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A life cycle perspective on the benefits of renewable electricity generation – Methodology and assumptions

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Contents

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1 Introduction

This report complements the ETC report *A life cycle perspective on benefits of renewable electricity generation* describing the greenhouse gas emission savings associated with increased use of renewable energy sources in the European electricity generation sector.

1.1 Purpose

The purpose of this report is to present a life cycle approach implemented by ETC/CME and EEA to estimate ex-post a number of co-benefits and other impacts across the EU and its Member States in response to increasing the share of renewable energy in the electricity mix in the period 2005 to 2018. As a starting point for analysis, this method will build on the work of the [UN International Resource Panel](https://www.resourcepanel.org/reports/green-energy-choices-benefits-risks-and-trade-offs-low-carbon-technologies-electricity) (IRP) on co-benefits of increased renewable electricity generation (UNEP, 2016) ([1]). Methodological foundations and assumptions of the calculation procedure are detailed in this report. A detailed presentation and discussion of results are presented in a parallel report - *A life cycle perspective on benefits of renewable electricity generation* (ETC/CME, 2020).

1.2 Structure

This report contains three parts. Following this introduction (part 1), part 2 highlights in detail the methodology and assumptions behind the procedure of calculating avoided environmental impacts of renewable electricity consumption from a life cycle perspective. Part 3 presents the main data sources used in this study. Finally, part 4 discusses limitations of the methodology and assumptions.

([1]) https://www.resourcepanel.org/reports/green-energy-choices-benefits-risks-and-trade-offs-low-carbon-technologies-electricity

2 Methodology and assumptions

This Chapter describes the methodology and assumptions behind the calculation of the avoided environmental impacts of increased renewable electricity generation using a life cycle approach. While we aim for a comprehensive overview, it is recommended that the reader has some background knowledge on Life Cycle Assessment (LCA) modelling.

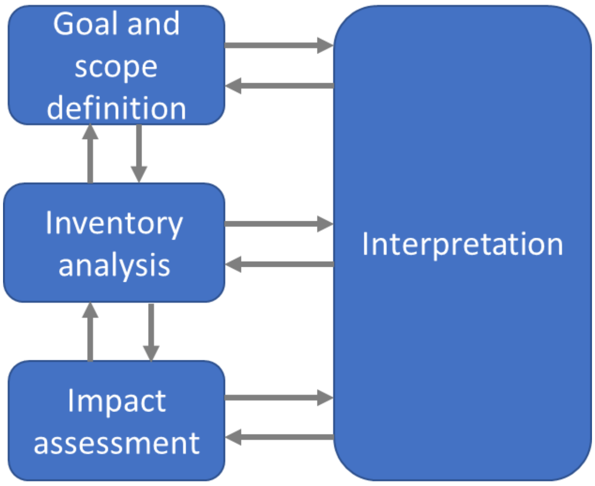
LCA is a tool to estimate the potential environmental impacts of a product, process or service over its life cycle. LCA results can deliver insight from two different perspectives:

1. Firstly, inventory analysis attributes pollutant emissions of singular environmental stressors, such as emissions of CO_2 or SO_2, 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 the emission of all greenhouse gases into the Global Warming Potential (GWP) 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.

A typical LCA study consists of four phases: (i) goal and scope definition, (ii) construction of the life cycle inventory, (iii) calculation of life cycle impact assessment results, and (iv) an interpretation phase that runs in parallel as LCA is a data intensive and often iterative process and outlined in Figure 2.1 (ISO, 2006).

Figure 2.1 Life cycle assessment framework



Source: ETC/CME based on (ISO, 2006).

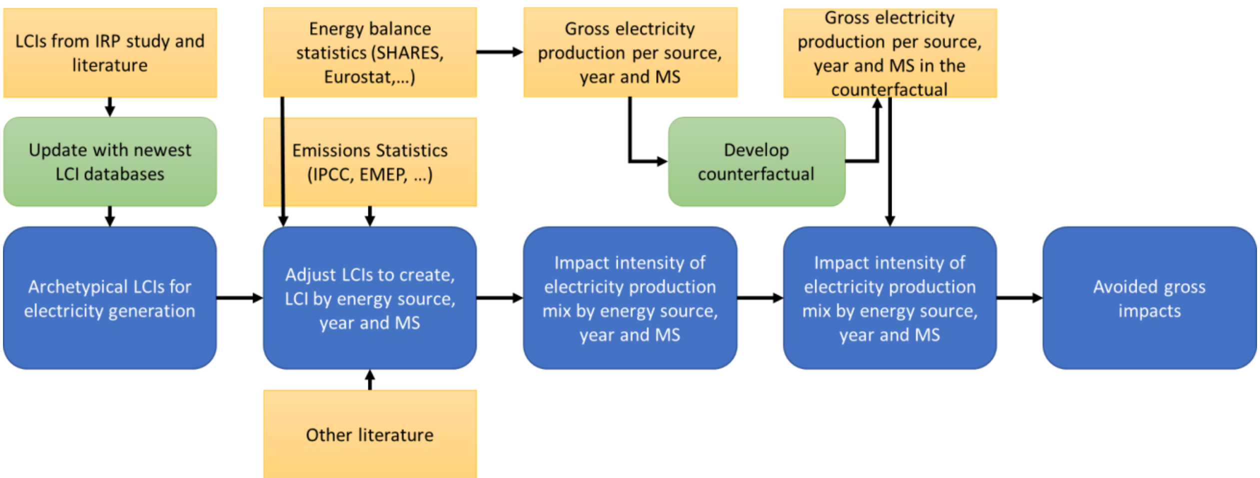
The Life Cycle Inventory (LCI) is a collection of process descriptions detailing the input and outputs to and from economy and environment. Often, LCA studies rely on extensive use of an LCI database and only a limited number of processes is modelled. The process model, coupled to the LCI database, results in the quantification of emissions to, and resource extraction from, the environment per functional unit. As such, the output of the LCI can be viewed as life cycle emissions intensity of the product, process or service under investigation. In the Life Cycle Impact Assessment (LCIA) phase an impact assessment method is used to aggregate the environmental emissions into impact indicators representative for a variety of impact categories, such as climate change, (freshwater) ecotoxicity potential, or acidification potential. Various LCIA methods are available to LCA practitioners. This expression of emissions into impact indicators allows for a meaningful comparison between different environmental emissions as the environmental fate, exposure and effect of singular emissions may vary greatly and their contribution to midpoint or endpoint impacts is not immediately apparent based on magnitude alone.

