union strategy (EC, 2015), along with minimum targets for electricity interconnection (10 % by 2020 and 15 % by 2030). Following the adoption of the first Renewable Energy Directive (EU, 2009), the use of RES in the European energy system has increased significantly over the past decades. In 2017, GHG emissions from the public electricity and heat sector in the EU-27 constituted a share of approximately 24% of total GHG emissions without land use, land use change and forestry (LULUCF), down from approximately 27% in 2012 (EEA, 2019). This decrease can largely be attributed to the increased use of renewables in electricity and heating (EEA, 2017, 2018b). Nonetheless, the public heat and electricity sector remains the largest single source of GHG emissions in the EU, and its transitions to include more RES is likely to be only accelerated given the latest ambitions of reducing greenhouse gas emission to at least 55% below 1990 levels by 2030 under the 2030 Climate Target Plan (EC, 2020).

As part of its 'Renewable energy in Europe' report series, the European Environment Agency (EEA) estimates the substitution of fossil fuel combusted for energy purposes by the growing use of renewable energy, and estimates the associated gross effects on GHG and air pollutant emissions in the European energy system (EEA, 2015, 2018a; ETC/CME, 2019). This is done by comparing the actual growth in renewable energy use across the EU since 2005 against a counterfactual scenario that assumes this growth would have been satisfied by non-renewable (essentially fossil) energy sources (EEA, 2015). The resulting difference between actual emissions and the counterfactual scenario can subsequently be interpreted as gross avoided GHG emissions ([1]). The latest report shows that gross avoided fossil fuel use in 2018 amounts to 168 Mtoe (13 % of the total primary fossil fuel consumption in the EU-27+United Kingdom), with corresponding gross avoided greenhouse gas emissions amounting to 543 Mt CO_2 (an estimated 11 % gross reduction in GHG emissions across the EU-27+United Kingdom in that year), of which 73 % (397 Mt CO_2) can be attributed to the electricity sector. Cumulative avoided emissions for the electricity sector in the period 2005-2018 amounted to 1559 Mt CO_2 (ETC/CME, 2019).

While the GHG emissions from non-combustion renewable electricity generation, such as photovoltaic (PV) power and wind power, are virtually zero during operation, the construction of renewable power generation components and plants is both material and energy intensive. Power generation from renewable sources is therefore not emission, nor impact, free. A benchmark study published by the United Nations Environment Programme's International Resource Panel (IRP) compared the emissions and environmental impacts per unit electricity generation over the entire cradle-to-gate ([2]) life cycle for a variety of fossil and renewable power generation technologies (UNEP, 2016). All direct and indirect emissions associated with construction, operation and decommissioning of power plants and their key components were included in the study. Direct emissions refer here to those emissions associated with an activity, such as construction of the power plants, whereas indirect emissions comprise all emissions occurring along the value chains that support the activity in question, such as the production and transport of steel and cement, or the extraction and transport of fossil fuels.

The IRP study found that renewable power requires larger amounts of metals and other minerals per unit electricity generated, but generally has consistently lower environmental impacts than fossil

([1]) Life cycle and upstream emissions, such as related to land use, land use change and forestry (LULUCF) due to the sourcing of biomass resources, are not taken into account in that methodology.

([2]) In the case of electricity generation, LCA models typically adopt a 'cradle-to-gate' approach, i.e. environmental impact indicators are calculated per unit of electricity delivered to the grid. Impacts associated with transmission infrastructure, transmission losses, as well as impacts associated with the use of the electricity are omitted.

generation in nearly all impact categories investigated. However, emissions and potential impacts associated with renewable electricity generation are non-zero and the environmental impact potential of electricity generated from different RES may vary considerably. It is therefore also of interest to shed light on the avoided environmental impacts due to the increased use of RES in the EU electricity system from a life cycle perspective.

Going beyond GHG emissions, the main aim of this report is to provide an estimate for the avoided environmental impacts, from a life cycle perspective, due to the increased utilisation of RES in the electricity supply across the EU-27, relative to the benchmark year 2005. To this extent, a bottom-up life cycle assessment (LCA) model is employed. The life cycle perspective adds a systemic overview of the potential environmental impacts associated with electricity generation over time.

The report consists of five Chapters: the **introduction** (Chapter 1); the **methodology** (Chapter 2), outlining shortly key methodological choices and data sources; the **results** (Chapter 3), which describes life cycle (LC) impact intensities for the individual electricity generation technologies, develops LC impact estimates for electricity generation in Europe since 2005 and estimates the avoided LC impacts relative to 2005; the **discussion** (Chapter 4); and **conclusions** (Chapter 5) summarizing the key findings.

2 Methods

This Chapter only summarises the methodology employed in this ETC/CME report. A fuller presentation of the employed methods, equations, and assumptions is presented in the separate ETC/CME report: *"A life-cycle perspective on benefits of renewable electricity generation – Methodology and assumptions."* (ETC/CME, 2020).

2.1 Life Cycle Assessment

LCA is a tool to estimate the potential environmental impacts of a product, process, or service over its life cycle. It is used to assist in environmental decision making, supporting policies and strategies, because it can help identify unforeseen consequences – so-called **'environmental problem shifting'**. Problem shifting may occur when a proposed solution to reduce environmental impacts due to emissions from an activity results in increased environmental impacts of the same or of different types, due to other emissions upstream or downstream in the value chain. LCA results can deliver insight from two different perspectives:

1. Firstly, inventory analysis attributes pollutant emissions of singular environmental stressors, such as CO_2 emissions, to a product or service.
2. Secondly, impact assessment aggregates groups of stressors into impact categories through calculation of an impact indicator. The classical example is aggregation of GHG emissions into the Global Warming Potential expressed in CO_2-equivalent.

The life cycle perspective and capacity of LCA to aggregate many environmental emissions into impact categories makes LCA well suited for the comparative assessment of technologies that vary widely, but ultimately provide the same service.

2.2 Overall approach

A bottom-up approach was taken to calculate the gross avoided potential environmental impacts ([3]) due to increased use of RES in the electricity production mix. A collection of life cycle inventories (LCIs) describing archetypical electricity generation processes using main energy sources (e.g. hard coal, natural gas, wind, or solar) was assembled, starting from the LCIs constructed for the IRP study (Hertwich et al., 2015; UNEP, 2016) and supplemented with LCIs from other sources, such as the LCI database Ecoinvent (Ecoinvent, 2019). Using available national statistical data on fuel consumption, fuel characteristics, and gross electricity production, these LCIs were adapted to create an LCI specific to an energy source, year, and Member State. These specific LCIs were used to calculate potential impact intensities for electricity generation by source in a Member State in any given year in the period 2005-2018.

A counterfactual scenario was developed, which effectively assumes that the actual growth in renewable energy use across the EU-27 since 2005 would have been satisfied by non-renewable (essentially fossil) energy sources, in line with the approach taken in other reports estimating the effects of increased renewable energy deployment in Europe (EEA, 2015). Finally, the resulting difference between calculated impact and the calculated impacts of the counterfactual scenario can subsequently be interpreted as gross avoided life cycle impacts.

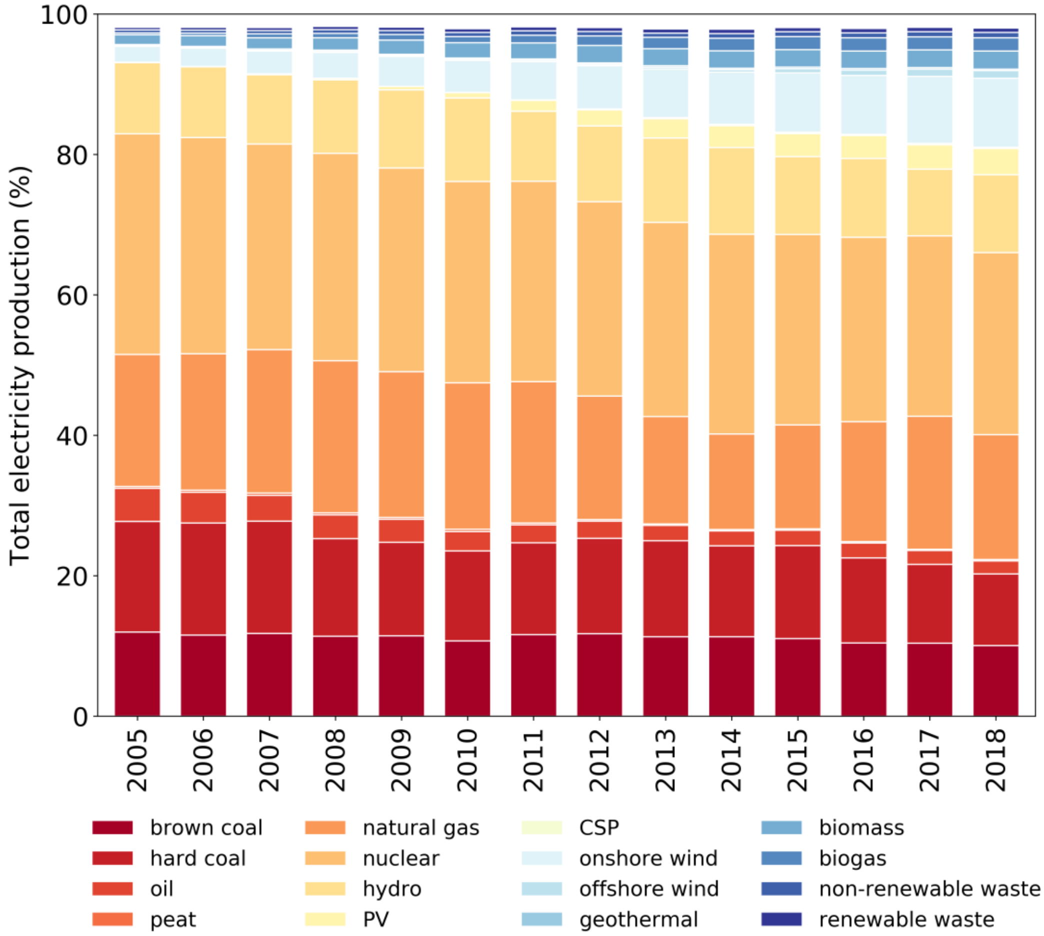
2.3 Sectoral coverage

National statistical data on fuel consumption, fuel characteristics, and gross electricity production was available from Eurostat in its energy balance tables as well as the Short Assessment of Renewable Energy

([3]) In LCA, environmental impacts are presented as potential impacts to account for the temporal scope covering activities, emissions and effects that may occur in past and present as well as are expected for the future. Consequently, an avoided impact calculation refers to avoided potential impact.

