Ref. Ares(2020)4515753 - 31/08/2020

XPRESS

Facilitating green
public procurement
in the energy sector

Deliverable 2.5

Deliverable 2.5

Partners

APRE | Eambiente | University of York | Element Energie | DIW Berlin | NTNU |
Ovgroup | Linnaeus University | LOBA | INSME | CIRCE | European Green Cities |
Alleanza per il Clima Italia | Climate Alliance | Slovensky zivnostensky zvaz | Eurada

info@xpress-h2020.eu
www.xpress-h2020.eu

This project has received funding from the European
Union's Horizon 2020 Research and Innovation
programme under Grant Agreement No 857831

Deliverable 2.5

Building a first LCA dataset of best practice examples

Programme	Contract Number	Duration	Start
H2020	857831	12 Months	September 2019

Deliverable Type	Report 2.5
Work Package	WP number 2
Dissemination Level	Public
Expected Date of Delivery	September, 2020
Month and Date of Delivery	September, 2020
Leader	eAmbiente
Authors	K. Saez de Bikuna, M. Vale, D. Zambrana, F. Bustos, J. Stokeld

XPRESS

Contributors

Name	Organisation
Koldo Saez de Bikuna	eAmbiente
Manfredi Vale	eAmbiente
David Zambrana	CIRCE
Jonathan Stokeld	Element energy

Peer Reviews

Name	Organisation
Paola Zerilli	University of York
Jonathan Stokeld	Element Energy
name three here	organisation 3

Revision History

Version	Date	Reviewer	Modifications
1.2	12/08/2020	J. Stokeld	modifications
1.3	28/08/2020	P. Zerilli	modifications

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

Table of contents

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

Index of tables

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

Index of figures

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

1. The D2.5 deliverable

1.1. Goal of the deliverable

The D2.5 is the fifth deliverable of WP2 and is embedded in the Task 2.4: "Data gathering from the good practice examples". This deliverable is meant to create the ground for the life-cycle datasets and LCA results that will be extended along the WP4 tasks and during the whole project. These first life-cycle datasets of "good practice examples" will form the basis for comparing the environmental performance of the real green public procurement (GPP) case studies and the specific LCA studies on selected innovative renewable energy (RE) technologies and RES technology solutions developed by European SMEs.

The first life-cycle datasets presented here are benchmarking model results of a selection of RE technologies relevant to the analysed TED database and which have been identified in many of the past GPP tenders thereof. The selected RE technologies have been applied to the context of ten European countries, which are the partner countries of the XPRESS project: Belgium (BE), Germany (DE), Denmark (DK), Spain (ES), Italy (IT), Norway (NO), Portugal (PT), Sweden (SE), Slovakia (SK) and the United Kingdom (UK). A proper contextualisation of RE technologies is fundamental for the assessment of the environmental performance of each and every particular solution – both the productivity (or energy production potential) and some environmental impacts are very context-dependent. Because the regional climates and ecosystems differ from country to country (and in many cases even within a country), the availability of different resources (e.g. water or sun) will change dramatically. This will in turn affect the productivity of RE technologies and, as a consequence, their environmental performance. Moreover, the same environmental interventions in different contexts and the release of the same pollutants to different ecosystems will have different effects. In order to take into account this geographical variability of the actual impacts, e.g. the utilization of 1 m^3 of water, the assessment has been carried out considering the key specificities of each country. Likewise, for those technologies that are not renewable *per se* but rather *potentially* – those that they rely on the electricity supplied from the net like heat pumps or electric vehicles (EV), their environmental performance will be tightly linked to the energy and technology mix of the country they are implemented in.

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

1.2. Scope of the deliverable

There are two main approaches to build a life cycle inventory when carrying out an LCA: attributional and consequential. The attributional approach, also known as retrospective LCA, aims at assessing the environmental performance of an existing technology, product or service, taking average data and often performing an allocation of material and energy inputs and process outputs (waste and emissions), according to a pre-established criterion (e.g. mass, exergy, etc.), in order to calculate the burden of the assessed product or service. This approach is followed to calculate the ecological footprints (environmental, carbon, water) of products and for eco-labelling and environmental product declarations like the international EPD system or the European Product Environmental Footprint (PEF) initiative.

The consequential approach instead, called prospective LCA by some, looks into the environmental consequences of a decision like a possible policy change with long-term implications in the future. The consequential approach tries to avoid allocation by instead considering system expansion and typically relies on scenario analysis for building plausible, although hypothetical, alternatives to the main product system analysed or to consider different baseline (reference system) options. A consequential model takes (some) market mechanisms into account to identify the marginal technologies and products that can effectively react to a change in demand (unconstrained markets) and which would therefore be affected by the decision concerned. Consequential LCA thus applies market logic (and its inherent values) to model long-term changes of decisions in order to predict the environmental implications that would follow at different scales (depending on the type of the decision, e.g. introducing a new eco-design material in a niche market product or a new European-level policy banning single-use plastic products).

For this specific deliverable, it has been decided to take an ***attributional modelling approach*** to look at the existing good practice RE technology examples related to past GPP tenders found in the TED database, so that a benchmark can be drawn to compare existing or “old” RE technologies (installed and functioning between 2000 and 2015) with more recent, prospective and innovative RE technology solutions developed by European SMEs (from 2010-2015 onward). For this second phase, we will look more into the future or not yet upscaled RE solutions, hence a consequential LCA approach will be adopted. The extended LCA dataset will be based on the

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

current attributional LCA dataset and the extension will be carried out with a consequential LCA approach in the upcoming deliverable D2.6.

During the definition of the life cycle sustainability assessment (LCSA) framework for this project, done in D4.1, a System and a Product approach for the modelling was also mentioned. In this distinction, the "Product Approach" would provide information about the specific RE technologies and their manufacturing and maintenance (raw) data, collected as *unit processes* (without allocation or partitioning). This primary data shall be collected directly from producers, vendors, assemblers and maintenance SMEs or public authorities (PA). The partners will be identified through the TED platform (WP2) and workshops and will be involved in the LCA case studies so as to obtain the information for the Life Cycle Inventory through surveys and/or interviews. In the System Approach, the geographical setting of the data will result in a technologies suitability assessment, according to the specific characteristics of each country. The LCA dataset built at this stage will serve as a reference basis for comparing the LCA results and environmental performance of the different RE technologies assessed through literature data and available databases with the state-of-the-art RE solutions and first-hand, updated data.

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

2. LCA model characteristics

2.1. Introduction

The present LCA dataset of good practice examples of RE technologies is built from a set of LCA models developed with the software SimaPro 9.1 and are primarily based on the Ecoinvent 3.6 database, since the European open LCA database (ELCD) was found to be very limited in scope (only a few processes covering two RE technologies: hydropower and a wind turbine) and not supported since 2018. The LCA models represent some of the most frequent GPP tenders identified during the extensive TED database search.

In the following subchapters, the technical details and the overall LCA model characteristics for the framing of the study are presented.

2.1.1. System boundaries

The life cycle stages included in the system boundaries of the models go from the raw material extraction to the installation and use phase. This means that in the model we considered the environmental loads from primary materials extraction, processing and the manufacturing of the parts and different components of the assessed RE technologies. The activities of installation, operation, and maintenance over the lifetime of the RE technologies are also included. The only stages that have been excluded are those of dismantling and decommissioning, namely the *End of Life* (EoL) activities, which usually comprise of sorting, transport, recycling and incineration for the non-recyclable parts and materials such as fibreglass from wind turbine blades.

For the particular case of RE technologies, the EoL stages do not usually represent an especially concerning issue from an environmental point of view. Moreover, their inclusion requires additional assumptions about the recyclability and substitutability, waste scenario modelling and sensitivity analysis to cover the uncertainty related to the unknown fate of many components. For the case of wind power for instance, 20% of the materials are not recyclable (e.g. the mentioned fiberglass blades) and the dismantling phase represents only around 3% of the total energy requirements over the entire life cycle (Guezuraga et al., 2012). Including EoL phases, as recycling potential of key materials like steel or copper together with their substitution

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

potential, could reduce the carbon footprint significantly (Bonou et al., 2016). Out attributional LCA approach however, uses a **cutoff** criterion for the system modelling of the life cycle inventory, which is more commonly known as ***the polluter pays principle***. With this particular attributional approach, potential substitution credits (accounted as negative environmental impacts) from avoided production are not considered, so that the presented results are more conservative (and transparent).

The system boundaries of the presented LCA datasets are thus a ***Cradle-to-Gate*** type with the Use/Production phase.

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

2.1.2. Impact categories, Indicators and LCIA methods:

In the first deliverable of WP4 (D4.1 *Construction of a framework for the full sustainability assessment of RE technologies in GPP*), the chosen life cycle impact assessment method for the characterisation of the resource consumption and emissions inventory, was the last **European Environmental Footprint** (**EF**) **method** v3 released in 2019 and which follows up the ***International reference Life Cycle Data*** system (**ILCD**) guidelines and previous methodology (ILCD 2011, v1). This compendium of environmental impact assessment methods gathers the last developments and updates of characterisation factors (CF) for several impact categories. This methodology also contains the best available science and consensus-based models such as the AWARE and USEtox methods for water scarcity and toxicity impacts, respectively.

This methodology has been supported by the European Commission since the beginning of the Product Environmental Footprint (PEF) initiative back in 2013, when it released a communication to the European Parliament (European Commission, 2013): *Building the single market for green products by facilitating better information on the environmental performance of products and organizations*. Consolidated models for measuring and communicating the environmental performance (the EF) of products and organisations have been pursued and gathered in the ILCD and EF methodologies, to be used together with specific PEF category rules for comparable LCA studies and to achieve harmonized LCA results.

This methodology adopts the format of the ILCD nomenclature and it has adapted the recommended models to meet the requirements of the PEF guidelines and the ILCD system.

Compared to the ILCD scheme, some models have been completely changed, others have simply been improved or not modified at all. The EF methodology takes a “problem oriented approach” instead of “damage oriented” ones like the ReCiPe or IMPACT 2002+, whereby recommending only midpoint level impact models. The reason for this is that extending the LCA to the Endpoint level (where all midpoint-level impact categories are connected to three end-point damage areas via cause-effect links with different -but considerable- levels of uncertainty), would introduce an additional degree of uncertainty in an already broad, complex and uncertain system. Since the proposed LCSA framework will include a further aggregation step to evaluate economic, energetic and social indicators to rank the best RES Technology options, it was decided in the D4.1 to stop at the midpoint-level assessment.

In the following pages a summary the impact categories and indicators (together with a brief explanation for each) is presented in Table 1.

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

Table 1. Summary table of the midpoint-level impact categories and the respective environmental indicators, models and short explanation.