In the following subsections, first the overall approach of the method is described (Section 2.1), followed by a presentation of each of the calculation steps involved in calculating impacts associated with electricity production per year and Member State (Section 2.2), as well as the calculation of the impacts in the counterfactual scenario to estimate gross avoided impacts due to increased use of renewable energy sources in the electricity production system (Section 2.3).

2.1 Overall approach

A bottom-up approach was taken to calculate the gross avoided potential environmental impacts ([2]) due to increased use of renewable energy sources in the electricity production mix. A collection of LCIs describing archetypical electricity generation processes using main energy sources (e.g. hard coal, natural gas, wind, or solar) was assembled. 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 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. A schematic representation of the above described steps is presented in Figure 2.2.

Figure 2.2 Overall approach



Source: ETC/CME.

([2]) 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, impact indicators refer to *potential impacts* and gross avoided potential impacts may have occurred in the future of the counterfactual scenario.

2.2 Life cycle impacts of electricity production in the EU-27 for a single year.

For electricity generation, life cycle models typically adopt a 'cradle-to-gate' approach ([3]). This means that potential environmental impacts are calculated per unit of electricity delivered to the grid and impacts associated with transmission infrastructure, transmission losses, as well as impacts associated with the use of the electricity are omitted from the LCA study.

In order to calculate the avoided GHG emissions and other impact indicators for the EU-27, a set of life cycle inventories (LCIs) used for the IRP study was chosen as the starting point, as they enable comparative analysis in single analytical structure, where the same background data is used for any common processes (Hertwich et al., 2015). These inventories were supplemented with LCIs from various other sources as the IRP study does not contain an inventory corresponding to all types of renewable and non-renewable energy sources. All individual LCIs were updated with current background databases, Ecoinvent 3.6 (Ecoinvent, 2019) and EXIOBASE 3.4 (Stadler et al., 2018). LCIs were collected for electricity production from the energy sources listed in Table 2.1. In the same Table, the technology and key plant parameters are listed as used in the original inventories.

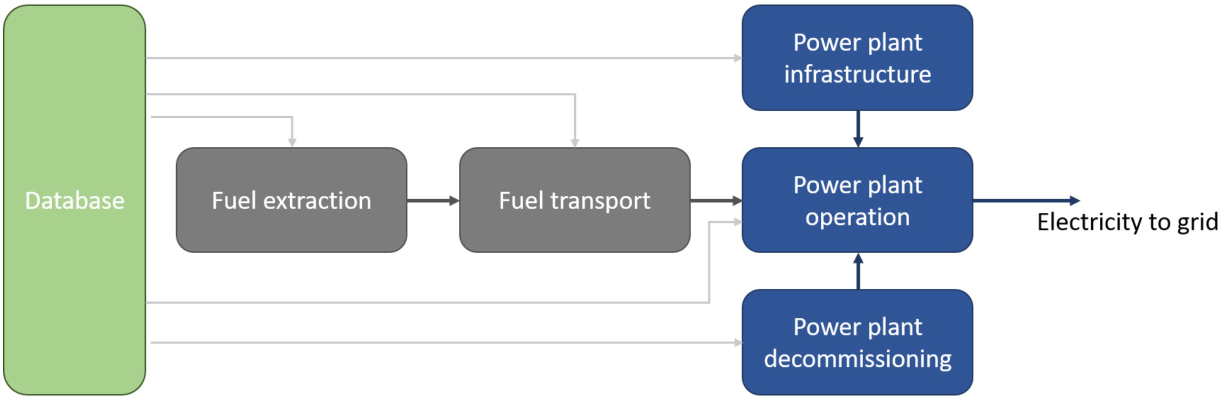
([3]) Other approaches are for example grade-to-grave where use and end-of-life are explicitly included as life cycle phases and typically used for material products.

Table 2.1 Overview of life cycle inventories

Energy source	Technology	Power rating (MW)	Efficiency	Lifetime	Adapted from
Brown coal	Subcritical coal fired power plant	550	38 %	30	(UNEP, 2016)
Hard coal	Supercritical coal fired power plant	550	41 %	30	(UNEP, 2016)
Peat	Peat fired power plant	500	37 %	33	(Ecoinvent, 2019)
Oil	Oil fired power plant	500	38 %	30	(Ecoinvent, 2019)
Natural gas	Natural gas combined cycle power plant	555	56 %	30	(UNEP, 2016)
Nuclear	Pressure water reactor nuclear power plant	1000	-	40	(Ecoinvent, 2019)
Hydro	Hydro power from dam	360	-	80	(UNEP, 2016)
Offshore wind	Offshore wind turbine	5	-	25	(UNEP, 2016)
Onshore wind	Onshore wind turbine	2.5	-	20	(UNEP, 2016)
Concentrated solar power	Trough based concentrating solar power plant	103	-	30	(UNEP, 2016)
Photovoltaic	Poly-Si rooftop mounted photovoltaic power module	260.E-6	-	25	(UNEP, 2016)
Geothermal	Geothermal power plant	172	-	100	(Martínez-Corona et al., 2017)
Biomass	Wood chip combustion in combined heat and power generator	1	29 %	20	(Ecoinvent, 2019)
Biogas	Biogas combustion in combined heat and power generator	0.16	37 %	20	(Ecoinvent, 2019)
Non-renewable MSW	Waste combustion in combined heat and power generator	100 kt waste	36 %	40	(Ecoinvent, 2019)
Renewable MSW	Waste combustion in combined heat and power generator	100 kt waste	36 %	40	(Ecoinvent, 2019)

Each of the inventories can be represented in the simplified generic structure presented in Figure 2.3. The construction of power plant infrastructure, power plant operation and power plant decommissioning were included in each inventory. For the fuel combustion technologies, in addition, unit processes describing fuel extraction and transport were included. Each of the processes was connected to the background databases for any other requirements, e.g. steel for power plant infrastructure, or diesel for operating construction machinery. Note that while environmental emissions or resource use may occur at every process, these flows are not depicted in Figure 2.3.