Sources (SHARES) ([4]). These data sources distinguish more energy sources than the life cycle inventories assembled for this report. For example, an LCI for electricity production from tidal energy was not available. As a result, the bottom-up approach taken in this report does not cover all electricity production in the EU-27, but approximately 98 % of total annual production. The percentage of total electricity production covered by the LCIs is shown in Figure 2.1. For further information on the correspondence between the coverage of LCI in this report and the standard international energy product classification (SIEC) used to distinguish between energy sources in energy balance statistics, we refer to section 3.1 of the methodology and assumptions report (ETC/CME, 2020).

Figure 2.1 Percentage of total electricity production covered by the life cycle inventories



Source: ETC/CME; (Eurostat, 2020a, 2020b).

([4]) A public version is available here: https://ec.europa.eu/eurostat/web/energy/data/shares

3 Results

Key messages:

- Life cycle impact intensities for electricity production differ considerably across energy sources, energy conversion technologies and between Member States and years.
- Impact intensities are driven by a wide range of processes and emissions to the environment, but opportunities exist to decrease impact intensities for singular processes, either by focusing efforts to increase efficiency, or to implement emission mitigation technology.
- The increased use of RES has led to an absolute decrease in potential impacts in the period 2005-2018 for most impact indicators investigated in this study.
- Gross avoided impacts are driven by the increased production of onshore wind power and solar photovoltaic (PV) power, followed by electricity production from bioenergy sources.
- The increased use of RES comes at a cost in terms of freshwater ecotoxic impacts (related to solar PV and combustion of renewable wastes) and land occupation impacts (related to the combustion of solid biomass).
- These costs are partially compensated for by the use of other RES to produce electricity.

In this Chapter the results of the analysis are described. First, the impact intensities (i.e. impact per unit electricity generation) associated with electricity production from each of the fuel sources is presented in Section 3.1 as well as those processes and emissions that drive potential impacts in Section 3.2. Second, in Section 3.3 the impact trends in the EU-27 for the *midpoint impact* categories **climate change**, **freshwater eutrophication**, **particulate matter formation**, **terrestrial acidification**, **freshwater ecotoxicity**, and **land occupation** are identified. Finally, in Section 3.4 the results for the counterfactual scenario and gross avoided life cycle impacts are presented at the level of the EU-27.

3.1 Life cycle impact intensities for individual electricity production technologies.

As a starting point for analysis, the life cycle impact assessment results were calculated for each of the individual life cycle inventories by Member State and year. The ranges of impact intensities are shown in Figure 3.1 and Figure 3.2, split up over electricity production from combustive processes and electricity production from non-combustive processes. The boxplots show the median impact intensity in the period 2005-2018, with the boundaries of the box representing respectively the first and third quartile of the data. Finally, the whiskers indicate the range outside the box corresponding to 1.5 times the interquartile range. Note that impact intensities are presented per MWh electricity produced.

Two main observations can be made from Figure 3.1 and Figure 3.2. First, impact intensities across different energy sources differ considerably. Second, there may be significant variability in impact intensities estimated for a single energy source. This variability is a direct consequence of the parameterization of the life cycle inventories to account for variation in efficiency and infrastructural use between Member States and years, as estimated from the energy balance statistics (see section 2.2).

As may be expected, the impact intensity of electricity production from fossil fuels is significantly larger than the impact intensity of renewable or nuclear electricity generation for those impact indicators that are heavily influenced by combustion products: GHG emissions, eutrophication, particulate matter formation, and acidification. For freshwater ecotoxicity and land occupation, the impact intensities are more balanced across the different LCAs, with fossil technologies oil, peat and natural gas showing lower impact intensity for freshwater ecotoxicity, compared to all renewable sources except for hydropower.

How to interpret life cycle impact indicators?

The results from a life cycle inventory (LCI) contain the emissions and extraction to and from the environment of numerous pollutants, substances, and materials. The main purpose of calculating a life cycle impact indicator is to allow aggregation into meaningful impact categories, such that individual LCAs of processes that perform the same function may be compared. The relation between emission and impact indicator is expressed through a characterization factor.

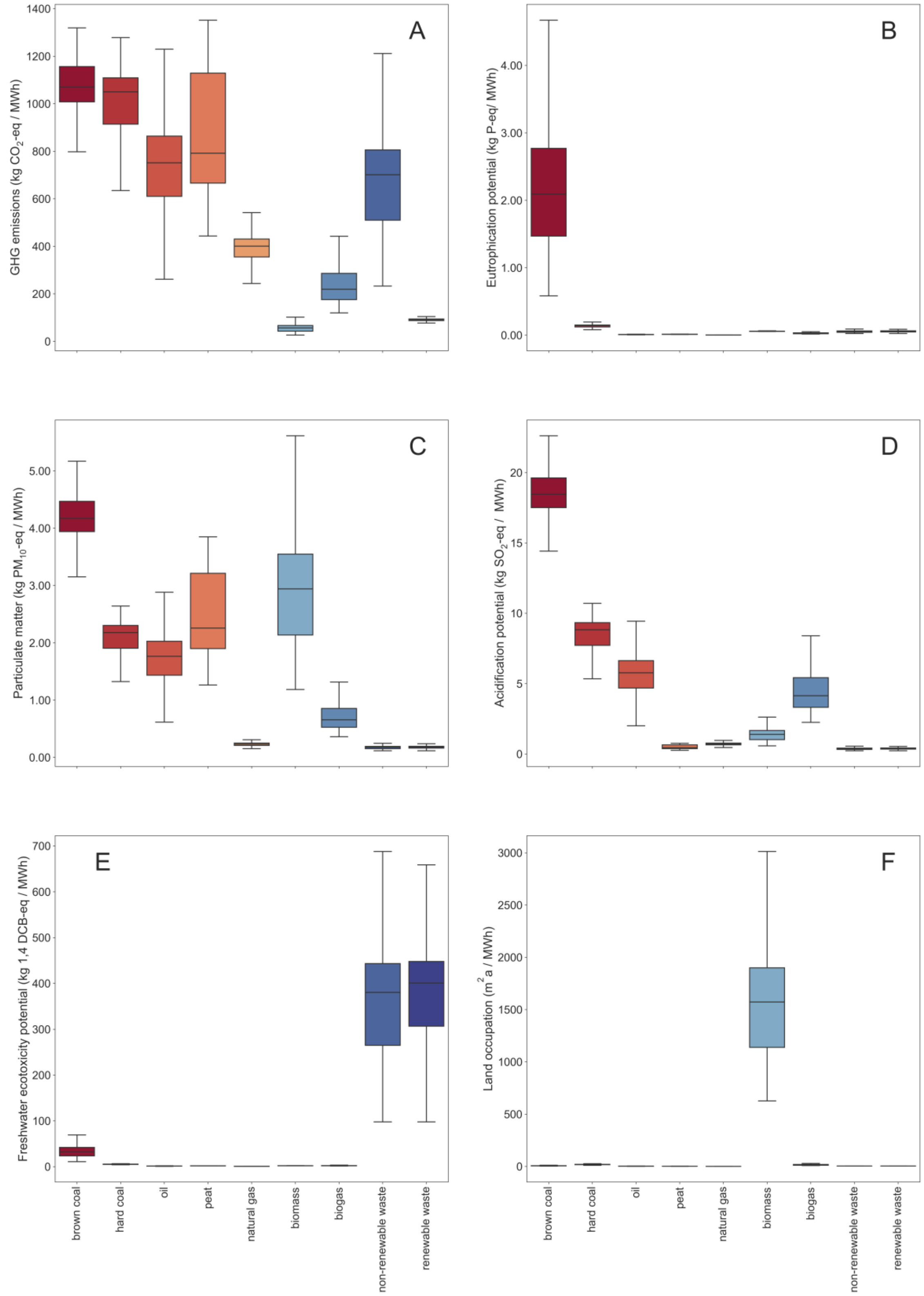
The calculation of some characterization factors is relatively straightforward. For example, the Global Warming Potential is calculated by comparing the integral of radiative forcing of a greenhouse gas (e.g. methane) to the integral of radiative forcing of carbon dioxide within a 100-year timeframe. However, for other impact indicators there is considerable uncertainty associated with the establishment of the characterization factors linking environmental emissions to impact indicator. For example, the characterization factors to calculate ecotoxic impacts are dependent on much simplified multimedia fate models as well as toxicity data on humans and lab animals, resulting in a large range of uncertainty.

Note that an LCI model is bound neither geographically, nor temporally, due to the value chain and life cycle perspective. The value chain perspective connects the system under study to the global economy. This implies that emissions and resource use may occur across the globe, as the process or system under study (in the case of this report: electricity production) demands resources, materials, and services through the global value chains. These emissions and resource uses are subsequently attributed to the process or system of which an LCA is made. The lack of temporal dimension in LCA further implies that modelled emissions may have occurred in the past (for example during construction of a power plant), present (current operation of the power plant), or are likely to occur in the future (decommissioning of the power plant). Consequentially, in LCA impact indicators should be interpreted as impact potentials.

The production of electricity through the combustion of non-renewable and renewable waste is included in this study and presented in Figure 3.1. It should be noted that it is common practice to not associate any impact intensity with electricity production from waste processing, as usually all impacts associated with this combustion are allocated to the waste disposal process, with the generation of electricity and heat being treated as by-products from this process. However, to keep within the scope of this report as well as the energy balance statistics, it was chosen to calculate an impact intensity for both waste types, allocating impact intensities between heat and electricity production. The diverse feedstock in waste combustion, as well as subsequent disposal of residuals, generates a relatively high amount of ecotoxic emissions, such as metals leaching to water or being emitted to air.

Of the renewable technologies, photovoltaic generation has on average the highest impact intensity, as well as due to generally low capacity factors which increase the infrastructure related impacts per unit electricity production. A similar effect is observed for concentrated solar power. Some very high emissions intensities were calculated for the years 2007-2009. A significant increase in newly installed capacity was observed for these years, leading to temporary low capacity factors since not all new capacity was operational for the full year. Land occupation is high for electricity produced from solid biomass, fuelled in part with wood, as well as relatively high for the electricity produced using thermal solar energy in a concentrating solar power (CSP) plant. For the latter, land occupation potential is influenced mainly by the area occupied by the solar field (contributing 72 %).