Impact Category	Model	Indicator name and brief explanation
Climate change	IPCC 2013 (Myhre et al. 2013) + adaptations	*Global Warming Potential, 100 years (GWP$_{100}$)* This indicator represents the warming potential that greenhouse gas (GHG) emissions have on the Earth's surface temperature over time. Due to the scale (global), the irreversibility and permanent nature of this impact, it is considered an overarching environmental indicator. In fact, this impact is a further multiplier and precursor of additional local and regional impacts (ocean acidification, freshwater depletion from glacier loss, sea level rise, etc.), hence its importance.
Ozone depletion	World Metereological Organisation (WMO), 2014 + integrations	*Ozone Depletion Potential (ODP)* It shows the degradation potential of the stratospheric ozone layer due to emissions of ozone-damaging substances, such as chlorine-containing gases and long-lasting bromine (e.g. CFC, HCFC, halons). The ozone

Impact Category	Model	Indicator name and brief explanation
		layer filters carcinogenic UV radiation from the sun.
Human and Eco Toxicity	USEtox (Rosenbaum et al. 2008)	*Comparative Toxic Unit for Human Health (CTUh) and for Ecosystems (CTUe)* Negative effects on human health (CTUh) caused by the intake of toxic substances by air inhalation, ingestion of food/water, skin penetration. They are subdivided into carcinogenic and non-carcinogenic. Ecotoxicity impacts consider the damage potential of toxic substance releases to water bodies which affect individual species and changes the structure and function of ecosystems.
Particulate matter	UNEP 2016 (Fantke et al., 2016)	*Disease incidences* Adverse effects on health caused by inorganic substances inhaled by humans, from particulate matter (PM) emissions and its precursors (NOx , SOx , NH3).
Ionising radiation, human health	Frischknecht et al. 2000	*Ionizing Radiation Potentials (IRP)* Negative effects on human health caused by radioactive emissions.
Photochemical ozone formation	ReCiPe2008 (Van Zelm et al. 2008)	*Photochemical ozone creation potential (POCP)* Ground-level ozone formation in the troposphere caused by photochemical oxidation of volatile organic compounds (VOCs) and carbon monoxide (CO) in the presence of nitrogen oxides (NOx) and sunlight. High concentrations of tropospheric ozone at ground level are harmful to vegetation and humans' respiratory system.
Acidification	Seppala et al. 2006, Posch et al. 2008	*Accumulated Exceedance (AE)* Air emissions of NOx, NH_3 and SOx deposit and result in the release of hydrogen H+ ions when the substances are mineralized. Protons promote acidification of soils and water when released into surfaces where buffer capacity is low, resulting in forest deterioration and lake

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

Impact Category	Model	Indicator name and brief explanation
		acidification.
Eutrophication	EUTREND model in ReCiPe2008 (Struijs et al. 2009)	*P and N equivalents* The nutrients (mainly nitrogen and phosphorus) of sewage and fertilized farmland accelerate vegetation growth (phytoplankton blooms). This in turn changes the turbidity of water, worsening the conditions of predatory species. The algal bloom and subsequent degradation of the new organic matter consumes oxygen (hypoxic conditions), eventually causing fish death and abrupt ecosystem changes. The impacts are divided into Freshwater and Marine Eutrophication.
Land use	LANCA model (Bos et al. 2016)	*Soil Quality Index* Land use and land use changes from agriculture, road construction, etc. affect the soil in many ways. This model takes into account different indicators that cover different soil properties like groundwater replenishment or water filtration. These indicators are grouped and re-scaled to obtain a dimensionless index which is spatially differentiated.
Water Scarcity	Available WAter REmaining (AWARE) method, 2016 + Boulay et al. 2018	*Scarcity-adjusted water use* The model characterizes the water depletion according to scarcity-adjusted mass of remaining water available for aquatic ecosystems
Resource depletion – minerals and metals	Van Oers et al. 2012 (CFs from CML v4.8, 2016)	*Abiotic depletion (ADP), ultimate reserves* It represents the non-renewable resource depletion potential from the extraction, use and disposal (loss) of different substances and energy carriers. It is divided into Minerals and Metals (ultimate reserves) and Fossil Fuel reserves. The last indicator also represents in a way the *Cumulative Energy Demand*, since it is measured in MJ of fossil energy consumed or embodied.

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

2.2. Relevant databases

2.1.1. Tenders Electronics Daily (TED) Database

TED (Tenders Electronic Daily) is the online version of the 'Supplement to the Official Journal' of the EU, dedicated to European public procurement. TED publishes 746 thousand procurement award notices a year, including 235 thousand calls for tenders which are worth approximately €545 billion[1]. eAmbiente performed an analysis on the TED database focusing on tenders, providers of services and technologies related with renewable energy production.

Criteria guiding the analysis were:

- Coherence with the main goals of XPRESS, being namely low-impact renewable energy provision (services or technologies/plants/products);
- Providers being SMEs;
- Innovation potential, either concerning the technology/service or with regard to the innovativeness of the tender procedure or design (participatory methods, stakeholder engagement etc.).

Available tenders in the range 2010-2018 issued from the countries participating in XPRESS (BE, DE, DK, ES, IT, NO, PT, SE, SK, UK) were ranked according to the above criteria thus resulting in a short list of potential case studies of particular interest. The presented GPP cases are not exhaustive but merely illustrative. The XPRESS team is currently in the process of contacting and interviewing several stakeholders from the public and private sphere (SMEs), in order to have a mutually beneficial collaboration during the project. In **Table 2** we present a selection of these potential case studies, some of which will be analysed in detail for a full LCA in the upcoming deliverables of XPRESS.

Table 2. Summary of highly interesting GPP tenders identified in the TED database screening

Country	City	Technology	Project description
Belgium	Ghent	Solar energy	Supply of green electricity with citizen participation: participatory financing according to LCA principles.

[1] https://ted.europa.eu/udl?uri=TED:NOTICE:94533-2018:TEXT:EN:HTML

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

Germany	Lemgo	Wind energy	Planning, delivery, construction, commissioning and maintenance of wind energy plants including trial operation for 15-25 years.
Germany	Ludwigsburg	Solar energy	Planning, construction and commissioning services for an open-space solar thermal system with a technical building.
Germany	Weilheim	Heat Pumps	Erection of a ground-coupled heat pump system for cooling and heating a training and administration building.
Germany	Vaterstetten	Sustainable buildings	New construction of a primary and middle school with swimming pool and sports hall, PV system 99 kWp + complete storage system; E-car charging station for 2 vehicles.
Germany	Rosenheim	Biomass plants	Building+technical equipment for a wood chip power plant, bunker and a warehouse; local heating network with earthworks; Integration of existing boilers as peak load boilers.
Denmark	Sæby	Solar heating system	30,000 m2 solar heating system as a supplement to existing heat production. The solar heating system includes solar heating panels, heat exchanger building, dry cooling system and supply line.
Denmark	Aalborg	Hydrogen production	Prototype electrolysis plant for the production of hydrogen in a three-year pilot scheme with 3 hydrogen buses in North Jutland.
Sweden	Karlskrona	Car & Bike pooling	Open electric vehicle pool with electric cars and bicycles, portal service and collection of relevant data enabling follow-up.
Sweden	Uppsala	Solar & wind energy	Power supply facility: complete production unit with wind power and solar cells for off-grid power supply with reserve power.
United Kingdom	Nottingham	Solar energy	Solar PV Design, Supply & Installation Works
United Kingdom	Inverness	Multiple technologies	Management, operation and maintenance of renewable heat and associated services including Biomass, Gas Combined Heat and Power (GCHP) Systems, Ground Source Heat Pumps (GSHP) and Air Source Heat Pumps (ASHP).

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

2.2.1. Generic and Proxy process data

For this phase of LCA screening, the Ecoinvent version 3 (v3.6) has been used for the modelling of the life cycle inventory and as a reference database for key material processes (e.g. concrete production) and generic production processes like wafer production for PV cells or the electricity supply at the country level. In this regard, the technology mix, energy source shares for every country's electricity sector has been updated and substantially extended (Treyer & Bauer, 2016). Methods involved extraction of data and analysis from several publicly accessible databases and statistics, as well as from LCA literature. Depending on the power generation technology, either plant-specific or region-specific average data have been used for creating the new power generation inventories representing specific geographies.

2.2.2. Resource availability databases

For the availability of annual solar irradiation potential per country and site, the European PVGIS tool[2] has been identified as the most convenient for the project.

For the availability of annual wind resources per country and site, the Global Wind Atlas[3] database has been selected for the wind power case studies.

2.2.1. ILCD system database

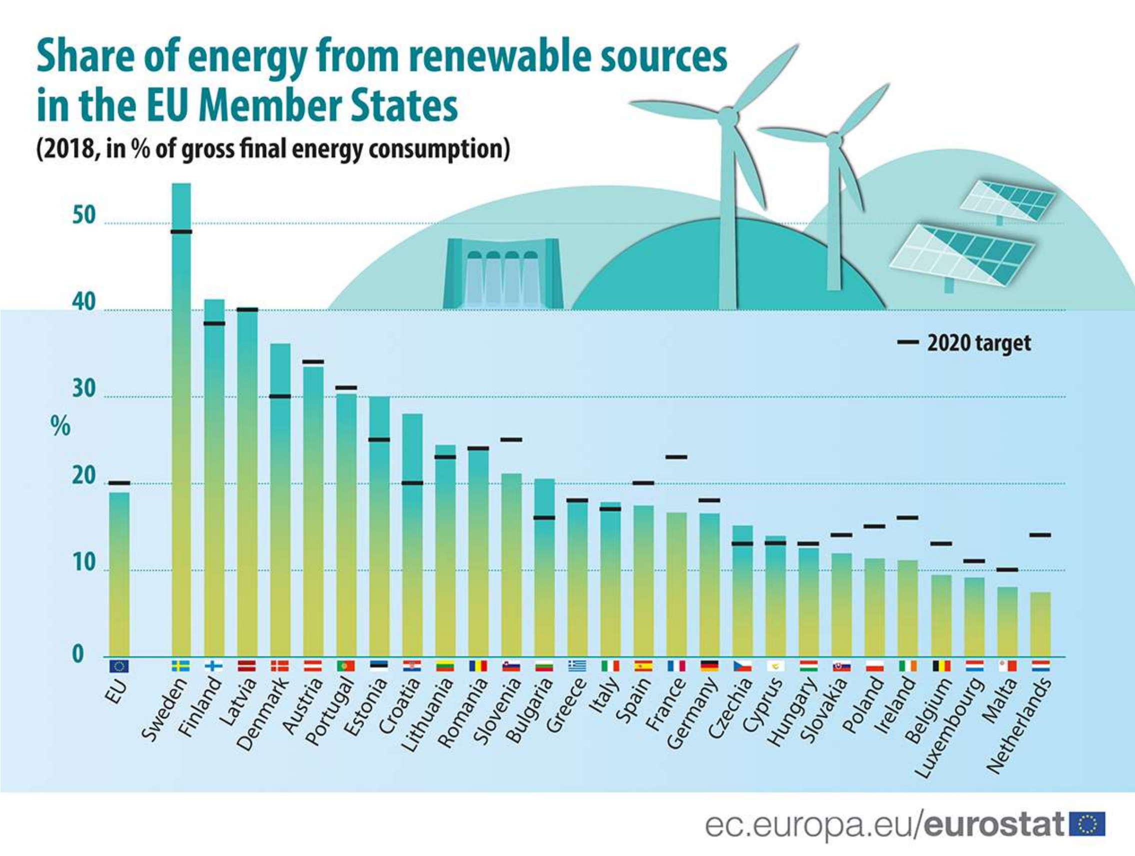
The Characterization Factors (CF) for the impact assessment phase have been taken from the ILCD system database, included in the last EF method (v3) and which consists of XML files in ILCD format to allow electronic import into the LCA software. Each LCIA method is implemented as separate datasets that contain all the descriptive documentation of the metadata and the characterization factors. The imported database also contains datasets of all elementary flows, flow properties and unit groups, as well as source and contact data sets (e.g. data sources and reference publications, as well as authors, developers of data sets data and so on). In addition to XML files in ILCD format, the datasets are also available in an MS Excel file, containing the list of flows, the list of models for the EF scheme and the CF available for each model.

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

2 https://ec.europa.eu/jrc/en/pvgis
3 https://globalwindatlas.info/

2.3. Selected RE technologies

The share of RES in the total gross electricity consumption in the EU reached a 32% in 2018 (Eurostat, 2020). Wind and hydro power each contributed about one third (36% and 33%, respectively) of the total RE share, followed by solar power (12%) and solid biofuels (10%).



2.3.1. Hydropower

Water and windmills are perhaps the oldest forms of RE technology developments of human societies, used to grind cereals to produce flour, to pump and derive water through irrigation channels or to deliver free mechanical work in the first industries of the 19th century. Massively developed during the 20th century, the installed capacity of large hydropower sources can be considered to be already exploited to its maximum potential in Europe. The remaining two technology alternatives are thus small-scale dams (0.1 - 10 MW) and run-of-river hydropower.

An assessment of small hydropower potential in Europe was done in 2000 within the BlueAGE Project (Blue Energy for A Green Europe), a “Strategic study for the development of

Small Hydro Power in the European Union" carried out under the Fourth Framework Programme. According to this study the remaining potential from small hydropower could be around 2 700 MW of installed new capacity and 11.5 TWh of electricity production annually, while the total production from this RES in the EU could lay at 51.5 TWh with an installed capacity of 12 850 MW. The study also pointed that, provided the economic incentives for producers are improved and the environmental constraints from the Water Framework Directive (WFD) of 2000 could decrease, the total contribution from small hydropower in the EU 15 member countries could reach 60 TWh at 2020 – 2030.

Both the *Water Framework Directive* (WFD) and *the RES-electricity Directive* have some impacts on the further development of Small Hydropower and, at a first glance, there might be a risk of conflict between the implementation of these different policies. While the WFD aims at a "good ecological status" (GES) of all water bodies (European Commission, 2000), the RE Directive sets clear targets on the RE share of the gross energy consumption of member states (European Commission, 2009).