Figure 2.3 **General structure of processes in life cycle inventory**



Source: ETC/CME.

The collected set of individual LCIs acted as basis for calculating the impact intensities of delivering 1 MWh electricity from a specific energy source (e.g. hard coal, natural gas, wind or solar) to the grid. The calculation of impact indicator results of a general LCA is presented in section 2.2.1.

The collected LCIs are based on an archetypical power plant model and electricity production process, often representing best available technology. Therefore, key parameters for each of these archetypical LCIs were adjusted programmatically in order to reflect better the status of electricity production per energy source, year, and Member State. For fuel combustion technologies, this meant adjusting for fuel combustion efficiency and corresponding change in direct emissions to air of selected pollutants. For non-combustion renewable generators this meant changing the infrastructural requirements per unit electricity generation, based on the annual historic capacity factors. The procedure for adjusting these key parameters is described in section 2.2.2.

Through this method, impact intensities (II, impact potential per unit of electricity generated) were obtained, that allowed for distinguishing between energy source (es), year (y)and Member State (ms). By multiplying the impact intensities with historical electricity production data, and aggregating, EU-27 annual life cycle impacts were estimated.

$$I_{EU27,y} = \sum_{ms \in MS} \sum_{es \in ES} EP_{ms,es,y} II_{ms,es,y}$$

Impact intensities are expressed for different impact indicators listed in Table 2.2. Several midpoint impact indicators were chosen, reflective of the climate, pollution of water, air and land, as well as land footprint. Note that in LCA, the total value for each impact indicator is calculated by summing over all contributing emissions expressed in the emissions indicator, obtained through multiplication with a characterization factor. For example, characterization factors for key greenhouse gases CO_2, CH_4 and N_2O are equal to GWP100 and respectively 1, 25 and 298 kg CO_2-eq/kg (IPCC, 2007).

Table 2.2 List of impact indicators

Label	Full name	Unit	Type	Reference
GWP	Global Warming Potential (100-year timeframe)	kg CO_2-eq	Midpoint	(Huijbregts et al., 2016)
PMF	Particulate Matter Formation Potential	kg PM_{10}-eq	Midpoint	(Huijbregts et al., 2016)
TAP	Terrestrial Acidification Potential	kg SO_2-eq	Midpoint	(Huijbregts et al., 2016)
FEP	Freshwater Eutrophication Potential	kg P-eq	Midpoint	(Huijbregts et al., 2016)
FET	Freshwater Ecotoxicity Potential	kg 1,4 DCB-eq	Midpoint	(Huijbregts et al., 2016)
LOP	Land Occupation Potential (agricultural and urban)	m^2a	Midpoint	(Huijbregts et al., 2016)

2.2.1 Calculating environmental impact indicators in LCA

Traditionally, Life Cycle Inventories are built using an LCI database, containing a large amount of LCI processes. This database is referred to as the background. The model of the specific process, such as coal-fired electricity generation, is referred to as the foreground. Foreground processes can obtain inputs from other foreground processes, as well as from the background database. Each of these flows can be represented as part of a coefficient matrix A where each of the coefficients (i,j) represents the process inputs i per unit output j. In mathematical terms, this is represented by:

$$A = \begin{bmatrix} A_f & \emptyset \\ A_{pf} & A_{pp} \end{bmatrix}$$

Where A_f designates the foreground, A_{pp} the background and A_{pf} contains the amount of inputs required from background by the foreground.

Total output x of all processes, subject to a final demand y for a product from a single process (or for multiple outputs) is given by:

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

Where I is an identity matrix of appropriate size. This mathematical representation of a process-based LCA is equivalent to the equation for calculating economic outputs of an Input-Output table and the inverse term is therefore named Leontief inverse ([4]) (Leontief, 1970).

The LCIs provided by the UN IRP are built for hybrid LCA. Hybrid LCA is an extension of the traditional process-based LCA where in addition to the process-based background, an economic background in the form of an environmentally extended Input-Output table is added. Matrix A can thus be expanded to include the economic background, such that the foreground system can source not only processes from the process background database, but also from the economic database. It is argued that for this reason hybrid LCA leads to more complete system definitions. Note that in the representation below there are no flows from foreground into either process-based or economic background and that both background databases are independent from each other.

([4]) After the economist Wassily Leontief who introduced the equation studying the input-output structures of economies.

$$A = \begin{bmatrix} A_f & \emptyset & \emptyset \\ A_{pf} & A_{pp} & \emptyset \\ A_{mf} & \emptyset & A_{mm} \end{bmatrix}$$

Similar to economic or physical inputs, one can record the environmental emissions and resource requirements per unit of production for all processes in the A-matrix.

$$S = [S_{sf} \quad S_{sp} \quad S_{sm}]$$

As the number of environmental emissions and resource requirements is very large, Life Cycle Impact Assessment aims to aggregate these emissions into meaningful impact categories expressed by impact indicators. One such impact category is climate change and the corresponding impact indicator is the GWP100, expressed in (kg) CO_2-eq. This is represented by a characterization matrix containing characterization factors used to convert environmental emissions and resource requirements to impact indicators.