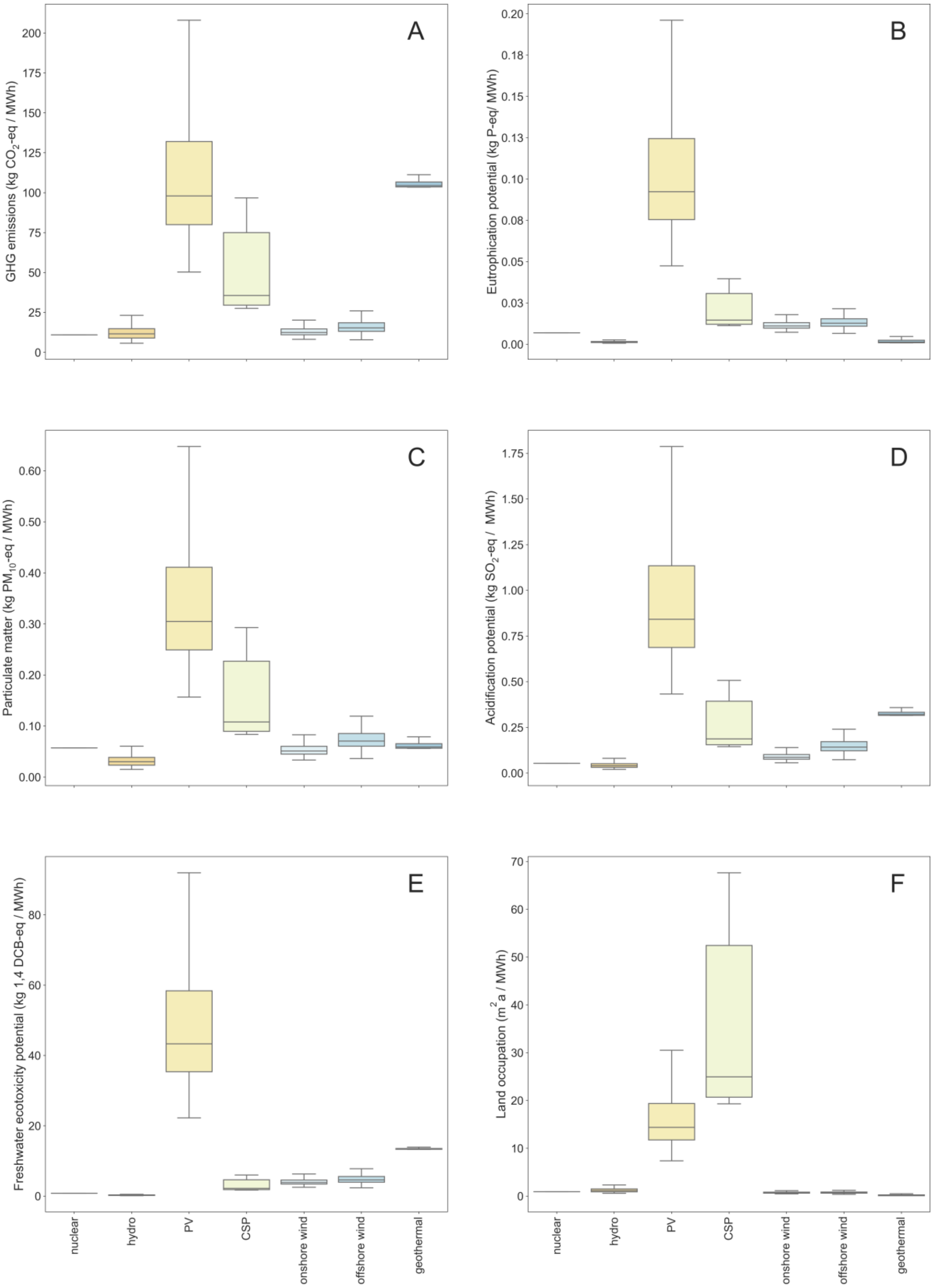
Figure 3.1 Life cycle impact intensities for fuel energy sources



Notes: A – Global Warming Potential; B – Eutrophication potential; C – Particulate matter formation potential; D - Terrestrial acidification potential; E – Freshwater ecotoxicity; F – Land occupation.

Source: ETC/CME.

Figure 3.2 Life cycle impact intensities for non-combustion energy sources



Notes: A – Global Warming Potential; B – Eutrophication potential; C – Particulate matter formation potential; D - Terrestrial acidification potential; E – Freshwater ecotoxicity; F – Land occupation.

Source: ETC/CME.

3.2 Drivers of impact intensities

To shed more light on the drivers of impact intensities by energy source, a contribution analysis was performed. Contribution analysis shows the main contributing processes and environmental emissions to the impact indicator. Note that, due to the nature of LCA, this process may be both in the foreground model, or in the background due to the value chain perspective. Here, a selection of contribution analysis results is presented, focusing on the energy sources and impact indicators that are high in comparison with the other energy sources. The combination of sixteen energy sources and six impact categories makes a one-by-one treatment impractical. Finally, in section 3.2.2 an advanced contribution analysis is presented, where, rather than investigating the contribution of process or emissions, contributions are attributed to several phases in the life cycle of the electricity production process, i.e. plant infrastructure, fuel chain, plant operation or end-of-life.

3.2.1 Contribution from processes and emissions

In this section a selection of process and emission contribution analyses is shown for electricity production from solar PV, municipal waste incineration, solid biomass, and brown coal.

The greenhouse gas impact intensity of solar PV is among the highest of the RES (see Figure 3.2). In Table 3.1, the top five relative process and emissions contributions are listed and the values presented in the table correspond to the median of all contribution analysis results across Member States and year. Apparent from Table 3.1 is that there is no single dominant process contributing to life cycle PV emissions, but rather a collection of processes contributing a few percent. The construction of PV modules requires heating and electricity services across the globe, as reflected by this Table. Not surprisingly, the main emission drivers of the GWP are the major greenhouse gases carbon dioxide and methane. Note that the background database Ecoinvent distinguishes to which environmental compartment emissions are released, resulting in carbon dioxide being listed thrice and methane twice.

Table 3.1 Relative process and emissions contributions to global warming potential for electricity production from PV power

Process	Contribution (%)	Emission	Contribution (%)
heat, district or industrial, natural gas/Europe without Switzerland	5	Carbon dioxide, fossil/air/non-urban air or from high stacks	56
electricity, high voltage/DE	4	Carbon dioxide, fossil/air/urban air close to ground	23
heat, district or industrial, other than natural gas/RoW	3	Carbon dioxide, fossil/air/unspecified	13
residue from mechanical treatment, industrial device/CH	3	Methane, fossil/air/non-urban air or from high stacks	5
hard coal/CN	2	Methane, fossil/air/non-urban air or from high stacks	1

Solar PV power also has a relatively high ecotoxicity impact indicator. Table 3.2 lists the top five contributing processes and emissions to freshwater ecotoxicity potential. Here, it is a variety of metal ions (mainly copper) contributing most to ecotoxic impacts, as well as emissions of chlorine to water. The main contributing processes are mining and metal operation, except for the foreground process purification of solar grade silicon. It is for this process that a relatively large flow of chlorine to water is included in the life cycle inventory.

Table 3.2 Relative process and emissions contributions to freshwater ecotoxicity potential for electricity production from PV power

Process	Contribution (%)	Emission	Contribution (%)
scrap copper/RoW	22	Copper, ion/water/ground-, long-term	82
sulfidic tailings, from copper mine operation/CN	14	Chlorine/water/surface water	10
scrap copper/Europe wo Switzerland	11	Nickel, ion/water/ground-, long-term	2
SOG-Si Purification	10	Silver, ion/water/ground-, long-term	2
sulfidic tailings, from silver mine operation/MX	6	Zinc, ion/water/ground-, long-term	1

The ecotoxic impacts related to the combustion of renewable and non-renewable waste are specified in Table 3.3. Almost all ecotoxic impact potential can be related to the incineration process itself, with very little contribution from other processes in either foreground or background system. The main pollutants are emissions of metal ions to water, with a specifically high contribution from the emission of Beryllium. It should be noted that it is unsure to what extent this flow is representative for processing and incineration of MSW and given its large contributing share, it may have artificially increased the ecotoxic impact intensity considerably and unfavorably in comparison to the other electricity production processes investigated in this report. If, however, the emission of Beryllium does occur substantially in the life cycle of electricity production from MSW, this would provide a potential impact mitigation opportunity.

Table 3.3 Relative process and emissions contributions to freshwater ecotoxicity potential for electricity production from municipal waste incineration

Process	Contribution (%)	Emission	Contribution (%)
MSW incineration	<100%	Beryllium/water/ground-, long-term	64
		Copper, ion/water/ground-, long-term	30
		Nickel, ion/water/ground-, long-term	2
		Zinc, ion/water/ground-, long-term	1
		Bromine/water/surface water/	1

From panel C in Figure 3.1 it can be seen that the combustion of brown coal and biomass have relatively high particulate matter (PM) formation potential impact intensities. Results from the contribution analysis are presented in Table 3.4 and Table 3.5 respectively for these two fuel sources. In both cases, it is apparent that the fuel combustion during operation is the main contributor to particulate matter formation, though individual pollutants contribute differently. For combustion of solid biomass, the formation of particulates appears to be the driving force for PM emissions, with lesser contributions from nitrogen oxides and ammonia. For the combustion of brown coal, the main contributor is the emission of sulfur dioxide and nitrogen oxides, with only a minor contribution from particulates. Note that the emission of particulate matter, SO_x and NO_x at the power plant can to a large extent be mitigated by appropriate emissions mitigation technology, but that these may not be reflected in the tier I emissions factors for applied throughout the model (EMEP and EEA, 2016).

Table 3.4 Relative process and emissions contributions to particulate matter formation potential for electricity production from combustion of solid biomass

Process	Contribution (%)	Emission	Contribution (%)
Biomass operation	97.0	Particulates, > 2.5 um, and < 10um/air/unspecified	88
diesel, burned in building machine/GLO	0.2	Nitrogen oxides/air/unspecified	6
iron ore, crude ore, 46% Fe/GLO	0.2	Ammonia/air/urban air close to ground	3
wood chipping, chipper, mobile, diesel, at forest road/RER	0.1	Sulfur dioxide/air/unspecified	1
harvesting, forestry harvester/RER	0.1	Nitrogen oxides/air/non-urban air or from high stacks	1

Table 3.5 Relative process and emissions contributions to particulate matter formation potential for electricity production from combustion of brown coal

Process	Contribution (%)	Emission	Contribution (%)
PC operation	96	Sulfur dioxide/air/unspecified	80
Lignite transport	2	Nitrogen oxides/air/unspecified	15
diesel, burned in building machine/GLO	0.2	Particulates, > 2.5 um, and < 10um/air/unspecified	3
iron ore, crude ore, 46% Fe/GLO	0.1	Sulfur dioxide/air/non-urban air or from high stacks	0.3
waste natural gas, sour/GLO	0.1	Particulates, < 2.5 um/air/non-urban air or from high stacks	0.3

The last contribution analysis presented in this section shows the relative contributions of processes and emissions to the eutrophication potential for electricity production from brown coal (presented in Table 3.6). Here, the emissions of phosphates to fresh groundwater from lignite mining spoil are a single clear contributing source.