The WFD is an environmental directive focusing on water quality. The WFD implies that any decrease of ecological quality is strictly forbidden and puts a strong emphasis on the hydro-morphological conditions, as they support the type-specific aquatic communities that constitute good ecological status. The past developments of hydropower generation, navigation infrastructures and activities, and flood defence facilities have often required major hydro-morphological changes. However, whilst impacting on aquatic ecosystems, such activities can also deliver important environmental benefits (e.g. reducing the impacts of climate change) or socio-economic benefits (human safety, employments). In principle, the use of water to gain energy is not ruled out by the WFD. However, depending on the strictness of its interpretation, the small hydropower potential can be affected by the WFD because this RE technology unavoidably brings important hydromorphological alterations to water bodies. The typical interventions associated with hydropower include: impoundment and diversion of the water courses, sediment accumulation, impact on water balance and water levels due to storage effects, interruption of biological continuity (impeding upstream and downstream fish migration). Many of these impacts can be mitigated by different measures, but some alterations are so significant that they don't allow the water body to reach a good ecological status.

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

As the *BluAGE project* points out, "the crucial question is how to reach a balance and equilibrated solution between the characteristics of the plant and the ecological quality in the most economically and technologically feasible way". In fact, these delicate compromise solutions and trade-offs are always at the core of sustainability decision-making. In practice, the last WFD restricts all the new small hydropower capacity installations since 2000 to those sites with previous ecological deficiencies (flood control, river regulation etc.). In the report, commissioned by the association of small hydropower producers, it was highlighted that a "strict implementation of the WFD will therefore cause a remarkable reduction of SHP production (…) higher investment and operational costs [would] reduce profitability of SHP (…) [leading to] the shutdown of small sites and to the slowdown in the development of new plants". As a corollary, they called for financial compensation schemes at a European level to lessen "the disproportionate economic burden that in many cases the fulfilment of such [ecological quality] requirements implies for the SHP", as well as a more clear definition of vague terms from the WFD such as *Good Ecological Status* or *Heavily Modified Water Body*, which could be interpreted in many ways, thus leaving too much room for legislative uncertainty and making difficult long-term planning for investments.

Hydropower is nowadays a fundamental RES in countries like Norway, Sweden and Austria, which meet most of their energy needs, e.g. around 77% of the electricity consumed in Austria. Due to the barriers mentioned above, the share of electricity generated from hydropower has remained quite similar for the last ten years (Eurostat, 2020), which is around 11% of the total RE primary production in the EU-28 (normalised values to last 15 years to account for meteorological variations), but its share in the total installed capacity has dropped from 20% in 2000 to 15% in 2017.

Given the conflicts between these European Directives, and due to the multiple impacts that micro hydropower dams can cause in the biodiversity of small streams and water basins (Premalatha et al., 2014), the present sustainability assessment through LCA will focus on run-of-river hydropower technology, which are hydropower plants without important reservoirs or dams.

Depending on the net head of the power plant, high-pressure, medium-pressure and low-pressure systems can be distinguished. To some extent, high-pressure as well as medium-

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

pressure run-of-river systems can be considered as reservoir power stations, e.g. as unit in plant groups that are dominated by storage power plants, but also include alpine run power stations. The efficiency losses in turbines depend on the turbine type (Kaplan, Francis, Pelton, etc.), the turbine output and on the ratio between turbined water amount and the rated water amount.

2.3.2. Wind power

Wind power is one of the RE technology sectors that has experienced a sharp increase in installed capacity and its contribution share to the national electricity grids in Europe has grown considerably in the last two decades. It is now the second largest contributor to the RE mix in EU-28, representing around 14% the of the total primary production and 37% of the total RE electricity production (see Figure 1, Eurostat 2019[4]).

Wind is a clean, free and abundant energy source that is used to generate electricity, as wind turbines capture the kinetic energy created by airflows to power a generator supplying an electric current. Several wind turbines are typically configured into windfarms that can cover several square kilometres of land or sea to harness both onshore and offshore wind. Continued improvements in manufacturing and turbine design, as well as improved capacity factors, have driven down the costs of wind power and confirmed its position as a key driver of the clean energy transition.

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

[4] Eurostat (2019) Energy, transport and environment statistical books, 2019 edition

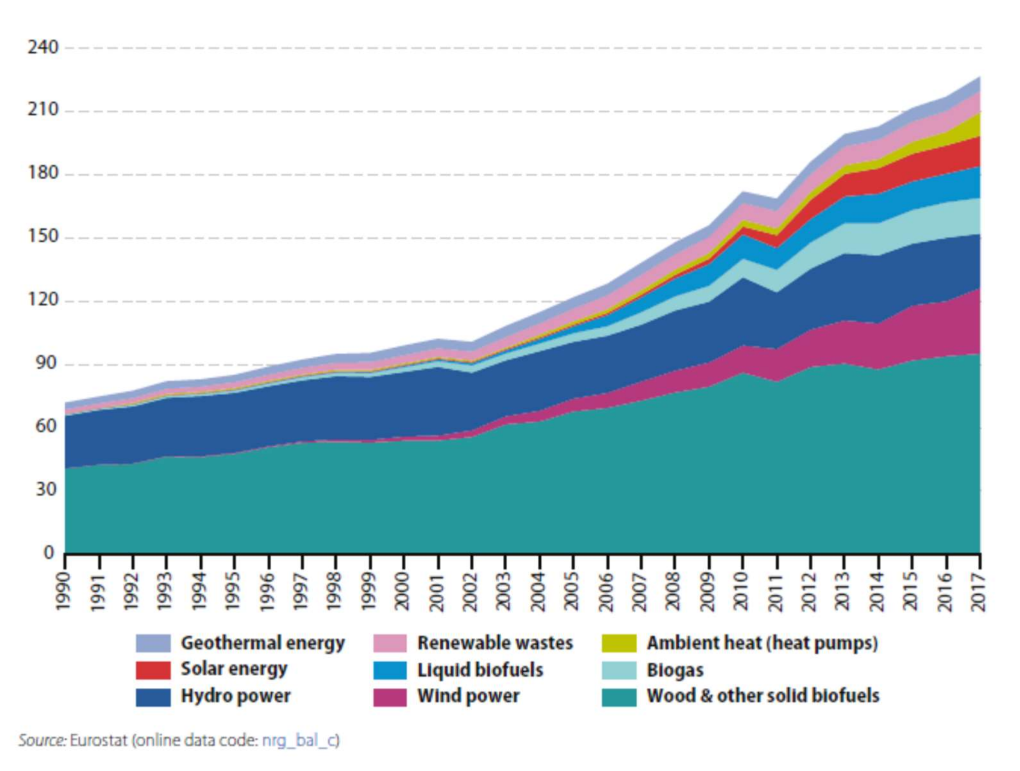


Figure 1 - Primary production of energy from renewable sources, EU-28, 1990-2017

In addition, the wind sector is a significant contributor to the European economy in terms of boosting growth and creating long-term sustainable jobs. The sector provided 356,700 full time jobs in the EU in 2017, out of the estimated 1.45 million people working in the renewables sector as a whole.

The European Commission estimates between 240 and 450 GW of offshore wind power is needed by 2050 to keep the global temperature rise to below 1.5°C. Electricity will represent at least 50% of the total energy mix in 2050 and 30% of the future electricity demand will be supplied by offshore wind. The EU is committed to drive offshore wind development and explore the potential of offshore wind in Europe's seas and along its coasts while respecting the ecological limits of natural resources and the interests of other sea users. In 2020, a new strategy on offshore renewable energy will be published as part of the European Green Deal.

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

The XPRESS project, however, focuses on onshore wind power as the projects in which Public Administrations are involved are more aimed at this kind of RES. According to The Wind Power Database 2014, around 3% of the capacity is installed offshore. Solar panels and onshore wind turbines are now a common sight across the EU, which in large part is due to increased market activity. The cost of solar power production has for instance decreased by 75% between 2009 and 2018, and in 2014, onshore wind became cheaper than coal, gas and nuclear.

2.3.3. Solar power

The growth in electricity generated from renewable energy sources during the period 2007 to 2017 largely reflects an expansion in three renewable energy sources across the EU, principally wind power, but also solar power and solid biofuels (including renewable wastes).

The growth in electricity from solar power has been dramatic and one of the sharpest of all RES, rising from 0.7% of all electricity generated in EU-28 in 2008 to 12.3% in 2017 (Eurostat, 2020). As a result, the quantity of electricity generated from solar in the EU-28 was 31.6 times as high in 2017 as in 2007, rising from just 3.8 TWh in 2007 to overtake geothermal energy in 2008, reaching a level of 119.5 TWh in 2017.

After the temporary silicon shortage between 2004 and 2008, silicon prices fell dramatically, and so did the cost of wafer-based silicon solar cells. In 2017, their market share was over 95 % and they continue to be the main technology. Commercial module efficiencies range widely from 12% to 22%, with monocrystalline modules from 16% to 22% and polycrystalline modules from 12% to 18%. Single or mono-crystalline photovoltaic (PV) panels are more expensive to manufacture and their application is also more marginal, e.g. in stand-alone, off-grid modules and in any application where efficiency is an important parameter for the fulfilment of the technical requirements. For most applications, multi or poly-crystalline PV panels are the norm, and this is hence the RE technology type that has been modelled.

In the utility PV power plant sector, the fastest growing segment is PV systems with tracking systems. It is expected that the market share of utility scale PV plants with tracking will

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

rise from approximately 20% in 2016 to over 40% in 2020. The tracking systems are relevant only for the PV installations that are mounted on the ground.

Regarding other solar power technologies, there are also thin-film PV cells, which are silicon-based and use either amorphous silicon or an amorphous/microcrystalline silicon structure. Their use has declined steeply in the last 5 years due to the low efficiencies, still at the bottom end of the scale. Only a few companies use Cu(In,Ga)(Se,S)2 or CdTe (cadmium telluride) as absorber material for their thin-film solar modules. Hence, these marginal solar power technologies have not been considered here.

One last solar power RES, which is not based on the photovoltaic phenomenon of Si-cells, is concentrated solar. This family of technologies use the thermal energy from the sun to heat up a fluid through different settings of mirrors. The fluid follows then a Rankine cycle in a closed loop, producing power after its expansion in the turbine. Despite of their demonstrated feasibility, these technologies are struggling to continue the reduction of costs to become competitive and the number of companies active in the field has declined sharply over the last years. Within CPV, there is a differentiation according to concentration factors[5] and whether the system uses disk mirrors or trough mirrors. The economic viability of this RE technology in the future is a possibility, thus it will be analysed in the LCA dataset extension of prospective RE technologies.

2.3.3.1. Rooftop PV installations

Rooftop solar PV systems can make a significant contribution to Europe's energy transition. Realising this potential raises challenges at policy and electricity system planning level. According to a recent study by Bòdis et al (2019), rooftops in EU countries could potentially produce 680 TWh of solar electricity annually (representing 24.4% of current electricity consumption), two thirds of which at a lower cost than current residential tariffs. Country-aggregated results illustrate existing barriers for cost-effective rooftop systems in countries with low electricity prices and high investment interest rates. Policies at country- and regional-level to exploit this potential can bring benefits a) for employment in the manufacturing, installation and

[5] High concentration > 300 suns, medium concentration 5 < x < 300 suns, low concentration < 5 suns.

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

operational sectors, and b) to stimulate greater involvement of citizens in achieving the EU's transition to a low-carbon energy system.

2.3.3.2. On ground PV plants

As recalled above, the increasing penetration of solar PV technology has been facilitated by incentives and public policy support that are being offered in various jurisdictions. On ground PV plants tend to have higher installed capacities (since the area is less of a constraint) and are more and more frequently equipped with sun-tracking systems. The choice between rooftop, building integrated and on ground PV installation options has been typically driven by economic competitiveness and thus lower costs per kWh produced. The single criterion of price has been questioned and challenged long ago, starting with the first studies on market failure to include environmental externalities. The pure economic cost indicator, translated into a price, typically ignores complicated trade-offs between society and environment. In this case, on ground PV plants may show considerable drawbacks from indirect land use impacts if such RE technology is actually installed on fertile agricultural area. One study developed a framework to highlight and quantify such trade-offs between life cycle costs, land use footprints and consequent land use impacts across various options of implementing PV systems (Lakhani et al., 2014), highlighting the potential impact of on ground PV systems and their higher environmental footprint with respect to roof-top or building-integrated PV systems.