$$C = [C_{is}]$$

Combining all of the above, a vector of life cycle impact indicators d, associated with a final demand for a process y, can be calculated as:

$$d = CS(I - A)^{-1}y$$

2.2.2 Adjustment of LCI for combustion technologies

For fuel combustion technologies the LCI is adjusted as follows. Fuel inputs (i) to plant operation (j) are Member State, energy source, and year specific. We calculated the fuel requirements per unit generation (FI) by dividing the electricity related fuel input over the annual electricity production (EP). The fuel input for electricity generation is calculated by assuming a 90 % efficient heat generation process and subtracting the fuel requirements for heat (calculated from the efficiency and heat production, HP) from the total fuel requirements (F).

$$[A_{i,j}]_{ms,es,y} = FI_{ms,es,y} = \left[F_{ms,es,y} - \frac{HP_{ms,es,y}}{0.9}\right]\frac{1}{EP_{ms,es,y}}$$

Note that for technologies that are not combined heat and power generators the above equation reduces to:

$$[A_{i,j}]_{ms,es,y} = FI_{ms,es,y} = \frac{F_{ms,es,y}}{EP_{ms,es,y}}$$

In addition to fuel requirements, emissions (i) per unit electricity generation (j) are also adjusted for each Member State, energy source and year, by applying an emissions factor (EF) (see Table 3.4 for specific EF values).

$$[S_{i,j}]_{ms,es,y} = FI_{ms,es,y}EF_i$$

For compounds for which no external emissions factor was available, the original emissions per unit electricity generation were scaled with the implicit power plant efficiency η from the energy balance statistics ($EP \,/\, FI$).

$$[S_{i,j}]_{ms,es,y} = \frac{\eta_{es-orig}}{\eta_{ms,es,y}} S_{i,j}^{orig}$$

2.2.3 Adjustment of LCI for non-combustion renewable technologies

For non-combustion renewable technologies, we scale the required infrastructure inputs for construction of the renewable generator. This can be done by establishing a capacity factor for the renewable generators by dividing historic annual electricity production over the theoretical annual maximum production based on the power rating (PR):

$$CF_{ms,es,y} = \frac{EP_{ms,es,y}}{PR_{ms,es,y} * 8760}$$

and scaling the infrastructural inputs with the ratio between the thus calculated capacity factor and the capacity factor calculated from the original LCI model.

$$SF_{ms,es,y} = \frac{CF_{es-orig}}{CF_{ms,es,y}}$$

This scaling factor is subsequently used to scale the coefficients in the foreground matrix A_f relating to infrastructural requirements (i) per unit electricity generation (j).

$$[A_{i,j}]_{ms,es,y} = SF_{ms,es,y} A_{i,j}^{orig}$$

2.3 Calculation of avoided impacts

This section describes the employed method to estimate gross avoided impacts from electricity production due to the increased utilization of RES in the production of electricity. The method follows closely the method employed by the EEA to calculate gross avoided GHG emissions without including life cycle effects (EEA, European Environment Agency, 2015; EEA, 2018). In line with that study, the term gross here also implies the theoretical nature of the contribution from increased renewable electricity generation and does not necessarily represent net impact savings.

The calculation of avoided emissions or impacts works under the assumption that the renewable electricity generation replaces electricity generation that would otherwise be supplied by fossil means. Gross avoided emissions are therefore calculated as the annual differences between actual life cycle emissions and a counterfactual scenario. The counterfactual scenario – in essence a frozen-policy scenario – assumes that renewable electricity generation would have remained at the level of 2005, with energy demand being met by an increased generation from non-renewable energy sources. Thus, there are no avoided emissions or impacts attributed to renewable electricity generation up to 2005.

The potential life cycle impacts $I_{ms,y}^{IC}$ for impact category IC (e.g. life cycle GHG emissions in Mt CO_2-eq or life cycle acidification potential in Mt SO_2-eq) per Member State and year is obtained by summing over the product of annual electricity production and impact intensities for all energy sources present in the model:

$$I_{ms,y}^{IC} = \sum_{es \in ES} EP_{ms,es,y} II_{ms,es,y}^{IC}$$

For the calculation of the counterfactual it is necessary to distinguish between the non-renewable energy sources (NR), fossil energy sources (FS) and the renewable energy sources (R). For the year 2006 to 2018, the counterfactual life cycle impacts $CI_{ms,y}^{IC}$ for impact category (IC) per Member State and year can be defined as the sum of:

i) The impact contributions of non-renewable energy source:

$$I_{ms,y,NR}^{IC} = \sum_{es \in NR} EP_{ms,es,y} II_{ms,es,y}^{IC}$$

ii) The impact contributions of renewable energy sources in 2005:

$$I_{ms,2005,R}^{IC} = \sum_{es \in R} EP_{ms,es,2005} II_{ms,es,2005}^{IC}$$

iii) The impact contributions from the additional electricity production from renewable energy sources relative to 2005 and attributed to fossil electricity production (here indicated by FSA) weighted by fossil electricity production shares in year y.

$$I_{ms,y,FSA}^{IC} = \sum_{es \in FS} \left(\Delta EP_{ms,y,R} \frac{EP_{ms,es,y}}{\sum_{es \in FS} EP_{ms,es,y}} \right) II_{ms,es,y}^{IC}$$

Where: $\Delta EP_{ms,y,R} = \sum_{es \in R} EP_{ms,es,y} - EP_{ms,es,2005}$

The counterfactual potential life cycle impacts (CI) are:

$$CI_{ms,y}^{IC} = I_{ms,y,NR}^{IC} + I_{ms,2005,R}^{IC} + I_{ms,y,FSA}^{IC}$$

The calculation of gross avoided potential life cycle impacts (AI) for a given year and Member State is the difference between the benchmark and the counterfactual scenario.

$$AI_{ms,y}^{IC} = I_{ms,y}^{IC} - CI_{ms,y}^{IC}$$

Aggregate EU-27 values can be obtained by summing over the values for individual Member States.

$$AI_{y}^{IC} = \sum_{ms \in MS} I_{ms,y}^{IC} - CI_{ms,y}^{IC}$$

A quick overview of variables in the equations above is given in Table 2.3 below.