Table 3.6 Relative process and emissions contributions to eutrophication potential for electricity production from combustion of brown coal

Process	Contribution (%)	Emission	Contribution (%)
spoil from lignite mining/GLO	99	Phosphate/water	<100
hard coal ash/DE	1		

3.2.2 Advanced contributions

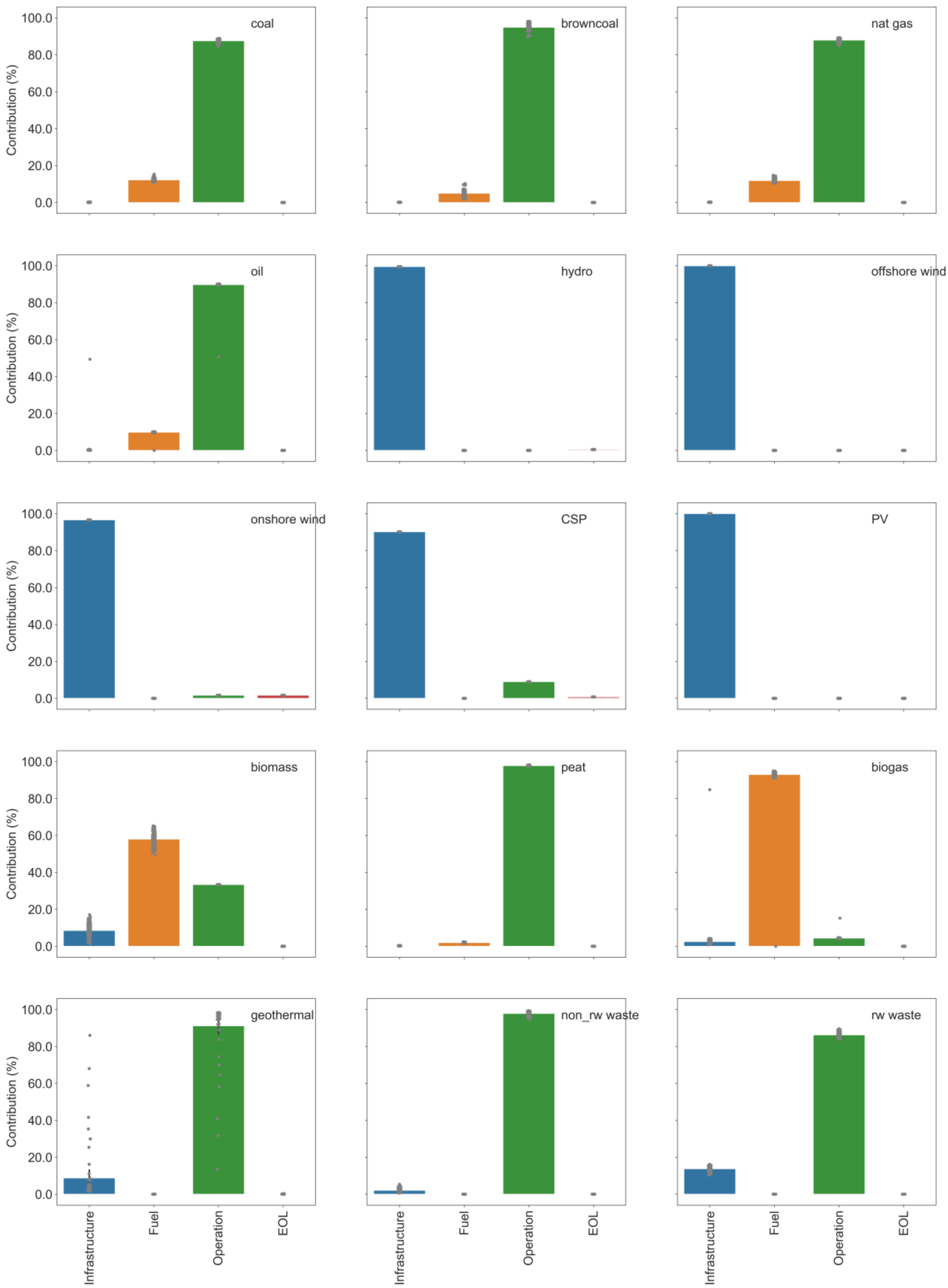
In addition to the process and emissions based contribution analysis, here it is exemplified how each of the foreground processes of the individual life cycle inventories is contributing, either directly or indirectly to the impact intensity. The foreground processes of each life cycle inventory model were classified as belonging to either plant infrastructure, the fuel chain, operation of the power plant, or end-of-life (EOL). Subsequently, direct and indirect contributions were quantified for each of the impact categories. The advanced contribution does not aid in quantifying the direct contributions of the foreground process, but rather shows to which part of the foreground model impacts can be attributed. This is of relevance as often in LCA impact mitigating efforts can only be made at foreground level, especially when made from the perspective of a process owner. For example, while it is unlikely a power plant operator can decrease the emissions of phosphates from spoil in lignite mining, it is possible to increase efforts to improve power plant efficiency, thus reducing fuel chain related potential eutrophication impacts.

The advanced contribution analysis results are shown here for two impact indicators, global warming potential and freshwater ecotoxicity in respectively Figure 3.3 and Figure 3.4. The figures show the average contribution across all Member States and years for each fuel source, with the range of contribution results plotted as dots on top of the bar graph and with the exception of nuclear energy, as no Member State and year specific impacts were estimated. For a single energy source, contributions differ between Member State and year as the implicit efficiencies and capacity factors coming from the national energy balance statistics change, thus having an influence on the relative contributions of e.g. infrastructure-related impacts and operational impacts.

Figure 3.3 shows that for combustion technologies, emissions associated with power plant operation (e.g. CO_2, and methane) are the dominant contributor to the life cycle impact intensity. The fuel chain may be an important contributor too, depending e.g. on the energy and emissions spent during fuel extraction and fuel transport. This is particularly the case for the bioenergy related impact intensities. This becomes also apparent form the freshwater ecotoxicity impact intensity for combustion technologies which is driven also by emissions occurring along the fuel chain and its associated infrastructure (see Figure 3.4).

Note that the classification of foreground processes into infrastructure, fuel chain, operation and EOL is to an extent artificial and dependent on the nature of the foreground process in question. For example, the while the construction of a wind turbine is classified as infrastructure, all underlying processes in the life cycle that contribute indirectly may be either infrastructural, operational, fuel chain, or EOL in nature. Thus, a contribution from infrastructure does not signify that all underlying processes in the value chain are infrastructure, but rather that they contribute to infrastructure construction in the foreground life cycle inventory model. In addition, due to the nature of the underlying LCIs some processes (mainly EOL) are lumped in the infrastructure classification.

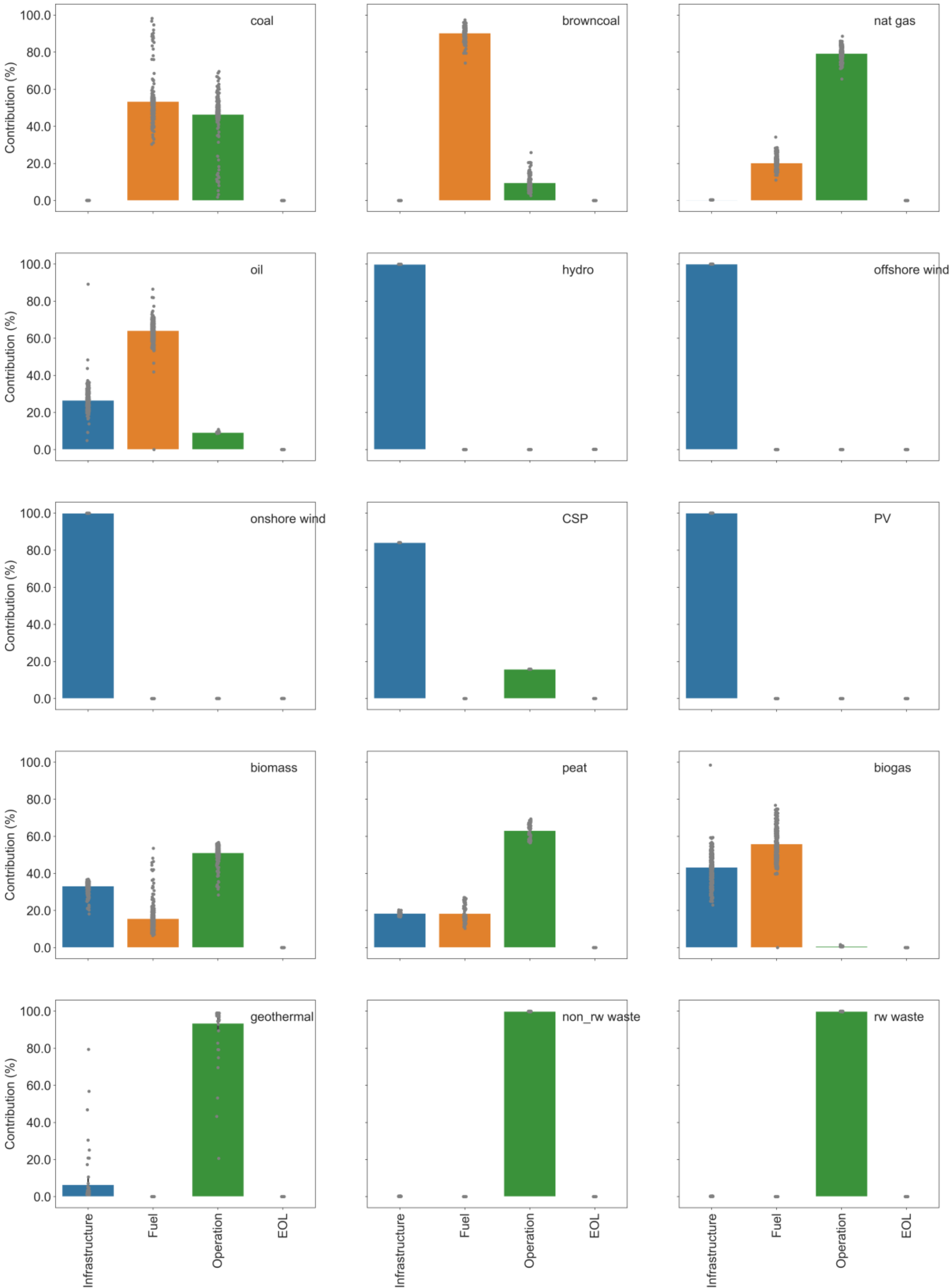
Figure 3.3 Relative direct and indirect contributions of foreground to global warming potential



Notes: For some inventories, EOL contributions are included as integral part of the infrastructure process. Nuclear not included as an impact intensity is not generated per MS and year.