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

2.3.4. Electric Vehicles

The transport sector alone is one of the main drivers of GHG emissions and therefore, Climate Change (Pachauri et al., 2014). It is the first sector in the EU-28 by final energy consumption (30.8% in 2017), in front of Households (27.2%) and Industry (24.6%) (Eurostat, 2019). The EU agreed in the RE Directive (European Commission, 2009) to set a common target of 10% for the share of renewable energy (including liquid biofuels, hydrogen, biomethane, ‘green’ electricity, etc.) in the transport sector by 2020. The average share of energy from renewable sources in transport increased from 1.4 % in 2004 to 7.6 % in 2017 (Table 3). Among the EU Member States the relative share of renewable energy in transport fuel consumption ranged from 38.6 % in Sweden, 18.8 % in Finland and 9.7 % in Austria down to less than 2.0 % in Croatia, Greece and Estonia.

Table 3 - Renewable energy sources in transport, in selected years, 2004-2017

	2004	2006	2008	2010	2012	2014	2016	2017
EU-28	1.4	2.4	3.9	5.2	5.3	6.1	7.2	7.6
Belgium	0.5	0.6	0.6	4.7	4.8	5.8	6.0	6.6
Bulgaria	0.9	1.0	0.9	1.4	0.6	5.7	7.2	7.2
Czechia	1.6	1.2	2.7	5.1	6.1	6.9	6.4	6.6
Denmark	0.4	0.5	0.5	1.1	6.4	6.7	6.8	6.8
Germany	2.2	6.8	6.4	6.4	7.4	6.9	7.0	7.0
Estonia	0.2	0.2	0.2	0.4	0.4	0.4	0.4	0.4
Ireland	0.0	0.1	1.3	2.5	4.9	5.3	5.2	7.4
Greece	0.1	0.7	1.1	1.9	0.9	1.3	1.6	1.8
Spain	1.0	0.8	2.2	5.0	0.9	1.1	5.3	5.9
France	1.5	2.3	6.2	6.5	7.4	8.2	8.7	9.1
Croatia	1.0	1.0	1.1	1.1	1.1	4.3	1.3	1.2
Italy	1.2	1.0	2.6	4.7	6.1	5.0	7.4	6.5
Cyprus	0.0	0.0	1.9	2.0	0.0	2.7	2.7	2.6
Latvia	2.1	2.2	1.7	4.0	4.0	4.1	2.8	2.5
Lithuania	0.4	1.9	4.3	3.8	4.9	4.3	3.6	3.7
Luxembourg	0.1	0.2	2.2	2.1	2.8	5.5	5.9	6.4
Hungary	0.9	1.1	5.1	6.1	5.9	6.9	7.6	6.8
Malta	0.0	0.0	0.0	0.0	3.2	4.6	5.5	6.9
Netherlands	0.5	0.8	2.9	3.3	5.2	6.5	4.9	5.9
Austria	4.5	7.5	9.5	10.7	10.0	11.0	10.6	9.7
Poland	1.4	1.6	3.5	6.6	6.5	6.2	3.9	4.2
Portugal	0.4	1.6	2.5	5.5	0.8	3.7	7.7	7.9
Romania	1.6	1.4	3.5	3.4	4.9	4.7	6.2	6.6
Slovenia	0.9	1.1	1.8	3.1	3.3	2.9	1.6	2.7
Slovakia	1.5	3.5	4.3	5.3	5.4	7.6	7.7	7.0
Finland	1.0	1.0	2.9	4.4	1.1	24.7	9.0	18.8
Sweden	6.3	7.1	8.3	9.2	15.2	21.9	33.8	38.6
United Kingdom	0.3	0.7	2.3	3.3	1.6	1.9	5.0	5.1

In 2017 there were 262 million cars registered in the EU Member States. Around 2 million (0.8 %) of these were classified as either electric cars or hybrid electric cars that can be driven in combination with a petrol or a diesel engine. There has been a steady increase in the number of electric and hybrid electric cars registered across the EU in recent years. In particular, the number of hybrid electric-petrol cars in 2017 (1.5 million) was almost seven times the number recorded in 2013 (0.2 million). This trend is an indicator of the continuous electrification efforts of the transport sector, which is the main fossil fuel and energy consumption sector and one of the main airborne pollutant (like particle matter (PM) and NOx emissions which are cause of multiple diseases and premature death to humans) emitters in highly populated areas. Electric vehicles (EVs), if charged with electricity from a grid with high RE shares, are therefore a potential solution for the damaging airborne pollution in cities and the fossil fuel dependency of the EU (liquid fossil fuels are difficult to be substituted by biofuels in a sustainable way at the required scale).

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

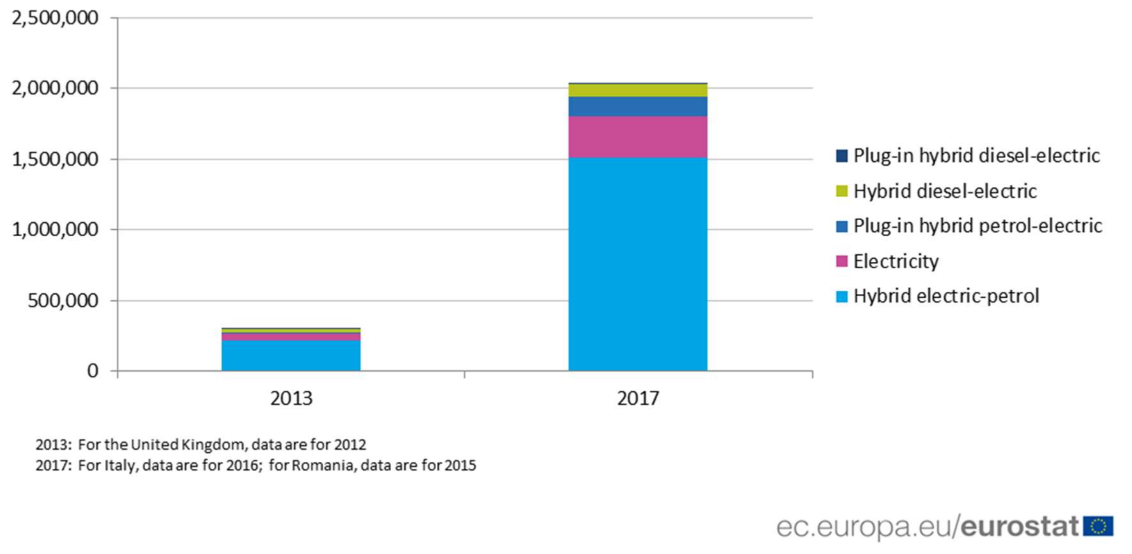


Figure 2 - Number of electric and hybrid cars registered in the Eu, 2013-2017

Since 2010, the number of EV models offered, the size segment coverage, the number of registrations, the electric vehicle market share and available recharging infrastructure have increased significantly, albeit still small to be characterised as full-scale commercialisation[6]. Further research and development efforts are needed while the European political trajectory should be adjusted according to the needs introduced by current technological trends, towards a sustainable and economically viable future.

There are currently several tenders on the TED Portal targeted at EVs, (e.g. small electric cars, small long-range electric cars, chargeable hybrid vehicles with 4-wheel drive, etc.). Also, on the mass transport side, the demand for EV is increasing, concerning e.g. electric buses but also the delivery of depot charging for such means of transportation. Many municipalities aim at testing and demonstrating the benefits of such technologies. The present LCA screening will thus focus on two EV types identified in the TED database: e-car and e-bus.

Some public or private-public partnerships are also pushing on alternative models of mobility such as car sharing, car-pooling etc. The IT sector is cooperating in this direction by

[6] https://publications.jrc.ec.europa.eu/repository/bitstream/JRC112745/jrc112745_kjna29401enn.pdf

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

developing mobile applications supporting such trends on the organisational and management sides.

2.3.5. Heat pumps

Heat pumps can be a very efficient way to heat spaces at a low environmental cost. However, heat pumps are electrically powered and so their ultimate environmental performance will depend on how the electricity is supplied. Depending on the configuration of the grid (RE share, technology mix, etc.), a massive shift of traditional heating systems to heat pumps may be challenging or, in the worst case, an extra burden to the electric system, since they would increase the overall electricity demand. In the best case scenario, they can be part of the future RE solution, if integrated in a smart-grid where the renewable electricity supply technologies can predict their production peaks and valleys and communicate them to the system, so that electricity demanding devices like heat pumps have their demand turned up (e.g. when cheap and abundant wind power is supplied into the grid) or down (e.g. when the supply is more constrained and the rest of the demand is peaking) accordingly.

The most efficient systems make use of the soil's geothermal heat to warm up the air, which is circulated through a piping system that is drilled down to 80-100 meters below the surface. These are the borehole heat pumps. Air-water heat pumps on the other hand use ambient air as heat source. External ambient air is the most diffuse but the worst from a thermodynamic point of view, as the buildings' heating loads generally increase as the air temperature decreases.

In 2017 ambient heat (captured by heat pumps[7]) accounted for 5.0 % among renewable energies. In the same year, renewable energy accounted for 19.5 % of the total energy use for heating and cooling in the EU-28. This is a significant increase compared to 2004 (10.4 %). Aerothermal, geothermal and hydrothermal heat energy captured by heat pumps is taken into account, to the extent reported by countries. The share of energy from renewable sources in heating and cooling is presented in Table 4.

[7] Heat energy at a useful temperature level, extracted (captured) by means of heat pumps that need electricity or other auxiliary energy to function. This heat energy can be stored in the ambient air, beneath the surface of solid earth or in surface water.

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

Table 4 - Renewable energy sources in heating and cooling, in selected years, 2004-2017

	2004	2006	2008	2010	2012	2014	2016	2017
EU-28	10.4	11.8	13.8	15.4	17.0	18.4	19.0	19.5
Belgium	2.8	3.7	5.0	6.1	7.3	7.7	8.1	8.0
Bulgaria	14.1	14.8	17.3	24.4	27.5	28.3	30.0	29.9
Czechia	9.9	11.2	12.9	14.1	16.3	19.5	19.8	19.7
Denmark	20.6	23.8	28.1	31.0	33.6	38.5	42.2	46.5
Germany	7.1	8.4	10.3	12.1	13.5	13.5	13.1	13.4
Estonia	33.2	30.7	35.5	43.3	43.1	45.2	51.2	51.6
Ireland	2.9	3.7	3.5	4.3	4.9	6.3	6.3	6.9
Greece	12.8	12.4	14.2	17.9	23.4	27.0	24.6	26.6
Spain	9.5	11.3	11.6	12.6	14.1	15.7	17.1	17.5
France	12.5	11.7	13.3	16.1	17.5	19.1	21.1	21.3
Croatia	29.4	29.1	28.6	32.8	36.5	36.1	37.6	36.5
Italy	5.7	10.1	15.3	15.6	17.0	18.9	18.9	20.1
Cyprus	9.3	10.4	14.5	18.2	20.7	21.6	23.0	24.5
Latvia	42.5	42.6	42.9	40.7	47.3	52.2	51.8	54.6
Lithuania	30.4	29.2	32.0	32.5	34.5	40.6	46.6	46.5
Luxembourg	1.8	3.6	4.6	4.7	5.0	7.2	7.3	8.1
Hungary	6.4	11.4	12.0	18.1	23.3	21.2	20.9	19.6
Malta	1.0	1.4	1.7	5.7	13.1	14.8	16.5	20.2
Netherlands	2.2	2.7	3.1	3.1	3.8	5.1	5.4	5.9
Austria	20.2	22.9	25.1	28.7	30.0	32.9	32.2	32.0
Poland	10.2	10.2	10.8	11.7	13.4	14.0	14.7	14.5
Portugal	32.5	34.2	37.5	33.9	33.2	34.0	35.1	34.4
Romania	17.3	17.6	23.2	27.2	25.7	26.7	26.9	26.6
Slovenia	18.4	18.5	19.2	28.1	31.5	32.4	34.0	33.2
Slovakia	5.1	4.5	6.1	7.9	8.8	8.9	9.9	9.8
Finland	39.5	41.4	43.3	44.2	48.4	52.0	53.7	54.8
Sweden	46.6	56.3	61.0	60.9	65.8	67.9	68.5	69.1
United Kingdom	0.7	0.9	1.9	2.6	3.2	4.7	7.0	7.5
Montenegro	:	51.4	46.0	76.5	79.8	67.6	69.2	67.5
North Macedonia	23.3	24.9	24.6	26.5	29.6	35.0	30.9	36.4
Albania	33.1	31.0	37.1	31.3	39.1	31.0	33.8	24.9
Serbia	14.0	15.8	16.7	23.2	23.2	28.8	24.7	24.4
Turkey	17.6	15.2	15.0	14.4	12.1	12.3	11.7	10.3
Kosovo (¹)	51.9	48.9	47.8	45.5	49.3	51.8	51.8	50.5

(¹) This designation is without prejudice to positions on status, and is in line with UNSCR 1244/1999 and the ICJ Opinion on the Kosovo Declaration of Independence.