Table 2.3 Overview of variables in equations

Variable	Description	Includes
I	Potential life cycle impacts	
CI	Counterfactual potential life cycle impacts	
AI	Gross avoided potential life cycle impacts	
II	Impact intensity	
EP	Electricity production	
ms	Member State	
es	Energy source	
y	year	2005-2018
IC	Impact category	Global Warming Potential, Particulate Matter Formation, Terrestrial Acidification Potential, Freshwater Eutrophication Potential, Freshwater Ecotoxicity Potential, Land Occupation Potential (agricultural and urban), Human Health, External costs (monetized)
MS	Set of Member States	All Member States of the EU-27
ES	Set of energy sources	Brown coal, Hard coal, Peat, Oil, Natural gas, Nuclear, Hydro, Offshore wind, Onshore wind, Concentrated solar power, Photovoltaic, Geothermal, Biomass, Biogas, Non-renewable MSW, Renewable MSW
NR	Set of non-renewable energy sources, subset of ES	Brown coal, Hard coal, Peat, Oil, Natural gas, Nuclear, Non-renewable MSW
FS	Set of fossil energy sources, subset of NR.	Brown coal, Hard coal, Peat, Oil, Natural gas
R	Set of renewable energy sources, subset of ES	Hydro, Offshore wind, Onshore wind, Concentrated solar power, Photovoltaic, Geothermal, Biomass, Biogas, Renewable MSW
FSA	Fossil source attributed	

2.3.1 Hypothetical example of avoided impact calculation

To provide an example of the gross avoided impact calculation for a single impact category, a hypothetical single-region electricity system with only four energy sources, two fossil and two renewable, is presented here. For the year 2005, annual electricity generation of 16 TWh is provided by these four energy sources. Using life cycle greenhouse gas emissions as an example impact indicator, Table 2.4 shows the life cycle impacts broken down by energy source and the region for the year 2005.

Table 2.4 Hypothetical calculation of annual life cycle GHG emissions for a single region with electricity production from four energy sources in the year 2005

Energy source	Annual electricity generation (GWh)	Impact intensity (kg CO_2-eq / MWh)	Life cycle impact (kt CO_2-eq)
Coal	10 000	1 000	10 000
Natural gas	5 000	500	2 500
Hydro power	600	15	9
Wind power	400	10	4
Region total	16 000		12 513

In the year 2010, the share of renewable energy sources in the electricity production has increased, while the production from fossil sources has remained constant. However, due to improvements in the fleet efficiency (some old power plants were shut down) the impact intensity of the fossil technology has decreased, reflecting the higher technological improvements of the fossil fleet. The corresponding 2010 results are presented in Table 2.5.

Table 2.5 Hypothetical calculation of annual life cycle GHG emissions for a single region with electricity production from four energy sources in the year 2010

Energy source	Annual electricity generation (GWh)	Change relative to 2005	Impact intensity (kg CO_2-eq / MWh)	Change relative to 2005	Life cycle impact (kt CO_2-eq)	Change relative to 2005
Coal	10 000	-	980	-20	9 800	-200
Natural gas	5 000	-	480	-20	2 400	-100
Hydro power	800	200	15	-	12	3
Wind power	1000	600	10	-	10	6
Region total	16 800	800			12 222	-291

The counterfactual scenario assumes that the 800 GWh increase in electricity production from renewable energy sources between 2005 and 2010 did not happen and rather is satisfied by fossil energy sources proportionate to the 2010 share between the two fossil sources. The corresponding counterfactual results are presented in Table 2.6.

Table 2.6 Hypothetical calculation of counterfactual annual life cycle GHG emissions for a single region with electricity production from four energy sources in the year 2010

Energy source	Annual electricity generation (GWh)	Change relative to 2010	Impact intensity (kg CO_2-eq / MWh)	Change relative to 2010	Life cycle impact (kt CO_2-eq)	Change relative to 2010
Coal	10 533	533	980	-	10 322	522
Natural gas	5 267	267	480	-	2 528	128
Hydro power	600	-200	15	-	9	-3
Wind power	400	-600	10	-	4	-6
Region total	16 800	0			12 863	641

Comparing the results in Table 2.5 and Table 2.6, the gross avoided life cycle GHG emissions for 2010 relative to 2005 can be calculated as the difference between total life cycle impacts, in this example 641 kt CO_2-eq emissions. The gross avoided impacts can be disaggregated over the renewable energy sources by calculating the avoided impact intensity of each renewable energy source. This is done by summing up the impact intensities from each fossil energy source, weighted by their share in the fossil mix and subtracting the impact intensity of the renewable energy source itself.

Table 2.7 Avoided annual life cycle GHG emissions for a single region by renewable energy source in the year 2010

Energy source	Change relative to 2005 (GWh)	Coal – weighted impact intensity (kg CO_2-eq / MWh)	Natural gas – weighted impact intensity (kg CO_2-eq / MWh)	Impact intensity (kg CO_2-eq / MWh	Avoided impact intensity (kg CO_2-eq / MWh)	Avoided impacts (kt CO_2-eq)
Hydro power	200	653	160	-15	798	160
Wind power	600	653	160	-10	803	481
Region total	800					641

3 Data sources

This report utilizes data primarily from the IRP report UNEP (2016) as well as from a variety of sources. The source of life cycle inventories was described in section 2.2. Here, the source of energy data and the source of specific emissions data in the following sections. Finally, this Chapter concludes with an overview of correspondence between the separate data sources used for the modelling.