Source: ETC/CME.

Figure 3.4 **Relative direct and indirect contributions of foreground to freshwater ecotoxicity potential**



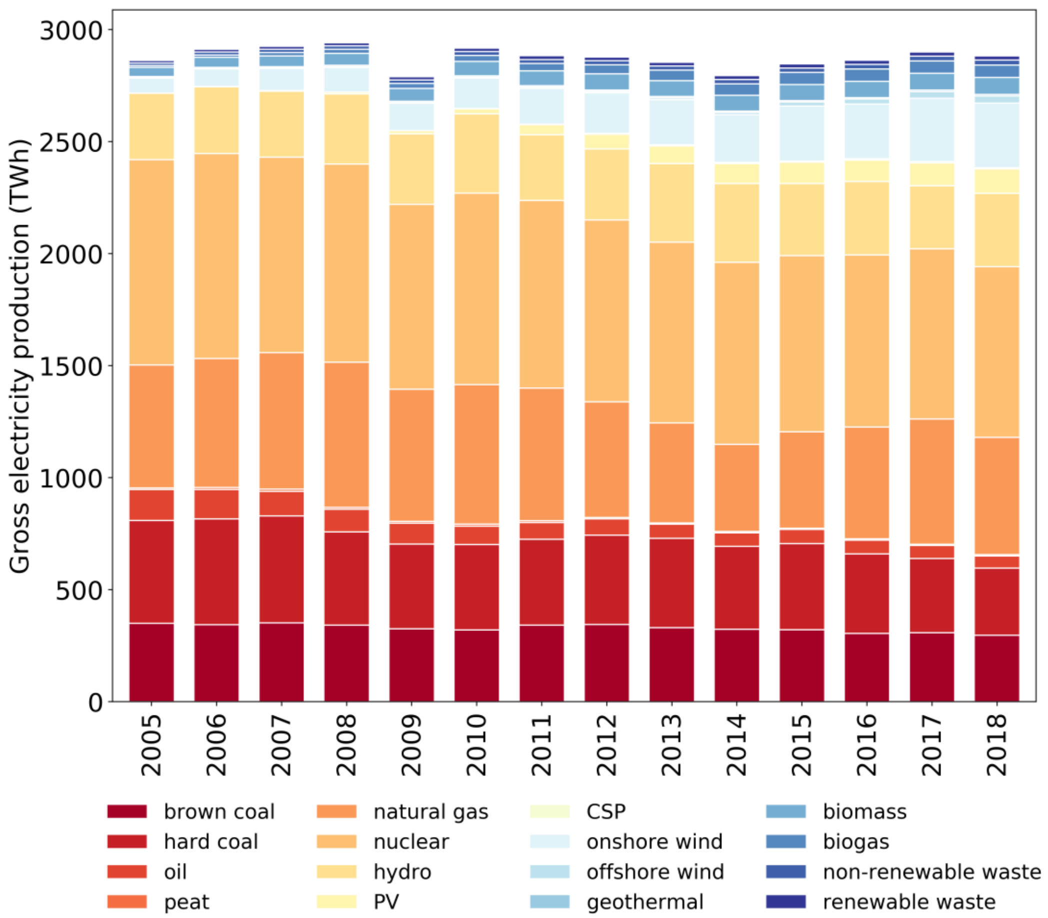
Notes: For some inventories, EOL contributions are included as integral part of the infrastructure process. Nuclear not included as an impact intensity is not generated per MS and year.

Source: ETC/CME.

3.3 Life cycle impacts associated with electricity production in the EU-27

In this Section, we present the results for life cycle impacts associated with electricity production in the EU-27. At a European level, these results are driven by the gross electricity production (which appears to be relatively constant), the relative share of each energy source in the electricity production mix, as well as the individual impact intensities associated with electricity production from various energy sources as presented in the previous Section 3.1. Annual gross electricity production in TWh for the EU-27 is shown in Figure 3.5. Here, the phase out of fossil-based electricity production can be observed as well as an increasing share of RES in the period 2005-2018. At a European level, there is a clear reduction in the use of hard coal and oil for electricity generation. Increases in renewable generation since 2005 seem to come mainly from increases in onshore wind and solar PV production, as well as increases in electricity from bioenergy sources.

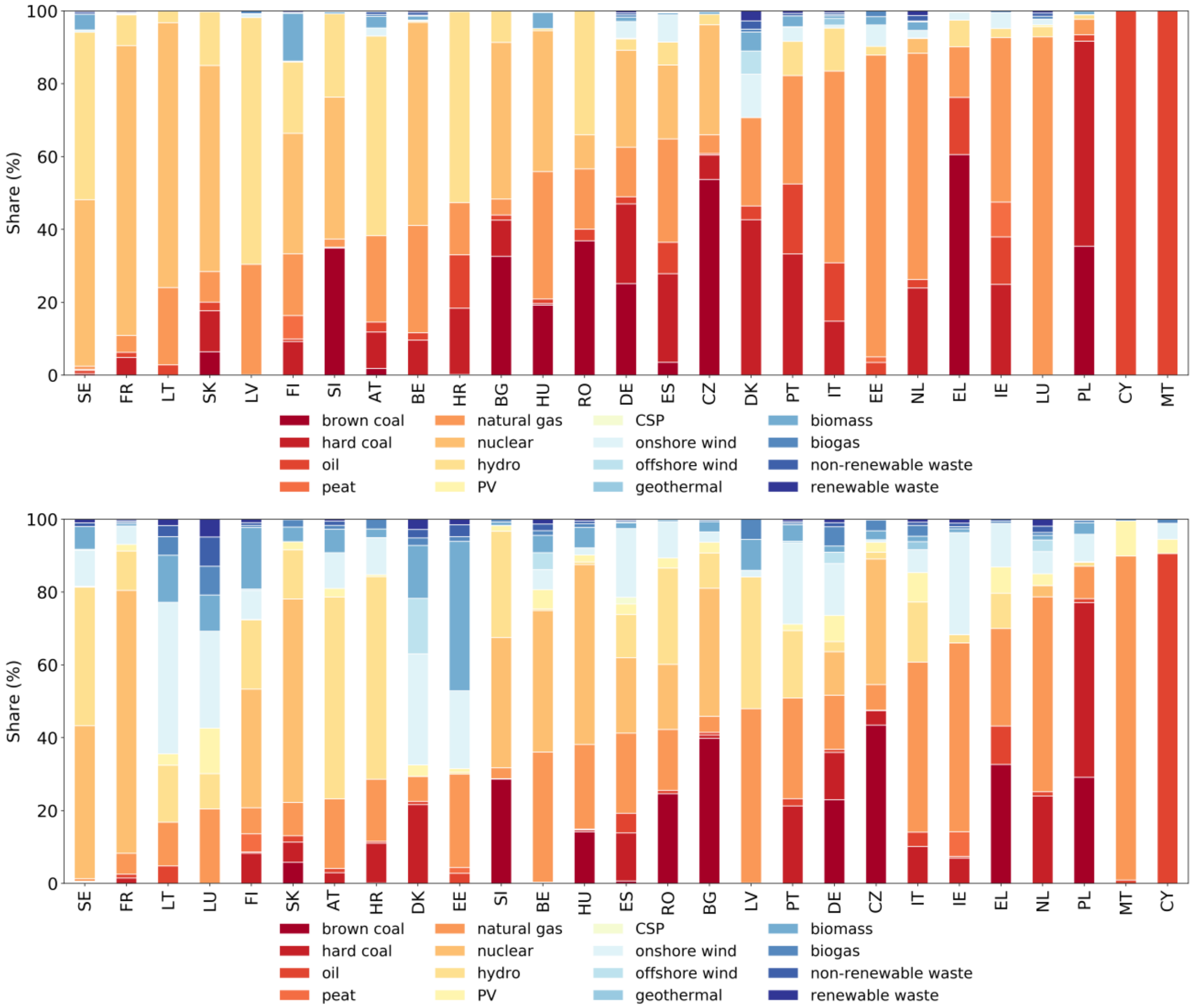
Figure 3.5 Gross electricity production by technology for the EU-27



Source: ETC/CME; (Eurostat, 2020a, 2020b).

Similar trends can be seen clearly also at the Member State level. Individual country mixes for 2005 and 2018 are shown in Figure 3.6. Whereas in 2005 few Member States had significant wind power production, virtually all Member States have solar photovoltaic or wind power production in 2018, reflecting the rapid installation of new PV and wind power plants. Note that in Figure 3.6, Member States are ranked from low to high shares of fossil fuels in their electricity mix and that therefore the Member State order differs between the top and bottom panels.