Source: SHARES_summary_results in http://ec.europa.eu/eurostat/web/energy/data/shares

The Seasonal Performance Factor (SPF) is an important figure which indicates the ratio between heat delivered by the heat pump (respectively at storage if available) and specific demand for electricity of the heat pump (including all common auxiliaries). New geothermal heat pumps in Europe achieve Seasonal Performance Factors of 4 or even higher. This is due to improved components and lower temperatures in the distribution system (below 35°C) based on improved heat insulation. The SPF is an indicator used for heat pumps to evaluate their efficiency expressed as a ratio of the total heat supplied to a building (by the heating system) to the electricity used by the heat pump (to drive the compressor of a heat pump) and other devices of the heating system over the year. This factor is used to calculate the renewable portion of the heat pump's heat output.

The SPF can also be used for active solar heating systems, being a measure of energy efficiency and utilization of renewables. In active solar space heating systems the SPF can be defined in a similar way as the ratio of the total heat Q_{useful} supplied to a building by the heating system over the year to the electricity E_{input} used by all electrically driven devices and subsystems, such as an electrical auxiliary heater and other auxiliary heating systems or devices based on fossil fuels, used to make the heating system operate over a year. Thus, the SPF can be described as the ratio between the useful heat and the total energy input (SPF = Q_{useful}/E_{input}).

For EU countries, the **minimum value of the SPF should be around 2.875** (considering an efficiency of η=>0.4, SPF > 1.15/η). Most of the heat pumps in Switzerland are operated in a monovalent way, i.e. even at low outdoor temperatures the heat pump provides enough heat and an auxiliary system is not necessary if buildings are well insulated and a low temperature heating system is used. Air-water heat pumps are often used for retrofitting the heating system. When retrofitting heating systems in old buildings, special conditions have to be considered. Usually the heat distribution system in old buildings is operated with higher temperatures than in new buildings. For this purpose, particular retrofit heat pumps were developed. The generic process taken from Ecoinvent dates back from 1998 and have a SPF (for retrofit heat pumps, air-water) in the range between 2.5 and 2.7 (Swiss conditions), which is below the minimum SPF threshold to consider a heat pump as a renewable energy source.

2.3.6. Excluded RE technologies

Bioenergy systems

The considerable modelling efforts required by this RES category may not, in most of the cases, translate into increased information for decision-makers, due to the large variability of bioenergy sourcing options, bioenergy technology solutions and final applications. Their modelling usually involves an additional agricultural or forest-management model, which are very complex due to their market interactions with other product systems, indirect effects (rebound and leakage effects) and, thereby, a considerable result uncertainty. More specifically, food-competing biofuels will induce a leakage or outsourcing effect known as *indirect land use changes* (iLUC), which can turn to be worse than the fossil counterpart (Fargione et al., 2008; Lapola et al., 2010;

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

Plevin et al., 2010; Saez de Bikuña et al., 2017), while forest-based bioenergy systems crucially depend on a span of variables (mainly: forest and fuel type, forest management, end-use application), which makes difficult a prospective assessment without a specific, well defined case-study and system boundaries (Dwivedi et al., 2019; McKechnie et al., 2011; Withey et al., 2019; Zanchi et al., 2012). Given all the difficulties identified and the uncertainties involved in the impact modelling of such TED categories, we preliminarily suggest to exclude them from the scope of the LCSA tool of WP4.

Fuel dependent applications: district heating and cogeneration plants, biofuel supply services

Similar to previous approaches, a way to overcome the inherent uncertainty related to the fuel used in these types of plants or the biofuel type, and given the nature of the prospective assessment of the LCSA tool, it is suggested that the sourcing part is left out of the scope. That is, the Use phase for the district heating and cogeneration plants, as well as the bioenergy systems and biofuel supply services altogether are recommended to be left out of the scope for the Product Approach, while for the System Approach the Energy and Abatement Models will come into play.

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

3. LCA screening results of selected RE technologies in different European contexts

3.1 Run-of-river hydropower

Depending on the net head of the power plant, high-pressure, medium-pressure and low-pressure systems can be distinguished. Low-pressure power plants including river power stations and canal power plants are very common, thus these two types of run-of-river power stations are covered in the dataset. This dataset represents the production of 1 kWh of electricity in a low-pressure, run-of-river power plant unit. The datasets include the estimated use of lubricant oil and the mass of water passing through the turbines, but it doesn´t include detailed specifications about land use due to methodical issues.

For today's power plants an efficiency of approximately 96% is assumed, modern generators show an efficiency of about 98%. The overall efficiency (current: 0,82; modern: 0,88) is composed of the efficiency of the turbine (current: 0,87; modern: 0,91), the generator (current: 0,96; modern: 0,98) and the transformer (current: 0,98; modern: 0,99).

The calculations are based on the information and data of the following run-of-river power plants (Aegerter et al. 1954): Rupperswil-Auenstein, Wildegg-Brugg, Birsfelden, Donaukraftwerk Greifenstein and Rheinkraftwerk Albbruck-Dogern as well as the new construction of the power plant Ruppoldingen. The determined specific data was then related to the entire power plant park of Switzerland with an annual net electricity output of 15484 GWh (Ecoinvent database). The lifetime is assumed to be 80 years for the whole infrastructure, while 40 years for the moving parts and auxiliary equipment.

Unfortunately, there is a lack of information in the relevant documentation about the size of the modelled plant or the equivalent installed generation capacity (nominal power) that the dataset represents. Knowing only the annual mean power output, we can only amortize the modelled inventory data over the estimated lifetime and distribute the derived annual share of environmental burdens among the declared annual productivity (15484 GWh), to get the average impacts per kWh produced (our functional unit). Consequently, it was not possible to recalculate

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

the environmental performance of 1 kWh produced in such plants when installing them in different European contexts, i.e. taking into account the differences in regional availability and seasonal variabilities among the 10 European countries assessed (see **Table 5** below).

Table 5. New hydropower production potential in the relevant EU countries, as predicted by the model of Bodis et al. 2014, divided into Mini Hydro (100 kW – 1 MW) and Small Hydro (1 – 10 MW) plants. The economically feasible potential, considering the ecological restrictions of the WFD as well, will likely be much lower.

	BE	DE	DK	ES	IT	NO	PT	SE	SK	UK
Annual production potential (GWh)	156	2745	0	22873	15477	na	6180	3526	725	5727
Suitable locations Mini Hydro	47	960	0	3713	3403	na	909	751	368	1318
Suitable locations Small Hydro	3	41	0	500	226	na	133	70	4	124

This European assessment study of the hydropower potential for small (1-10 MW) and mini (0.1 – 1 MW) hydro plants revealed a high variability of the potential of this RES among the considered countries (Bódis et al., 2014), as depicted in **Table 5**. Considering that any hydropower plant will be designed and built according to the productivity potential of each site, taking into account ecological restrictions from the WFD, seasonal variability and long-term fluctuations (15-25 years peaks and lows); considering too, that any installation has gone through technical feasibility and economic viability studies, we present here the theoretical (potential) impact results of an average run-of-river hydropower production of 1 kWh in Europe.

This means that very good sites with abundant water resources all year round will perform better, while poorer sites (with longer periods during the year without any production) will perform worse than the presented results in **Table 6** below. The main difference regarding this RES assessment and the LCA results of run-of-river plants will therefore lay in the overall production potential at the country level.

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

Table 6– LCA impacts for the production of 1 kWh in a generic run-of-river plant (Swiss-Austrian average, data from a mix of plants from the 50-60s)

Impact category	Unit	Hydropower, run-of-river
Climate change	kg CO2 eq	0.004024
Ozone depletion	kg CFC11 eq	3.41E-10
Ionising radiation	kBq U-235 eq	0.000322
Photochemical ozone formation	kg NMVOC eq	1.97E-05
Particulate matter	disease inc.	4.02E-10
Human toxicity, non-cancer	CTUh	1.25E-10
Human toxicity, cancer	CTUh	1.14E-11
Acidification	mol H+ eq	1.98E-05
Eutrophication, freshwater	kg P eq	1.23E-06
Eutrophication, marine	kg N eq	5.97E-06
Eutrophication, terrestrial	mol N eq	6.44E-05
Ecotoxicity, freshwater	CTUe	0.07266
Water use	m3 depriv.	0.001588
Resource use, fossils	MJ	0.038435
Resource use, minerals and metals	kg Sb eq	3.49E-08

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

3.2 Onshore wind power

For the modelling of the power production of an onshore wind turbine, a medium size model (2 MW installed capacity) was selected, as this is the most common one in Europe (the Wind Power database). The LCI model is based on the environmental assessment of a Vestas V80/2 MW turbine (Elsam Engineering A/S., 2004), in which the Danish wind park Tjaerborg is analysed. This type of wind turbine is taken as reference technology of the turbines class with a capacity range between 1 and 3 MW. The dataset includes moving parts such as nacelle, rotor, rotor blades, generator, gear, main shaft, yaw system, etc., as well as fixed parts such as the tower and the foundation. The dataset also includes an estimated energy consumption for the assembly of the turbine of 0.5 kWh/kg material input, as presented in Sacchi et al., 2019. The LCI includes some operation and maintenance activities, like the change of lubricating oil every year, as well as infrastructure inputs, but not the change of replacements like the gearbox.

The electricity produced with the wind turbine is then connected to medium or high voltage systems, depending on the size of the windfarm. Normally, each wind turbine contains a transformer from low voltage to medium voltage. The network connection additionally transforms the electricity to high voltage electricity. It is assumed here, that there are no stand-alone grid-connected small wind turbines and that all electricity is connected to the network in form of high voltage electricity.

For the amortization of the emissions, resource consumption and embodied impacts in all the materials and processes necessary for the construction and installation of the wind turbine, a 20-year lifetime was assumed. Even though the design lifetime might be higher, around 25 years for commercial wind turbines (Bonou et al., 2016), a more conservative estimate was deemed more appropriate, following the findings of a recent statistical analysis and a spatially-explicit LCI study carried out for the Danish wind park (Sacchi et al., 2019). There, an average lifetime period of 18.4 years was found based on the actual decommissioned wind turbines in Denmark between 1977 and 2016.

Once the annualized impacts were derived, these were distributed over the average wind power production potential of each country. For this, we combined the ***Global Wind Atlas database*** (www.globalwindatlas.info) with the online "Wind turbine power calculator" of the Danish Wind Industry Association (www.windpower.org), where the technical and performance characteristics of the Vestas V80/2 wind turbine are found. Taking the mean windspeed for every country from the Global Wind Atlas at 50 m height, and using the different Weibull parameters that characterize the distribution and profile of the main winds in each site, and taking also the terrain roughness class for 10 different specific sites already included in the database of the online calculator, an approximation of the mean annual electricity output potential can be calculated for each country (see **Table 8)**. This allows to have country-specific average LCA datasets, representing the different environmental performance of the same RE technology applied in different contexts, as presented in the main results in **Table 7**.

This project has received funding from the European Union's Horizon 2020
Research and Innovation programme under Grant Agreement No 857831

Table 7. Environmental footprint of 1 kWh of onshore wind power production in ten European countries. Characterization method EF v3.