3.1 Gross electricity production

A variety of sources is used for data related to electricity production. Data related to fossil and nuclear electricity production are sourced from the Eurostat energy balance table nrg_bal_c (Eurostat, 2020b). The energy balance table contains data on transformation input, gross electricity production and gross heat production by fuel type. Each fuel is designated a standard international energy product classification (SIEC). Table 3.1 gives an overview of the energy source classifications grouped under each label in this report.

Table 3.1 Fuel types and classification codes

Label	SIEC	Energy source
Brown coal	C0210, C0220, C0320, C0311, C0312, C0340, C0330	Sub-bituminous coal, Lignite, Patent fuel, Coke Oven Coke, Gas Coke, Coal tar, Brown coal briquettes
Hard coal	C0110, C0121, C0129	Anthracite, Coking coal, Other bituminous coal
Peat	P1000	Peat and peat products
Oil	O4000XBIO	Oil and petroleum products (excluding biofuel portion)
Natural gas	G3000, C0350-0370	Natural gas, Manufactured gases
Nuclear	N9000H	Nuclear heat
Hydro	RA100	Hydro
Offshore wind	RA300	Wind ([a])
Onshore wind	RA300	Wind ([a])
Concentrated solar power	RA410	Concentrated solar power
Photovoltaic	RA420	Solar photovoltaic
Geothermal	RA200	Geothermal
Biomass	R5110-5150_W6000RI	Primary solid biofuels
Biogas	R5300	Biogases
Municipal Solid Waste	W6100, W6220	Industrial waste (non-renewable), Non-renewable municipal waste

Notes: ([a]) Production levels of offshore and onshore wind are distinguished using data available in SHARES.

The Eurostat energy balances are available at various levels designated by energy balance code. For electricity and heat production (EHG), main activity producers (MAP) and autoproducers (AP) are distinguished producing electricity (GEP) as a single product (E) or together with heat (CHP). The combustion processes in the life cycle inventory require the energy input per unit electricity as well as the gross electricity produced by a conversion technology. Table 3.2 gives an overview of the energy balance elements used to arrive at electricity. Transformation input cannot directly be used for the CHP plants as the energy input reflects both the electricity and heat produced. Therefore, as described in section 2.2.2, the fuel input for electricity generation is calculated by assuming a 90% efficient heat generation process and subtracting the fuel requirements for heat from the total fuel requirements. The detailed Eurostat Short Assessment of Renewable Energy Sources (SHARES) results were the source for electricity production from hydro power, wind power, concentrated solar power and solar photovoltaic, as well as time series of installed capacity of renewable technology (Eurostat, 2020c). SHARES data were available at the level of main activity production and autoproducers.

Table 3.2 Energy balance data used for calculation of key parameters per MS, year and fuel

Name	Energy balance codes
Electricity production	GEP_MAPE + GEP_MAPCHP + GEP_APE + GEP_APCHP
Heat production	GHP_MAPCHP + GHP_APCHP
Energy input	TI_EHG_MAPE_E + TI_EHG_APE_E + (TI_EHG_MAPCHP_E - GHP_MAPCHP /0.9) + (TI_EHG_APCHP_E - GHP_APCHP /0.9)

The LCI data specify the energy input of fossil fuels in terms of **mass** or **volume** (in the case of natural gas) instead of an energy unit. Energy input was therefore converted to mass or volume units through use of the Net Calorific Value (NCV). For the solid fuels, NCVs were obtained from the detailed SHARES results where possible. Otherwise, the Eurostat table nrg_bal_cv [(Eurostat, 2020a) was used or data from the International Recommendations for Energy Statistics (United Nations, 2018). Table 3.3 lists the data sources for the NCVs per fuel type.

Table 3.3 Data source for net calorific values

Label	NCV available[d]	Reference
Brown coal	By MS and year	SHARES[a]
Hard coal	By MS and year	SHARES
Peat	Generic	IRES
Oil[b]	By MS and year	SHARES
Natural gas	By MS and year	nrg_bal_cv[c]
Biomass	Generic	IRES
Biogas	Generic	IRES

Notes: ([a]) Table “Net calorific values – for other uses (all gaps filled)” for solid fuels and table “Net calorific values (all gaps filled)” for fuel oil.

([b]) Fuel oil NCV value is assumed for all oil-fired power production.

([c]) Eurostat table nrg_bal_cv was used with code NCV_AVG in kJ/m^3. Where data were not available for a certain year or MS gap filling was performed.

([d]) If data were available for only certain years for a MS the remaining years were filled with the average NCV available for the MS. If no data were available for a MS, the average of all years and MS for which data was available was used as NCV.

3.2 Emission factors for fuel combustion

Each of the fuel-combustion LCIs is adapted to account for fuel input and emissions during operation to obtain an estimate of **life cycle impacts per unit generation** that differs across years, Member States, and energy source, as described in section 2.2.2. Emissions factors for selected pollutants are specific for fuel input and sourced from the emission guidelines of the national greenhouse gas emissions inventory ([5]) (IPCC, 2006) and the air pollutant emissions inventory guidebook 2016 ([6]) (EMEP and EEA, 2016). Note that for CO_2, these are the same emissions factors as specified in annex VI of the Commission regulation 601/2012 (EU, 2012). This generic approach also implies that the model does not distinguish between specific technologies, such as emissions abatement technologies, that may have been implemented in individual power plants of Member States. Table 3.4 lists the implemented emissions factors. Note that only direct combustion emissions in the foreground are adapted, and that emission factors in all background processes remain the same.