Figure 3.6 Electricity production by technology and member state for the year 2005 (top) and 2018 (bottom)



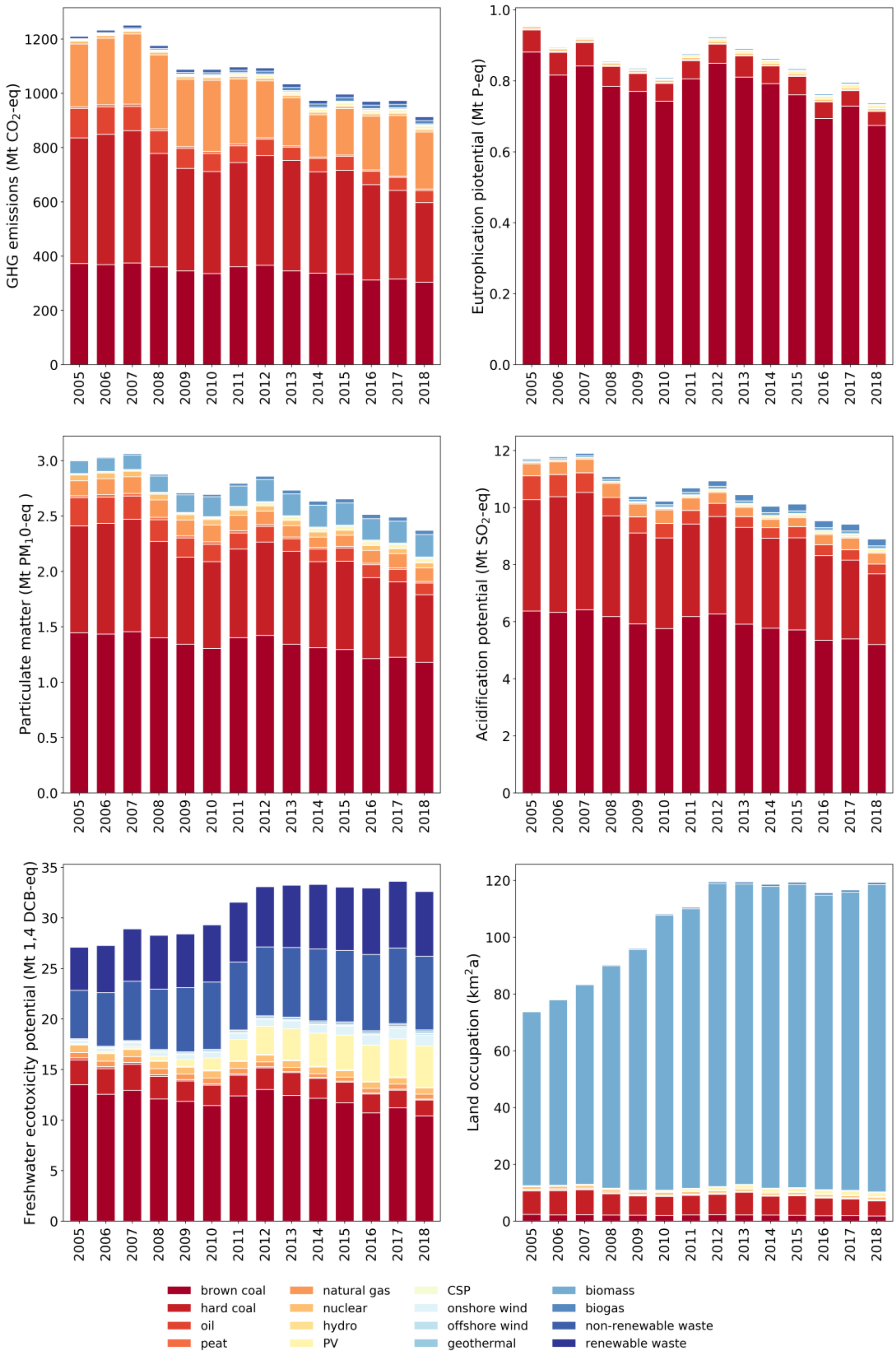
Source: ETC/CME: (Eurostat, 2020a, 2020b).

Figure 3.7 depicts the annual life cycle impacts of electricity production in the EU-27 for six different impact categories and broken down by resource. The impact categories presented are midpoint impact categories climate change, freshwater eutrophication, particulate matter formation, terrestrial acidification, freshwater ecotoxicity, and land occupation, expressed in the units of their respective impact indicators. Not surprisingly, annual impacts from a life cycle perspective are dominated by electricity production from brown and hard coal combustion for electricity generation, followed by emissions from natural gas and oil combustion. This is a result of the (still) large share of fossil fuels in the electricity mix, combined with the relatively high impact intensity of electricity production from fossil fuels. Whereas hard coal combustion was responsible for more than 38 % of all life cycle GHG emissions in the 2005 EU power mix, the significant reduction of hard coal in the electricity mix has led to more equal shares of hard coal and brown coal in life cycle GHG emissions in the EU power mix by 2018.

The life cycle impacts from electricity produced from RES contribute mostly to the ecotoxicity and land occupation impacts, along with a small but noticeable share of biomass related particulate matter impacts. Land occupation impacts can mainly be attributed to land occupation associated with solid biomass. For ecotoxicity, it is mainly the result of the production and installation of solar PV modules as well as a significant contribution from the combustion of renewable and non-renewable wastes.

If biomass were to be removed from the land occupation panel, a significant contribution of solar PV can be viewed. This contribution is not associated with the space the actual PV modules occupy, but rather the indirect and direct land occupation associated with the production of polycrystalline silicon and assembly of the PV modules, with a specific contributions from the use of pulpwood somewhere along the value chain. Note that in a life cycle model, the emissions and resource use may be dispersed geographically (to account for global value chains) and in time (to account for the life cycle). Consequentially, estimated potential impacts, while attributed to European electricity production, may partially occur elsewhere.

Figure 3.7 Annual life cycle impacts associated with electricity production in the EU-27



Source: ETC/CME.

3.4 Avoided impacts relative to 2005

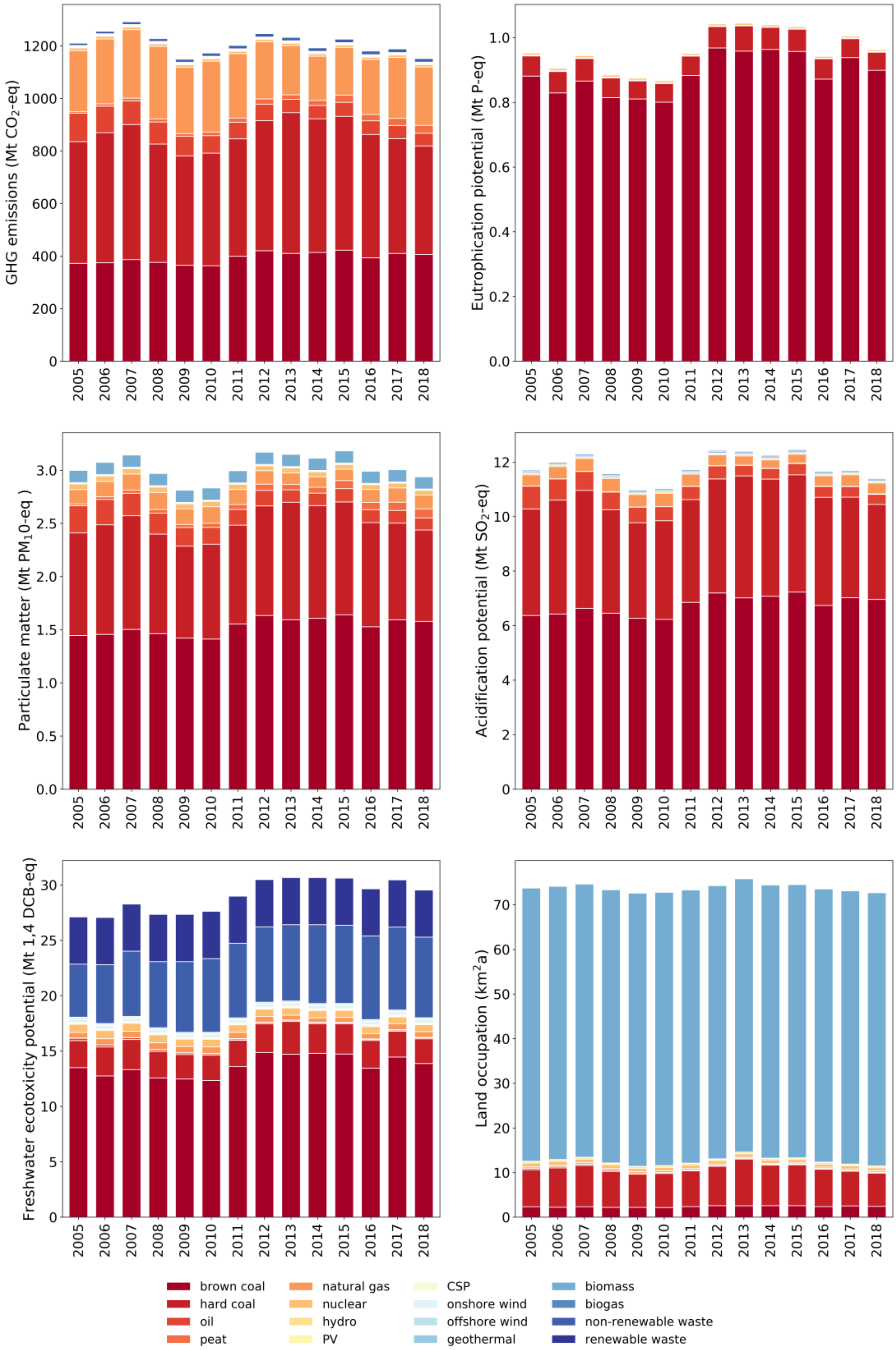
The following Section estimates the effect of increased use of RES for electricity generation. The relative reductions in life cycle impacts are obtained by comparing the actual growth in the use of RES with a counterfactual scenario where this growth would have not taken place. Under this scenario, the assumption is that any growth in renewables since 2005 would have been supplied by a mix of conventional fossil sources; the difference between the counterfactual and the actual data constitutes a measure of 'gross avoided potential impacts'.

3.4.1 Effects at EU-27 level

Figure 3.8 presents the annual life cycle impacts within the counterfactual scenario. In comparison with Figure 3.7 this shows that the absence of additional RES in the electricity mix does not decrease impacts. Note that while the total production from RES is frozen at 2005 levels, the redistribution of renewable energy over fossil energy sources changes each year with the relative share of fossil energy sources in the fossil energy mix. In addition, annual variation in estimated potential impacts is driven by the annual change in total electricity production.