Impact category	Unit	BE	DE	DK	ES	IT	NO	PT	SK	SE	UK
Climate change	kg CO2 eq	1.01E-02	9.17E-03	7.31E-03	1.04E-02	1.18E-02	6.86E-03	1.10E-02	1.31E-02	9.11E-03	6.76E-03
Ozone depletion	kg CFC11 eq	8.19E-10	7.46E-10	5.95E-10	8.45E-10	9.64E-10	5.59E-10	8.93E-10	1.07E-09	7.41E-10	5.50E-10
Ionising radiation	kBq U-235 eq	6.93E-04	6.31E-04	5.03E-04	7.14E-04	8.15E-04	4.72E-04	7.55E-04	9.03E-04	6.27E-04	4.65E-04
Photochemical ozone formation	kg NMVOC eq	4.81E-05	4.38E-05	3.49E-05	4.96E-05	5.66E-05	3.28E-05	5.24E-05	6.27E-05	4.35E-05	3.23E-05
Particulate matter	disease inc.	8.33E-10	7.59E-10	6.05E-10	8.59E-10	9.80E-10	5.68E-10	9.08E-10	1.09E-09	7.54E-10	5.60E-10
Human toxicity, non-cancer	CTUh	6.68E-10	6.09E-10	4.86E-10	6.89E-10	7.87E-10	4.56E-10	7.29E-10	8.71E-10	6.05E-10	4.49E-10
Human toxicity, cancer	CTUh	4.72E-11	4.30E-11	3.43E-11	4.87E-11	5.56E-11	3.22E-11	5.15E-11	6.16E-11	4.27E-11	3.17E-11
Acidification	mol H+ eq	6.62E-05	6.03E-05	4.81E-05	6.83E-05	7.80E-05	4.52E-05	7.22E-05	8.64E-05	5.99E-05	4.45E-05
Eutrophication, freshwater	kg P eq	6.06E-06	5.52E-06	4.40E-06	6.24E-06	7.13E-06	4.13E-06	6.60E-06	7.90E-06	5.48E-06	4.07E-06
Eutrophication, marine	kg N eq	1.31E-05	1.19E-05	9.53E-06	1.35E-05	1.54E-05	8.94E-06	1.43E-05	1.71E-05	1.19E-05	8.81E-06
Eutrophication, terrestrial	mol N eq	1.31E-04	1.20E-04	9.54E-05	1.35E-04	1.54E-04	8.95E-05	1.43E-04	1.71E-04	1.19E-04	8.81E-05
Ecotoxicity, freshwater	CTUe	4.40E-01	4.01E-01	3.20E-01	4.54E-01	5.18E-01	3.00E-01	4.80E-01	5.74E-01	3.98E-01	2.96E-01
Water use	m3 depriv.	3.40E-03	3.10E-03	2.47E-03	3.51E-03	4.01E-03	2.32E-03	3.71E-03	4.44E-03	3.08E-03	2.29E-03
Resource use, fossils	MJ	1.29E-01	1.18E-01	9.38E-02	1.33E-01	1.52E-01	8.80E-02	1.41E-01	1.68E-01	1.17E-01	8.67E-02
Resource use, minerals and metals	kg Sb eq	1.16E-06	1.06E-06	8.45E-07	1.20E-06	1.37E-06	7.93E-07	1.27E-06	1.52E-06	1.05E-06	7.81E-07

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

Table 8. Estimation of the annual production potential for a 2 MW Vestas V80 turbine installed in different European countries. This information is used to calculate an average country-specific environmental performance of wind power production.

	BE	DE	DK	ES	IT	NO	PT	SE	SK	UK
Annual production potential (GWh)	5.86	6.43	8.06	5.68	4.97	8.59	5.37	6.47	4.49	8.72
Capacity or Load Factor (%)	33	37	46	32	28	49	31	37	26	50
Weibull shape parameter	2.04	2.31	2.33	1.49	1.37	1.93	2.04	1.49	1.94	1.85
Mean windspeed at 50m (m/s)	6.8	7.16	8.16	6.7	6.2	8.8	6.52	7.42	5.94	9.04

The results shown in the previous tables represent thus a "good practice" of wind power production from a 2 MW onshore high-class wind turbine, installed in good sites in Europe. In **Figure 3** we show graphically the results for the impact category of Climate Change (thus showing the Carbon Footprint per kWh of wind power production in each country). The graphical results for other impact categories are not shown, since they follow the same pattern as the one in **Figure 3** and it would be therefore redundant. The specific numeric results for the rest of indicators can be checked in **Table 7**.

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

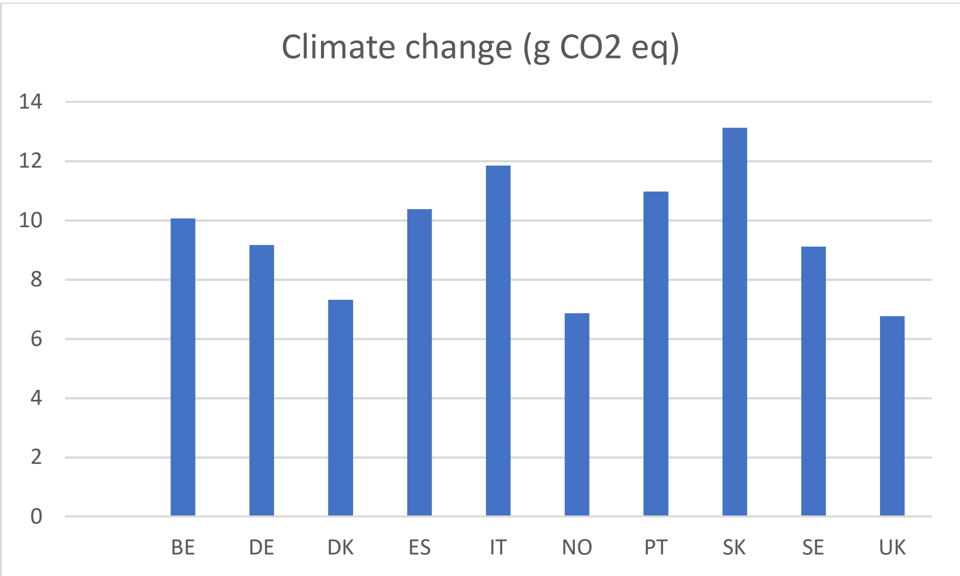


Figure 3. Global warming potential results (impact category Climate Change) for each country scenario of onshore wind power production.

Comparing our results to other analysis from literature, it is observed that the reported carbon footprint in Guezuraga et al., 2012 for a similar 2 MW wind turbine (5.98 GWh annual production) is of 9.7 g CO2e/kWh, which would be close to our results from Germany and in the range of the scenarios of Belgium, Spain and Sweden. A more recent study that collected the production and operational data for several wind turbines in Denmark (including spatially-explicit wind measurements, performance characteristics of different wind turbines, decommissioning information, etc.), came up with more conservative results (Sacchi et al., 2019). For 2 MW onshore wind turbines, they found an average carbon footprint of 17.8 g CO2e/kWh, which is approximately the double of our estimation and previous literature data (see **Figure 4**).

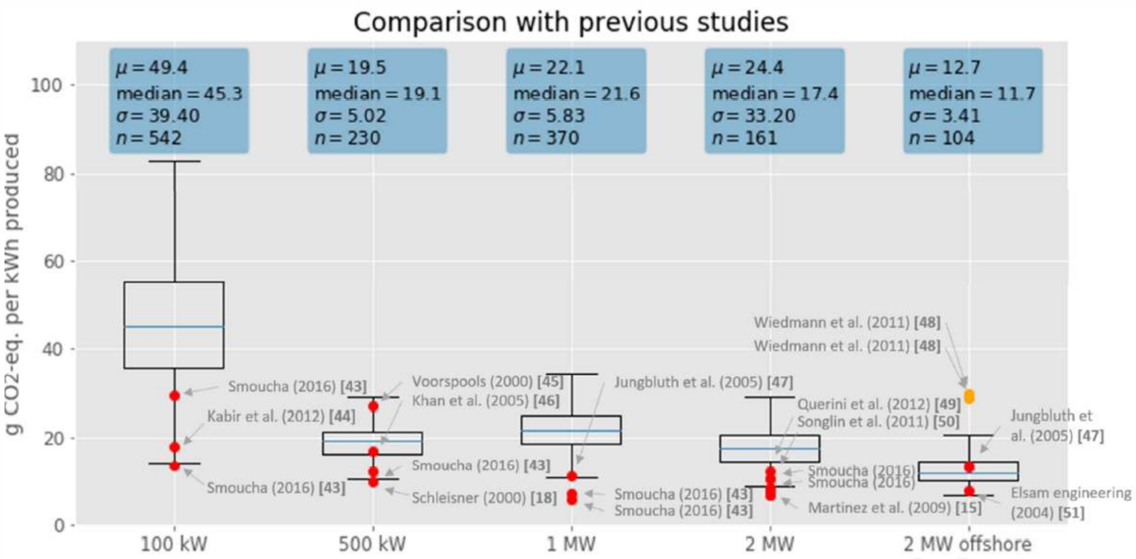


Figure 4. Comparison graph of carbon footprint results of wind power from different studies and the mean reported in Sacchi et al. 2019 (blue line represents the median).

This analysis indicates that some typical assumptions of this type of LCA studies may be too optimistic, like the lifetime assumption or the annual electricity production potential estimates: 8 GWh in our case (DK) vs. 5.6 GWh in Sacchi et al. 2019 (average of 2 MW onshore, n = 543, standard deviation of 1.5). Other authors argue that bottom-up LCA studies, compared to top-down LCAs which combine multi-regional input-output tables (hybrid LCAs), may truncate a significant part of the inventory and thus underestimate emissions (Wiedmann et al., 2011).

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

However, the bigger completeness of hybrid LCAs may come at a cost in accuracy, since the resolution of MRIO data is rather coarse as they group similar products in same categories which do not necessarily have similar impacts (Sacchi et al., 2019). All in all, the findings of Sacchi et al. 2019 reveal that the used electricity production potential figures in our calculations are likely in the upper limit of the probability distribution, so they indeed represent a “good example” or even best-case situation.

3.3 Multi-crystalline PV

The LCI data for the electricity production with multi-crystalline PV systems are based on the main source of the Ecoinvent database (Jungbluth & Stucki, 2012). The dataset represents a grid-connected 3 kWp system mounted on a slanted roof. It includes the structure to mount the panels, the electric installation and a power inverter. Also considered is a 570 kWp open ground PV plant which includes the PV panels, the mounting system, the electric installation and the power inverter. The selected dataset for XPRESS regards a unit process raw data for 1 m^2 of a multi-crystalline PV panel. A solar panel consists of 60 solar cells of 156 x 156cm with a capacity of 210Wp. The assumed efficiency of solar irradiation to electricity is of 17% with a productivity of 150 Wp/m^2, which represents more modern PV technology characteristics than the default values of Ecoinvent (Figures 12.2 and 12.3 in Jungbluth et al. 2012). This assumption implies that we include a surface of 20 m^2 of solar PV panels (instead of 23.4 m^2 as considered in Ecoinvent) to have a 3 kWp installation module and 3800 m^2 of solar PV panels (instead of 4400 m^2) to have a 570 kWp installation module. The 3 kWp installation module is the basic PV module for which the raw LCI data is available. The infrastructure and auxiliary equipment impacts are then amortized over the expected lifetime of the PV panels, 30 years (Hsu et al., 2012; Wong et al., 2016). The dataset includes the repairing of 2% of the modules during the lifetime and 1% of rejects.

The location specific irradiation and the resulting annual yield of photovoltaic plants is one of the decisive factors for LCA results of photovoltaics (Jungbluth & Stucki, 2012). Here we have calculated the country-specific productivity through the European PVGIS database, where the specific solar irradiation per site can be extracted and converted into PV productivity via the optimal solar incidence angle (see Table 9), by inserting the cell module efficiency and the

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

installed PV area. The estimated electricity output over the expected lifetime of the PV installation is finally used to derive the environmental footprint per kWh of this technology for each country assessed.

Table 9. Annual mean solar irradiation (kWh/m^2) and power production potential per country. H(h) is the irradiation on a horizontal plane and H(i_opt) represents the irradiation on an optimally inclined plane.

	H(h)	H(i_opt)	Lifetime power production estimate (MWh/ 3 kWp module)
Spain	1648.6	1863.5	190.1
Italy	1392.5	1597.6	163.0
Germany	995.1	1133.7	115.6
Portugal	1622.0	1863.9	190.1
Belgium	1157.2	1384.5	141.2
Norway	787.0	936.5	95.5
Sweeden	835.0	999.4	101.9
UK	886.0	998.4	101.8
Denmark	955.6	1132.5	115.5
Slovakia	1107.2	1236.3	126.1

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

3.3.1 Rooftop installations

In the next table the LCA results for the production of 1 kWh of electricity with a generic rooftop PV installation (multi-crystalline Si wafers, grid connected) are presented. The results include the variability of solar energy in the ten European countries where the PV is applied. The lowest environmental footprints belong to the southernmost countries (Spain and Portugal, closely followed by Italy), where the solar irradiation is highest, and vice versa. The lowest performing PV panels are those of UK, Norway and Sweden (see **Error! Reference source not found.**).

Solar PV production has a worse environmental performance compared to wind power, as it can be read from the results shown in **Table 7** and **Table 10** and from **Figure 3** and **Figure 5**. On average, it performs 3-4 times worse (three to four-fold higher impacts) per kWh produced and delivered.