Table 3.4 Emissions factors for selected pollutants

Pollutant	Brown coal	Hard coal	Oil	Natural gas	Biomass and peat	Biogas[a]	Unit	Reference
CO_2	1.01E+02	9.83E+01	7.74E+01	5.61E+01	1.12E+02	54.6	kg/GJ	IPCC, 2006
CH_4	1.00E-03	1.00E-03	1.00E-03	1.00E-03	3.00E-02	1.00E-03	kg/GJ	IPCC, 2006
N_2O	1.50E-03	1.50E-03	6.00E-04	1.00E-04	4.00E-03	1.00E-04	kg/GJ	IPCC, 2006
As	1.43E-05	7.10E-06	4.27E-06	1.20E-07	9.46E-06		kg/GJ	EMEP and EEA, 2016
Benzo(a)pyrene	1.30E-09	7.40E-10		5.62E-10	1.12E-06		kg/GJ	EMEP and EEA, 2016
Cd	1.80E-06	9.00E-07	1.29E-06	2.50E-10	1.76E-06		kg/GJ	EMEP and EEA, 2016
CO	8.70E-03	8.70E-03	5.00E-03	3.93E-02	9.00E-02	3.28E-01	kg/GJ	EMEP and EEA, 2016
Cr	9.10E-06	4.50E-06	2.73E-06	7.60E-10	9.03E-06		kg/GJ	EMEP and EEA, 2016
Cu	1.00E-06	7.80E-06	5.69E-06	7.60E-11	2.11E-05		kg/GJ	EMEP and EEA, 2016
HCB	6.70E-09	6.70E-09			5.00E-09		kg/GJ	EMEP and EEA, 2016
Hg	2.90E-06	1.40E-06	3.70E-07	1.00E-07	1.51E-06		kg/GJ	EMEP and EEA, 2016
Ni	9.70E-06	4.90E-06	2.73E-04	5.10E-10	1.42E-05		kg/GJ	EMEP and EEA, 2016
NMVOCs	1.40E-03	1.00E-03	8.00E-04	2.60E-03	7.31E-03	1.53E-02	kg/GJ	EMEP and EEA, 2016
NO_x	2.47E-01	2.09E-01	1.42E-01	8.90E-02	8.10E-02	2.17E-01	kg/GJ	EMEP and EEA, 2016
Pb	1.50E-05	7.30E-06	4.88E-06	1.50E-09	2.06E-05		kg/GJ	EMEP and EEA, 2016
Particulates	1.11E-02	1.11E-02	4.45E-02	1.78E-03	2.88E-01		kg/GJ	EMEP and EEA, 2016
Se	4.50E-05	2.30E-05	2.21E-06	1.12E-08	1.20E-06		kg/GJ	EMEP and EEA, 2016
SO_x	1.68E+00	8.20E-01	4.95E-01	2.81E-04	1.08E-02	1.64E-02	kg/GJ	EMEP and EEA, 2016
Zn	8.80E-06	1.90E-05	9.41E-05	1.50E-09	1.81E-04		kg/GJ	EMEP and EEA, 2016

Notes: ([a]) Emissions factors for biogas combustion were sourced from (Iordan et al., 2016) for the following pollutants: CO, NMVOCs, NO_x, and SO_x.

([5]) Chapter 2-stationary combustion, table 2.2.

([6]) Tables 3-2 to 3-7 for the Guidebook 2016 on NFR 1.A.1

3.3 Correspondences

The SHARES data, Eurostat energy balance data, and the emissions factors in the IPCC and EMEP/EEA inventory guidelines are available at different resolutions with respect to fuel type and technologies. Table 3.5 shows the correspondence between the fuel types used for this work and the energy balance and emission factor data sources. In addition, the name of the fuel type in the Ecoinvent database is listed.

Table 3.5 Correspondence between product names

Label	SIEC	IPCC	EMEP/EEA (table)	Ecoinvent fuel input
Brown coal	C0210, C0220, C0320, C0311, C0312, C0340, C0330	Lignite	brown coal (3-3)	Lignite
Hard coal	C0110, C0121, C0129	Anthracite	hard coal (3-2)	Hard coal
Oil	O4000XBIO	Residual fuel oil	Heavy Fuel Oil (3-5)	Heavy Fuel Oil
Natural gas	G3000, C0350-0370	Natural gas	Gaseous fuels (3-4)	Natural gas
Nuclear	N900H			Nuclear fuel element for PWR
Biomass	R5110-5150_W6000RI, R5160	Wood/wood waste	Biomass (3-7)	Wood chips
Biogas	R5300	Other biogas		Biogas (mixture of sources)

4 Discussion

The approach and methodology presented in the previous Chapters of this report offer an estimate of the potential life cycle impacts associated with electricity production in Europe using a bottom-up approach. Despite the effort to include a high level of resolution, this study suffers from the same issues as traditional process-based LCA studies of a single product or process, as well as some issues directly associated with the modelling approach. Here we discuss several topics influencing the direct and indirect contributions to calculating the life cycle impact indicators.

4.1 Input data

Contrary to a traditional LCA of a single product or process, in this study we assemble 16 different archetypical Life Cycle Inventories. These inventories are originally based on a single state-of-the-art electricity production process, deploying a specific set of technologies. For example, coal fired power generation is modeled using hard coal of a specific quality, combusted in a supercritical boiler with highly efficient selective catalytic reduction emissions mitigation measures in place, which subsequently is assumed to be an archetype of the coal combustion process. However, in order to make the model sensitive to differences in national and temporal variations, key parameters of this coal combustion process were changed in the calculation of life cycle emissions and impact indicators. The individual LCIs thus generated do not reflect a specific technology or combustion process any longer, but rather the more generic energy conversion of hard coal (or any other energy source) to electricity. For the combustion based generators, the use of tier I emissions factors in this conversion may not do justice to the specific combustion technologies and emissions abatement equipment installed in plants throughout Europe and may lead to an overestimation of direct emissions for certain plants. However, a time-series of detailed emissions data for key pollutants associated with the energy conversion at SIEC level is at present not publicly available, if at all.

A similar issue is at hand for the indirect impacts associated with infrastructure. While the model takes into account the utilization of each technology for every year and Member State by deriving the capacity factors, the lifetime assumptions of the individual LCIs are not changed. Thus, variations in lifetime between plants are not accounted for and may lead to variations in infrastructure related impacts, something particularly renewable generators are sensitive to. For example, extending the (expected) lifetime of an offshore wind farm from 20 to 25 years will decrease its impacts per unit generation by 20 %, all other things equal.