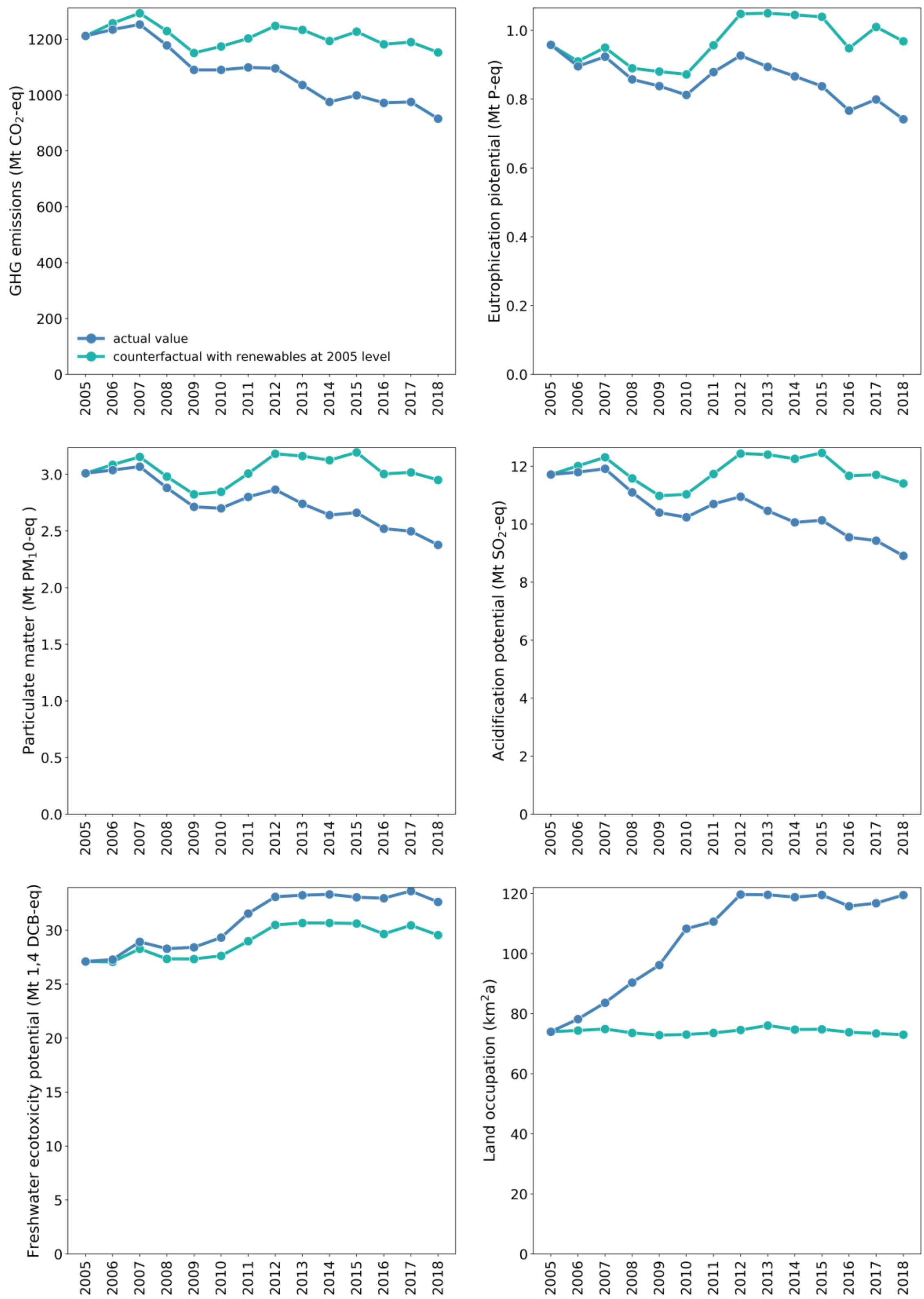
The difference between absolute annual life cycle impacts in the actual scenario and the counterfactual scenarios is shown in Figure 3.9. For most investigated impact categories, the switch from the combustion of fossil fuels to a renewable energy source has led to clear advantages. On an aggregate level, GHG emissions, eutrophication impacts, particulate matter formation, and potential acidification impacts have all decreased, both in the actual scenario and relative to the counterfactual. However, the increased use of renewable waste and increased production of electricity from solar photovoltaics has led to an increase in potential ecotoxic impacts and the increased use of solid biomass has increased potential land occupation impacts considerably.

Figure 3.8 **Annual life cycle impacts associated with electricity production in the EU-27 in the counterfactual scenario**



Source: ETC/CME.

Figure 3.9 Estimated gross effect on impact indicators in the EU-27



Source: ETC/CME.

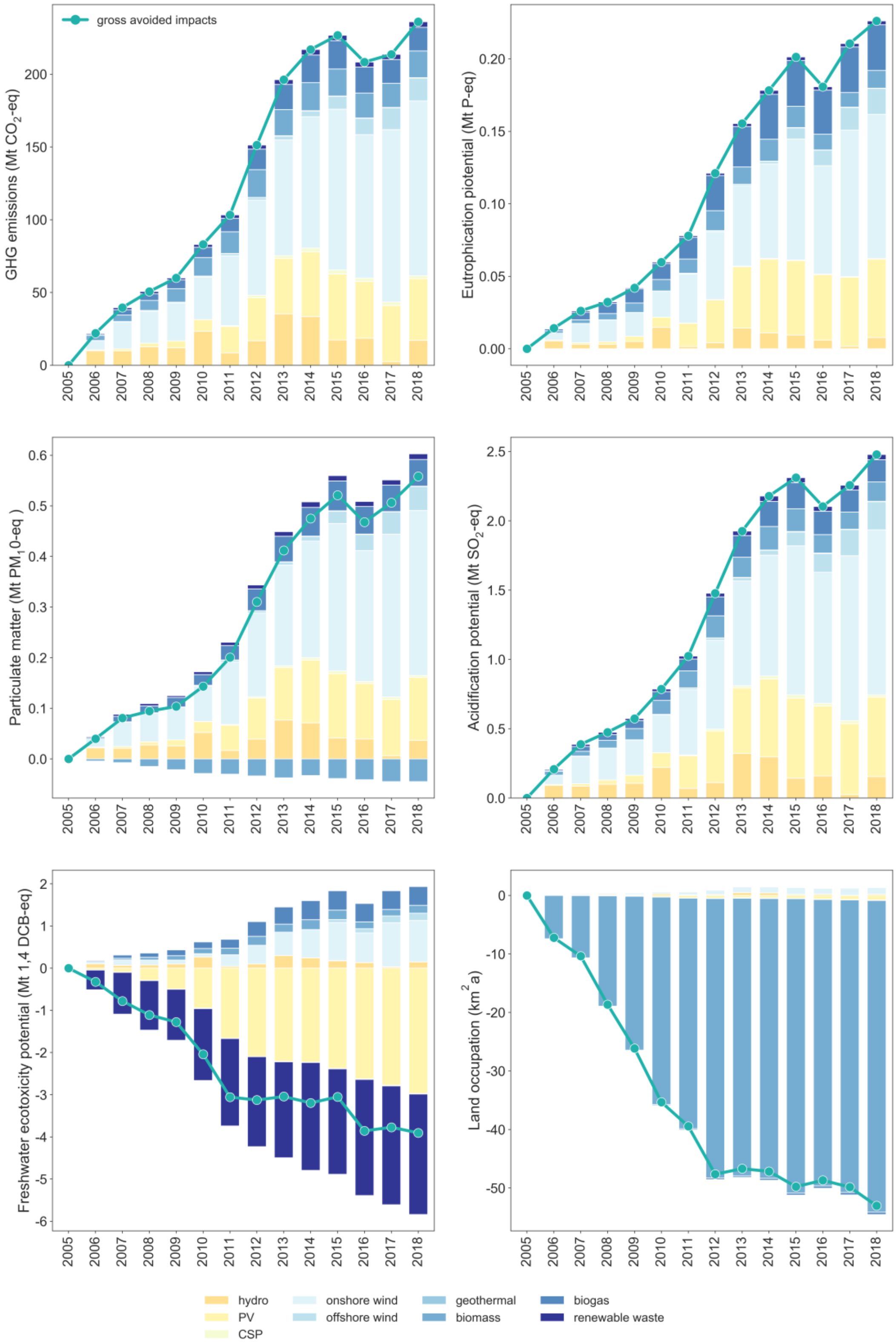
The cumulative gross avoided potential impacts over the period 2005-2018 are broken down by renewable energy source in Table 3.7. In this period, a total of approximately 1800 Mt of GHG emissions is potentially avoided, together with 3.9 Mt PM_{10}-eq, 18 Mt SO_2-eq and 1.5 Mt P-eq. Negative values in Table 3.7 indicate an increase in impact relative to the counterfactual scenario, and the 'cost' of the expansion of RES is shown in the last two columns. Freshwater ecotoxicity and land occupation impact potentials have increased considerably relative to the counterfactual. For freshwater ecotoxicity, this can be related to increased use of renewable waste, geothermal energy, and solar photovoltaics. For land occupation, this is related to the increased use of bioenergy sources, as well as solar photovoltaics and concentrated solar power. Overall however, Table 3.7 shows that a clear contributor to gross avoided impacts was the rapid expansion of onshore wind power, followed by relatively large contributions from the expansion in solar PV power and moderate contributions from the increased use of biogas and solid biomass (for non-land related impact categories).

Table 3.7 Cumulative gross avoided impacts in the period 2005-2018 broken down by RES

RES	GWP (Mt CO_2-eq)	PMF (Mt PM_{10}-eq)	TAP (Mt SO_2-eq)	FEP (Mt P-eq)	FET (Mt 1,4-DCB-eq)	LOP (km²a)
Biogas	1.5E+02	4.6E-01	1.4E+00	2.6E-01	3.7E+00	-3.1E+00
Solid biomass	1.8E+02	-3.8E-01	1.5E+00	1.2E-01	1.9E+00	-4.8E+02
Renewable waste	3.4E+01	9.6E-02	3.4E-01	2.2E-02	-2.6E+01	8.0E-02
Geothermal	2.3E+00	6.5E-03	2.6E-02	1.2E-03	-9.2E-02	4.8E-02
Hydro	2.2E+02	4.8E-01	1.9E+00	8.8E-02	1.8E+00	2.6E+00
Offshore wind	6.2E+01	1.7E-01	7.2E-01	5.6E-02	4.8E-01	6.6E-01
Onshore wind	8.3E+02	2.2E+00	8.2E+00	6.3E-01	6.0E+00	8.8E+00
Solar PV	3.1E+02	8.8E-01	4.0E+00	3.5E-01	-2.1E+01	-4.9E+00
CSP	1.7E+01	3.2E-02	1.4E-01	2.5E-03	1.7E-02	-6.2E-01
TOTAL	**1.8E+03**	**3.9E+00**	**1.8E+01**	**1.5E+00**	**-3.3E+01**	**-4.8E+02**

Finally, Figure 3.10 shows the annual contribution of each renewable energy source to gross avoided impacts in the EU-27. Here, one can even more clearly observe the strong effects of increased shares of solar PV and onshore wind in the European electricity mix. Furthermore, Figure 3.10 clearly depicts the effects of all non-biomass renewable sources counterbalancing increased particulate matter potential impacts from biomass combustion. This is even more apparent for freshwater ecotoxicity related impacts as the (negative) effects of combustion of renewable wastes and increased use of solar PV are partially compensated for by wind, biomass and biogas.