This project has received funding from the European Union's Horizon 2020
Research and Innovation programme under Grant Agreement No 857831

Table 10. Environmental footprint of 1 kWh production from roof-top PV installations in ten European countries. Solar radiation and PV yields from PVGIS tool. Characterization method EF v3.

Impact category	Unit	BE	DE	DK	ES	IT	NO	PT	SK	SE	UK
Climate change	kg CO2 eq	4.11E-02	5.02E-02	5.02E-02	3.05E-02	3.56E-02	6.07E-02	3.05E-02	4.60E-02	5.69E-02	5.70E-02
Ozone depletion	kg CFC11 eq	4.07E-09	4.96E-09	4.97E-09	3.02E-09	3.52E-09	6.01E-09	3.02E-09	4.55E-09	5.63E-09	5.64E-09
Ionising radiation	kBq U-235 eq	3.68E-03	4.50E-03	4.50E-03	2.74E-03	3.19E-03	5.45E-03	2.74E-03	4.13E-03	5.10E-03	5.11E-03
Photochemical ozone formation	kg NMVOC eq	1.76E-04	2.16E-04	2.16E-04	1.31E-04	1.53E-04	2.61E-04	1.31E-04	1.98E-04	2.44E-04	2.45E-04
Particulate matter	disease inc.	2.73E-09	3.34E-09	3.34E-09	2.03E-09	2.37E-09	4.04E-09	2.03E-09	3.06E-09	3.79E-09	3.79E-09
Human toxicity, non-cancer	CTUh	2.75E-09	3.36E-09	3.36E-09	2.04E-09	2.38E-09	4.06E-09	2.04E-09	3.08E-09	3.81E-09	3.81E-09
Human toxicity, cancer	CTUh	5.55E-11	6.78E-11	6.79E-11	4.12E-11	4.81E-11	8.21E-11	4.12E-11	6.22E-11	7.69E-11	7.70E-11
Acidification	mol H+ eq	3.51E-04	4.28E-04	4.29E-04	2.60E-04	3.04E-04	5.18E-04	2.60E-04	3.93E-04	4.86E-04	4.86E-04
Eutrophication, freshwater	kg P eq	3.49E-05	4.27E-05	4.27E-05	2.60E-05	3.03E-05	5.16E-05	2.59E-05	3.91E-05	4.84E-05	4.84E-05
Eutrophication, marine	kg N eq	5.17E-05	6.31E-05	6.32E-05	3.84E-05	4.48E-05	7.64E-05	3.84E-05	5.79E-05	7.16E-05	7.17E-05
Eutrophication, terrestrial	mol N eq	5.30E-04	6.47E-04	6.47E-04	3.93E-04	4.59E-04	7.83E-04	3.93E-04	5.93E-04	7.34E-04	7.34E-04
Ecotoxicity, freshwater	CTUe	2.51E+00	3.06E+00	3.07E+00	1.86E+00	2.17E+00	3.71E+00	1.86E+00	2.81E+00	3.48E+00	3.48E+00
Water use	m3 depriv.	3.82E-02	4.66E-02	4.67E-02	2.84E-02	3.31E-02	5.64E-02	2.84E-02	4.28E-02	5.29E-02	5.29E-02
Resource use, fossils	MJ	5.08E-01	6.20E-01	6.20E-01	3.77E-01	4.40E-01	7.50E-01	3.77E-01	5.68E-01	7.03E-01	7.04E-01
Resource use, minerals and metals	kg Sb eq	5.75E-06	7.03E-06	7.04E-06	4.28E-06	4.99E-06	8.51E-06	4.27E-06	6.44E-06	7.97E-06	7.98E-06

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

In the **Figure 5** below the Carbon Footprint results can be seen graphically for each country

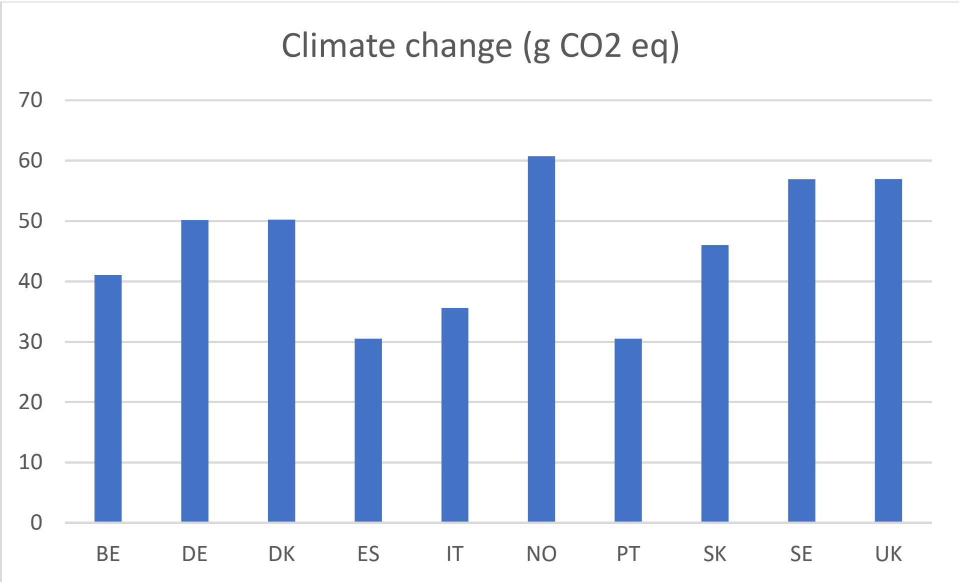


Figure 5. Global warming potential results (impact category Climate Change) for each country scenario for solar PV (rooftop) production

3.3.2 On ground installations

One of the main drawbacks of big solar plants is the large amount of land required to produce electricity. Unlike onshore wind plants, land transformed by PV plants becomes unavailable for other purposes. Furthermore, from an environmental perspective, impacts go beyond land occupation, given that soil is crucial for the supply of ecosystems services and to support biodiversity, for example.

In the last decade, developments have been carried out to adequately incorporate such impacts on the LCA of production processes. Many methodologies usually focus on the impact assessment of land use on biodiversity as the endpoint indicator, whereas midpoint indicators tend only to account for the area transformed and occupied for the functional unit. One of the key issues is the lack of understanding of the cause-effect chain of land transformation, also called impact pathway, that should serve to systematically calculate mid- and endpoint indicators given an amount and type of land used. Topics such as soil quality (i.e. fertility, stability), biotic

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

production and impact on habitats (e.g. fragmentation, degradation) are still to be included to produce robust land use change models.

Within XPRESS, differences are expected for on ground PV installations among all considered countries. For these first models, the default value for land use included in the database has been kept. New insights are required to determine which type of inventory data would be the most relevant to address this impact assessment, as well as how to incorporate land characteristics that are not usually taking on consideration for LCA, such as current use (e.g. forest, fruit crops), location (e.g. ecoregions, countries), and land occupation intensiveness (Vidal-Legaz et al., 2016).

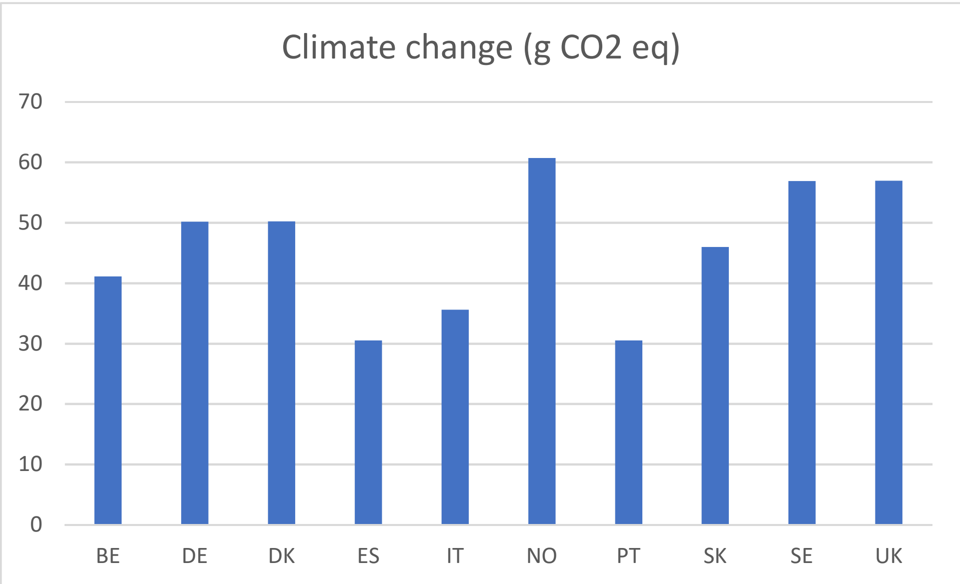


Figure 6. Global warming potential results (impact category Climate Change) for each country scenario of on ground PV production

Even without considering potential iLUC impacts, on ground PV installations perform slightly worse than their counterparts on rooftops, but in the range of wind power electricity. Regarding the indirect land use impacts that on ground PV installations could have, a study concluded that in the medium term, and with respect to more efficient land use, PV should be integrated into buildings and infrastructures (Lakhani et al., 2014).

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

Table 11. Environmental footprint of 1 kWh production from on ground solar PV installations in ten European countries. Solar radiation and PV yields from PVGIS tool. Characterization method EF v3.

Impact category	Unit	BE	DE	DK	ES	IT	NO	PT	SK	SE	UK
Climate change	kg CO2 eq	4.18E-02	5.10E-02	5.11E-02	3.10E-02	3.62E-02	6.18E-02	3.10E-02	4.68E-02	5.79E-02	5.79E-02
Ozone depletion	kg CFC11 eq	4.10E-09	5.00E-09	5.01E-09	3.04E-09	3.55E-09	6.06E-09	3.04E-09	4.59E-09	5.68E-09	5.68E-09
Ionising radiation	kBq U-235 eq	3.55E-03	4.34E-03	4.34E-03	2.64E-03	3.08E-03	5.25E-03	2.64E-03	3.98E-03	4.92E-03	4.92E-03
Photochemical ozone formation	kg NMVOC eq	1.67E-04	2.04E-04	2.05E-04	1.24E-04	1.45E-04	2.47E-04	1.24E-04	1.87E-04	2.32E-04	2.32E-04
Particulate matter	disease inc.	2.79E-09	3.40E-09	3.41E-09	2.07E-09	2.42E-09	4.12E-09	2.07E-09	3.12E-09	3.86E-09	3.86E-09
Human toxicity, non-cancer	CTUh	1.92E-09	2.35E-09	2.35E-09	1.43E-09	1.66E-09	2.84E-09	1.43E-09	2.15E-09	2.66E-09	2.66E-09
Human toxicity, cancer	CTUh	5.81E-11	7.09E-11	7.10E-11	4.32E-11	5.03E-11	8.59E-11	4.32E-11	6.51E-11	8.05E-11	8.06E-11
Acidification	mol H+ eq	2.83E-04	3.45E-04	3.46E-04	2.10E-04	2.45E-04	4.18E-04	2.10E-04	3.17E-04	3.92E-04	3.92E-04
Eutrophication, freshwater	kg P eq	2.49E-05	3.04E-05	3.04E-05	1.85E-05	2.16E-05	3.68E-05	1.85E-05	2.79E-05	3.45E-05	3.45E-05
Eutrophication, marine	kg N eq	4.90E-05	5.98E-05	5.99E-05	3.64E-05	4.25E-05	7.24E-05	3.64E-05	5.49E-05	6.79E-05	6.79E-05
Eutrophication, terrestrial	mol N eq	5.05E-04	6.17E-04	6.17E-04	3.75E-04	4.38E-04	7.46E-04	3.75E-04	5.65E-04	6.99E-04	7.00E-04
Ecotoxicity, freshwater	CTUe	1.67E+00	2.04E+00	2.04E+00	1.24E+00	1.45E+00	2.47E+00	1.24E+00	1.87E+00	2.31E+00	2.32E+00
Water use	m3 depriv.	3.82E-02	4.67E-02	4.67E-02	2.84E-02	3.31E-02	5.65E-02	2.84E-02	4.28E-02	5.30E-02	5.30E-02
Resource use, fossils	MJ	5.09E-01	6.22E-01	6.22E-01	3.78E-01	4.41E-01	7.53E-01	3.78E-01	5.70E-01	7.05E-01	7.06E-01
Resource use, minerals and metals	kg Sb eq	6.80E-06	8.31E-06	8.32E-06	5.06E-06	5.90E-06	1.01E-05	5.05E-06	7.62E-06	9.43E-06	9.44E-06

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

3.4 EVs

To model the two identified EVs in the TED database, the LCI of an old lithium-ion battery was taken from Ecoinvent. The modelled battery is based on Lithium Manganese Oxide (LMO - LiMn2O4) and LiPF6, which form the cathode material and the electrolyte, respectively. This type of battery is being progressively phased out in the EV sector as it is being replaced by a newer and more performing battery technology: the NMC battery. This type of battery is composed of Lithium Nickel Cobalt Manganese Oxide (LiNiCoMnO2) and has higher energy density than the older LMO batteries. NMC production has not yet been inventoried in Ecoinvent v3.6 hence it was left out of the scope of this study, for specific process data and primary industry data (impossible to get) would be necessary to build the LCI.