The construction of a life cycle inventory model is data intensive and relies heavily on the use of the background databases. Effectively, the background databases are a static depiction of the flow of goods and services, and their associated environmental emissions and resource requirements. In other words, the background LCI database describes the value chains. However, the background database is built up of a large collection of individual LCI studies collected over the past decades, with source data coming from a wide variety of studies that do not necessarily represent the production processes and situation in the European Union post 2005, even though Ecoinvent is regularly updated. The use of the EXIOBASE MRIO table as background could potentially shed more light on the value chains for a given year, but for the purposes of investigating specific production processes the resolution of the economic sectors present in EXIOBASE is often not high enough. In EXIOBASE, there are around 200 unique products, compared to thousands in Ecoinvent. It is unclear to what extent this uncertainty in the background contributes to variations in the calculation of indirect impacts.

One of the largest challenges in this exercise is to find a way to correctly represent the energy balance for each electricity generation technology, while keeping the amount of life cycle inventories manageable. This was achieved in this report by effectively parameterizing the LCI models, i.e. through adjusting key parameters is an archetypical model of the technology. However, a one-to-one correspondence between the energy input data, which is available at a high level of detail, and the life cycle inventories, does not exist. For example, the category 'hard coal' comprises three different types of coal in the Eurostat energy balances (i.e. anthracite, coking coal, and other bituminous coal) and a potential 4 different generators, the generation of electricity only or co-generation of heat and power as main activity producer or as autoproducer. While emissions factors for each of these feedstocks may be available, an extensive literature search was outside the scope of this report and default emissions factors for hard coal from readily available emission inventory guidelines were used instead. The aggregation also implies that there is no differentiation between upstream emissions associated with, for example, anthracite or coking coal.

Lastly, the scope of the LCIs included in this study does not contain the anticipated increase in transmission capacity required to ensure a stable operation of the electricity grid with increasing shares of electricity produced from intermittent and distributed renewable energy sources. While the environmental impacts of increasing grid capacity may be considerable (Jorge and Hertwich, 2014), the additional impacts per kWh electricity transmitted may be as low as 10.9 g CO_2-eq, 0.02 mg PM_{10}-eq, and 43 mg SO_2-eq (all per kWh) (Jorge and Hertwich, 2013).

4.2 Sensitivity, variability and uncertainty

The approach taken here has focused heavily on creating a diverse set of life cycle inventories by adjusting specific key parameters informed by among others energy balance statistics. As such, the calculated impact indicators vary considerably. Occasionally, this may lead to exceptionally high or low impact intensities, for example, when energy balance statistics indicate low efficiencies or underutilization of non-combustion renewable capacity. The latter may occur typically during large capacity expansion projects as installed capacity is accounted for in a Member State for a given year, but not operational for the full year, thus decreasing its capacity factor. It was chosen to not correct for these outliers as they are unlikely to perturb the aggregate results.

However, individual emission flows in the source life cycle inventories may be a cause for high impact indicators for an energy source across Member States and years. Contribution analysis was therefore performed in order to address the sensitivity of LCIs to such flows. In addition, contribution analysis provides a key tool to identify opportunities for mitigating impacts and decrease impact intensities. Contributions were calculated from three different perspectives: i) the contribution of individual unit processes in foreground or background, ii) the contribution of individual emissions to the environment and iii) the direct and indirect contributions of all processes in the value chain attributed to each foreground process. While the first two perspectives are useful from an identification point of view, the latter shows potential ways for mitigating potential impacts from a use or consumption perspective. For example, a decrease in fuel use, results in a reduction of emission all along the fuel value chain (per unit electricity generated).

4.3 Comparison of results to emissions accounts

While in principle at least the direct emissions from combustion generators could be compared to public historic emissions accounts, such as provided by the UNFCCC or E-PRTR, it is hard to compare the full LCA results to such accounts. LCA attributes emissions and impacts irrespective of time and place to a single production process, which is the opposite of most accounting schemes focused on the accounting of emissions at a specific power plant site, or for a Member State, for a given year. However, employing the life cycle and systems-based view does offer a perspective of unintended effects across a wide range of impact indicators. The life cycle benefits of renewable energy generators over traditional fossil generators have been well-documented, something also confirmed by the present study, even though some potential non-climate impacts may increase due to the infrastructure-related and land footprints of renewable technologies. As both economic and environmental accounts become more widely available at ever increasing resolutions, it is hoped that the current approach can be refined further in the future to better estimate the costs and benefits of the increasing share of renewable energy in the European electricity system.

4.4 Recommendations for the future

From a methodological perspective, it should be noted that life cycle impacts are calculated by collapsing the time dimension. In reality, the construction of, operation and decommissioning of power plants takes place over many decades and in a rapidly changing energy system impacts associated with production of (old and new) power generation capacity may vary based on power plant vintage. A power plant built with steel 30 years ago may have a very different impact footprint than one built at present with the current electricity mix. However, the construction of a European wide vintage stock model of electricity generation capacity requires significant efforts and was beyond the scope of this task.

Furthermore, an effort could be made to integrate the model, i.e. ensure that all European electricity production processes are satisfied by the foreground inventories. In its current iteration, electricity production processes are available in the background. The advantage of model integration is that also background processes contributing to environmental impacts indicators are updated with conversion efficiencies and capacity utilization (and associated emissions) available from the international energy balance statistics.

Lastly, only a limited number of impact categories and corresponding impact indicators was used in this study. The model could be improved by including more impact categories, as such covering a larger range of potential impacts. One such improvement could come from implementing all impact categories listed in the Product Environmental Footprint (PEF). The PEF in addition requires normalization and weighting of impact indicators which may aid in the interpretation and valuation of estimated gross avoided impacts.

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