Figure 3.10 Annual contribution of RES to gross avoided impacts in the EU-27



Source: ETC/CME.

4 Discussion

Key messages:

- Uncertainty remains with respect to the source data in the life cycle inventories.
- In individual cases results are sensitive to single environmental emissions in the LCI.
- Lifetime extension may be an option to mitigate negative consequences from the increased use of non-combustion renewables.
- Omission of impact indicators may obscure relevant results.
- It is recommended to expand future work across more impact indicators as well as a continued effort to update, improve and harmonize life cycle inventories.

This report summarises findings regarding gross avoided environmental impacts, from a life cycle perspective, due to increased use of RES in electricity generation. In this Chapter, the results are discussed. Section 4.1 addresses the robustness of the overall assessment. This robustness of the assessment is largely dependent on the methodology employed, and a more thorough discussion with respect to the data sources and methodology is presented in Section 4 of the accompanying methodology report (ETC/CME, 2020). Section 4.2 includes suggestions for future updates on this work.

4.1 Overall assessment

The findings presented in Chapter 3 are the result of a complex methodological exercise bringing together data and modelling from a variety of sources. Life cycle inventories are combined with international energy balance statistics, generic fuel-specific emissions factors, and two background life cycle databases. As such, it may be expected that there is uncertainty associated with the final results. To an extent, this uncertainty is expressed through the variability in impact indicator results (stemming from the energy balance statistics across Member States and years), but there an inherent uncertainty in relation to the source LCIs. Being separately constructed, often around a single specific technology and from a variety of sources, the individual LCIs are not all harmonized in terms of system and coverage, despite sharing many common elements. This becomes perhaps best apparent in the contribution analysis results. The results presented in section 3.2 show that some impact intensities are driven by a single emission to the environment in either foreground or background and changes in this estimate would lead to considerably lower or higher impact intensity. The advantage of such a single contributor is that mitigation of potential impacts may be easier, as it is clear what is the main driver for potential impacts. For example, the use of solid biomass feedstock with a low land footprint, or the improvement of toxic releases in the PV value chain may reduce the corresponding land occupation and freshwater ecotoxicity impact intensities considerably.

A related issue is that plant sizes, plant lifetimes and plant capacity factors may change considerably over time. While average capacity factors were taken into account for the non-combustion RES in this analysis, average plant lifetimes were not varied. Specifically, for the non-combustion RES an increase in lifetime would decrease the impact intensity of electricity production and lifetime extension of RES power plants could be a generic option to mitigate some of the potential negative effects of increased use of RES.

Another element not included in this report is the necessity for increased capacity of grid infrastructure to allow for the intermittent and distributed generation of renewable electricity. With high shares of renewable energy from solar or wind in the electricity mix, either the flexibility options or the transmission capacity and interconnectedness of the European power grid have to increase to avoid the need for backup capacity or power curtailing. While the increase of grid capacity does not necessarily need to be attributed only to RES, from a systemic perspective one could include various flexibility options, grid improvements and expansion into the annual life cycle impacts presented in Chapter 3.

4.2 Recommendations for future work

To allow for a comprehensive treatment of life cycle impact indicators it was chosen to limit the impact categories presented in this analysis to six. Consequently, this analysis does not address a wider scope of impact categories which may be thought of, such as ionizing radiation potential, human toxicity, and water and material footprints. One way to address this is to extend the method to allow for the estimation of impact indicators for all impact categories as outlined by the product environmental footprint (PEF), a life cycle based method to quantify the environmental impact of goods and services. The PEF requires in addition a normalization and weighting procedure to produce dimensionless normalized results (Zampori et al., 2019). These procedures may aid in estimating the value of gross avoided impacts in one impact category over the increase in impacts in another impact category, such as the trade-off between greenhouse gas emissions reductions and land occupation potential exemplified by the results in this report.

Most of this report focused on the life cycle inventory part of LCA. However, there is an element of uncertainty associated with LC Impact Assessment (IA) methods and the characterization factors they provide. The necessity of LCA to provide results of a comparative nature, requires IA methods generalize relations and results. For example, the influence of offshore wind parks on marine ecosystems are not well understood, and marine ecotoxic effects come with a larger degree of uncertainty. Other impacts categories are not well suited for capturing with LCIA, such as the use and release to surface water by thermal power plants of cooling water with a certain temperature. It is therefore recommended to underpin the conclusions on positive or negative effects of increased use of RES by additional studies that may provide additional insight for specific impact categories.

5 Conclusions

In this report, we calculate estimates for the gross avoided environmental impacts associated with the increased use of RES for electricity production in the EU-27. Based on a set of life cycle inventories, life cycle impact assessment results were calculated per unit of electricity generated by each of the key technologies assessed, per Member State and for each year in the time period 2005-2018. These results were subsequently scaled up to produce an estimate of life cycle GHG emissions at EU-27 aggregate level. Through comparison with a counterfactual scenario, an estimate of gross avoided potential environmental impacts from a life cycle perspective was obtained.

Results show that the increasing production of electricity generated from renewable sources has decreased GHG emissions significantly in the period 2005-2018, as it has substituted fossil fuel use. Cumulatively, avoided GHG emissions amounted to approximately 1800 Mt CO_2-eq, together with gross avoided 3.9 Mt PM_{10}-eq, 18 Mt SO_2-eq and 1.5 Mt P-eq. These gross avoided impacts come at a cost of increased toxicity and land occupation (respectively -33 Mt 1,4DCB-eq and -480 km^2a). Despite the trade-offs, it was also shown that individual RES balance out negative effects of other RES and contribute positively to gross avoided impacts.

A large part of avoided impacts reduction can be attributed to the phase out of hard coal power plants in favour of renewable and natural gas generation technologies. Most notably, the gross avoided impacts were driven by an increase in electricity generation from onshore wind power and solar PV power, followed by electricity from solid biomass and biogas combustion. The combustion of fossil fuels for electricity remains a large contributor to all impact categories investigated except for land occupation and there are significant potential gains associated with focusing on its phase out in favour of increased use of RES.

Based on the underlying LCA data, it is possible to identify single processes and environmental emissions contributing significantly to impact intensities. While it cannot be ignored that these results are an artefact of uncertainty in the underlying life cycle inventory, it also shows where and how to focus impact mitigation efforts, either through technological means (emission abatement equipment), or by reduction in consumption (e.g. an increased power plant efficiency reduces fuel use and land occupation impacts upstream).

6 References

EC, 2015, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, the Committee of the Regions and the European Investment Bank — Energy Union Package — a framework strategy for a resilient Energy Union with a forward-looking climate change policy (COM(2015) 80 final).

EC, 2020, 2030 Climate target plan (https://ec.europa.eu/clima/policies/eu-climate-action/2030_ctp_en) accessed 20 November 2020.

Ecoinvent, 2019, 'Ecoinvent database v3.6' (www.ecoinvent.ch) accessed 1 September 2019.

EEA, 2015, *Renewable energy in Europe — approximated recent growth and knock-on effects*, EEA Technical Report No 1/2015, European Environment Agency (http://www.eea.europa.eu/publications/renewable-energy-in-europe-approximated) accessed 31 July 2015.

EEA, 2017, *Analysis of key trends and drivers in greenhouse gas emissions in the EU between 1990 and 2015*, EEA Report No 8/2017 (https://www.eea.europa.eu/publications/analysis-of-key-trends-and) accessed 4 January 2019.

EEA, 2018a, *Renewable energy in Europe — 2018: recent growth and knock-on effects*, EEA Report No 20/2018, European Environment Agency (https://www.eea.europa.eu/publications/renewable-energy-in-europe-2018) accessed 1 September 2019.

EEA, 2018b, *Trends and drivers in greenhouse gas emissions in the EU in 2016*, Briefing No 5/2018, European Environmental Agency (https://www.eea.europa.eu/publications/trends-and-drivers-in-greenhouse) accessed 19 October 2018.

EEA, 2019, 'EEA greenhouse gas — data viewer', European Environment Agency (https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer) accessed 10 November 2019.

EEA, European Environment Agency, 2015, *Renewable energy in Europe - approximated recent growth and knock-on effects*, EEA Technical Report No 1/2015, Copenhagen (http://www.eea.europa.eu/publications/renewable-energy-in-europe-approximated) accessed 14 April 2020.

EMEP and EEA, 2016, *EMEP/EEA air pollutant emission inventory guidebook 2016: Technical guidance to prepare national emission inventories* (https://www.eea.europa.eu/publications/emep-eea-guidebook-2016).

ETC/CME, 2019, *Renewable energy in Europe - 2019: Recent growth and knock-on effects*, Eionet Report ETC/CME No 8/2019, ETC/CME (https://www.eionet.europa.eu/etcs/etc-cme/products/etc-cme-reports/renewable-energy-in-europe-2019-recent-growth-and-knock-on-effects) accessed 14 June 2020.

ETC/CME, 2020, *A life cycle perspective on the benefits of renewable electricity generation - Methodology and assumptions*, EIONET Report ETC/CME No 5/2020 (https://www.eionet.europa.eu/etcs/etc-cme/products/etc-cme-reports/etc-cme-report-5-2020-a-life-cycle-perspective-on-the-benefits-of-renewable-electricity-generation-2013-methodology-and-assumptions/view).

EU, 2009, Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC (OJ L 140, 5.6.2009, p. 16-62).

Eurostat, 2020a, ‘Complete energy balances’ (https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_bal_c&lang=en) accessed 20 May 2020.

Eurostat, 2020b, ‘SHARES - Short Assessment of Renewable Energy Sources’ (https://ec.europa.eu/eurostat/web/energy/data/shares) accessed 25 May 2020.

Hertwich, E. G., et al., 2015, ‘Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies’, *Proceedings of the National Academy of Sciences* 112(20), pp. 6277-6282 (DOI: 10.1073/pnas.1312753111).

UNEP, 2016, *Green Energy Choices: The benefits, risks and trade-offs of low-carbon technologies for electricity production*, United Nations Environment Programme, Paris.

Zampori, L., et al., 2019, *Suggestions for updating the organisation environmental footprint (OEF) method.* (http://publications.europa.eu/publication/manifestation_identifier/PUB_KJNA29682ENN) accessed 15 June 2020.

European Topic Centre on Climate change
mitigation and energy
Boeretang 200
B-2400 Mol, Belgium
Tel.: +32 14 33 59 77
Web: www.eionet.europa.eu/etcs/etc-cme
Email: etccme@vito.be

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