The modelled EVs are thus equipped with LMO batteries. The LMO battery pack has 14 single cells and has a power load of 2.1 kWh and a nominal voltage of 48 V. The full battery weighs 262 kg as installed in the e-car and has a power density of 114 Wh/kg, with a total electric capacity of ca. 30 kWh[8]. This should correspond to about 120 km of driving range. The assumed battery lifetime is given in distance (km) rather than years, taking 100,000 km as a conservative estimate. The same battery module is assumed to be used in the e-bus, which is modelled by scaling the previous module up to 240 kWh of electric capacity. The LMO battery for the e-bus has an extrapolated weight of 1232 kg.

3.4.1 E-cars

This dataset describes a journey of 1 km with an electric passenger car. The dataset is parametrised with respect to the mass of the vehicle, mass of the battery and lifetimes of vehicle and battery. The EV is described in terms of a vehicle without battery plus the battery. The amount of battery includes battery exchange due to maintenance. Currently, default values for a compact size car with a weight without battery of 918 kg was taken. An average life expectancy for the car of 150000 km was assumed, so it consumes 1.5 batteries during its lifetime. An electricity consumption of 0.2 kWh/km was taken, as described in the database Ecoinvent v3 (representative of modern cars, up to 2015).

[8] Modern NMC batteries have a capacity around 51 kWh

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

In **Figure 7** we present the carbon footprints of e-car transportation in the 10 European countries where the assessment was carried out. As expected, the environmental performance of the e-car transportation is closely related to the electricity grid-mix of each country (Norway showing the lowest carbon footprint and Germany the highest). However, from the contribution analysis in **Figure 8** it can be observed that electricity is not the dominant driver, but there are other key processes and components that contribute significantly to the environmental load of an e-car's transportation. Besides the electricity consumption to load the battery, the e-car transportation's environmental burden also heavily depends on the battery stack itself and the car (without battery). Taking an average load factor of 1.2 passengers per car in Europe, the carbon (and environmental) footprint figures are still much higher for e-cars than for e-buses (see next chapter 3.4.2 and results therein).

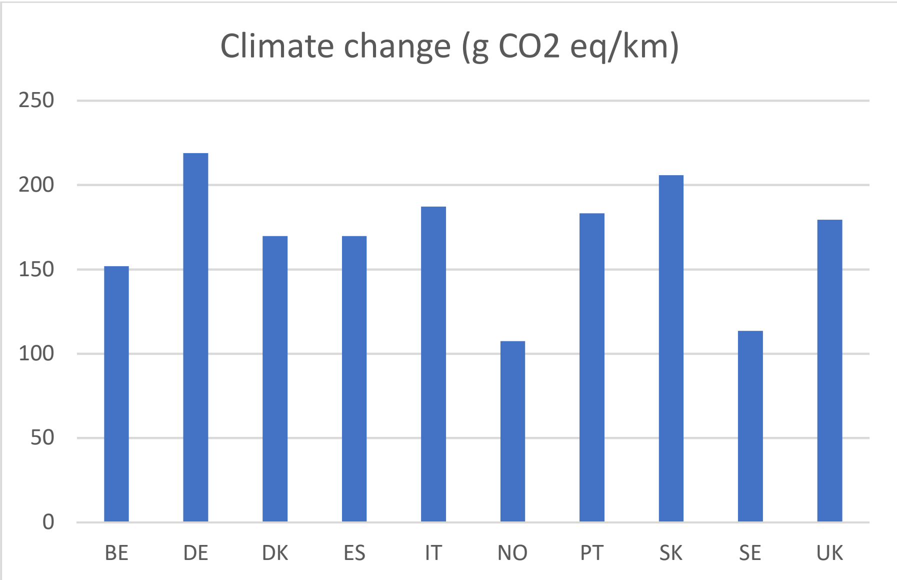


Figure 7. Global warming potential results (impact category Climate Change) for each country scenario of e-car transportation

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

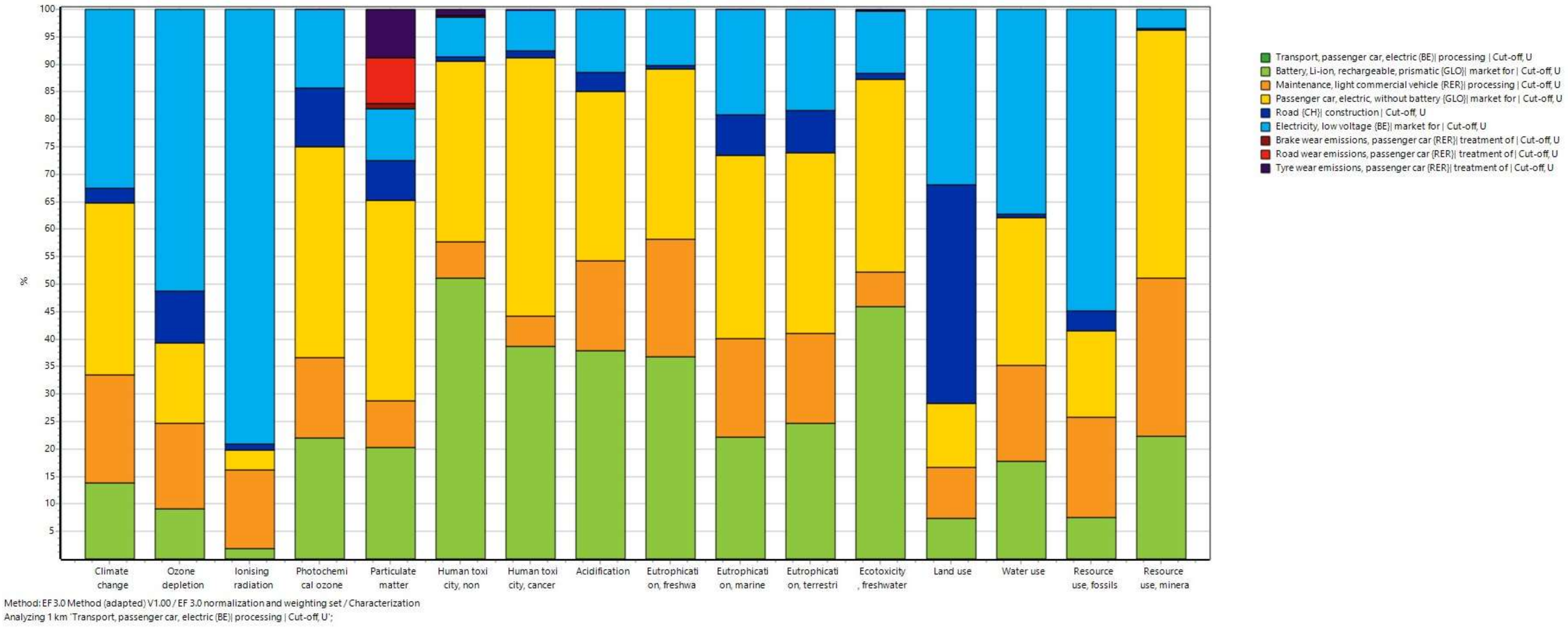


Figure 8. Contribution analysis: main inputs and processes driving the environmental impacts of an e-car transportation. Analysis for 1 km driven in an e-car in Belgium.

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

Table 12. Environmental footprint of 1 km transport in an average e-car, calculated for ten European countries. Characterization method EF v3.

Impact category	Unit	BE	DE	DK	ES	IT	NO	PT	SK	SE	UK
Climate change	kg CO2 eq	1.52E-01	2.19E-01	1.70E-01	1.70E-01	1.87E-01	1.07E-01	1.83E-01	2.06E-01	1.13E-01	1.79E-01
Ozone depletion	kg CFC11 eq	2.00E-08	1.42E-08	1.20E-08	1.70E-08	2.12E-08	1.00E-08	1.38E-08	1.82E-08	1.47E-08	1.75E-08
Ionising radiation	kBq U-235 eq	9.75E-02	4.07E-02	3.05E-02	6.76E-02	3.07E-02	2.28E-02	2.57E-02	9.25E-02	1.04E-01	8.17E-02
Photochemical ozone formation	kg NMVOC eq	5.49E-04	6.25E-04	6.07E-04	7.29E-04	6.64E-04	4.85E-04	7.40E-04	7.22E-04	5.04E-04	6.33E-04
Particulate matter	disease inc.	9.06E-09	9.58E-09	9.55E-09	9.73E-09	1.00E-08	8.48E-09	9.84E-09	1.07E-08	8.88E-09	9.31E-09
Human toxicity, non-cancer	CTUh	7.73E-09	8.35E-09	8.08E-09	8.19E-09	7.95E-09	7.50E-09	8.13E-09	8.43E-09	7.60E-09	8.01E-09
Human toxicity, cancer	CTUh	2.74E-10	2.83E-10	2.82E-10	2.85E-10	2.81E-10	2.67E-10	2.81E-10	2.92E-10	2.71E-10	2.78E-10
Acidification	mol H+ eq	1.06E-03	1.27E-03	1.20E-03	1.54E-03	1.39E-03	9.75E-04	1.61E-03	1.67E-03	1.00E-03	1.23E-03
Eutrophication, freshwater	kg P eq	1.22E-04	2.73E-04	1.57E-04	1.37E-04	1.33E-04	1.13E-04	1.42E-04	2.51E-04	1.16E-04	1.28E-04
Eutrophication, marine	kg N eq	1.58E-04	2.13E-04	1.82E-04	2.20E-04	1.91E-04	1.32E-04	2.21E-04	2.38E-04	1.42E-04	1.87E-04
Eutrophication, terrestrial	mol N eq	1.67E-03	2.18E-03	2.01E-03	2.33E-03	2.21E-03	1.42E-03	2.35E-03	2.27E-03	1.51E-03	2.00E-03
Ecotoxicity, freshwater	CTUe	7.58E+00	8.02E+00	8.24E+00	7.99E+00	7.82E+00	7.02E+00	8.13E+00	7.99E+00	7.35E+00	7.91E+00
Water use	m3 depriv.	5.00E-02	3.73E-02	4.15E-02	7.71E-02	8.01E-02	3.63E-02	7.38E-02	5.69E-02	4.62E-02	3.47E-02
Resource use, fossils	MJ	3.56E+00	3.17E+00	2.47E+00	3.15E+00	2.84E+00	1.67E+00	2.61E+00	3.89E+00	2.79E+00	3.47E+00
Resource use, minerals and metals	kg Sb eq	1.67E-05	1.70E-05	1.67E-05	1.66E-05	1.67E-05	1.64E-05	1.66E-05	1.69E-05	1.65E-05	1.67E-05

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

3.4.2 E-buses

This dataset describes a journey of 1 km of 1 passenger in an electric city bus. The dataset is parametrised with respect to the mass of the vehicle, mass of the battery and lifetimes of vehicle and battery. This dataset combines the electric passenger inventory (the mentioned LMO battery) with a modified passenger coach inventory taken from Ecoinvent v3. Taking a full diesel coach weight of 11000 kg, we estimated a full bus weight of 10696 kg and an empty bus (without battery and without engine) of 8991 kg. The size of the electric engine has been extrapolated from that of the e-car, which is 53 kg for the latter and 472 kg for the former. An average life expectancy of 1 Mkm was assumed for the bus and an average EU passenger load of 30 persons per trip was considered for all countries (Steer Davies Gleave, 2016).

The dataset of "Operation, trolleybus (CH)" was also used to derive the non-combustion emissions from tyre and brake wear, as well as for the consumption estimate of electricity (3.04 kWh/km), which was then distributed among the passenger load.

In Figure 9 the carbon footprint figures for the transportation of passengers in electric buses for the ten European countries can be seen.

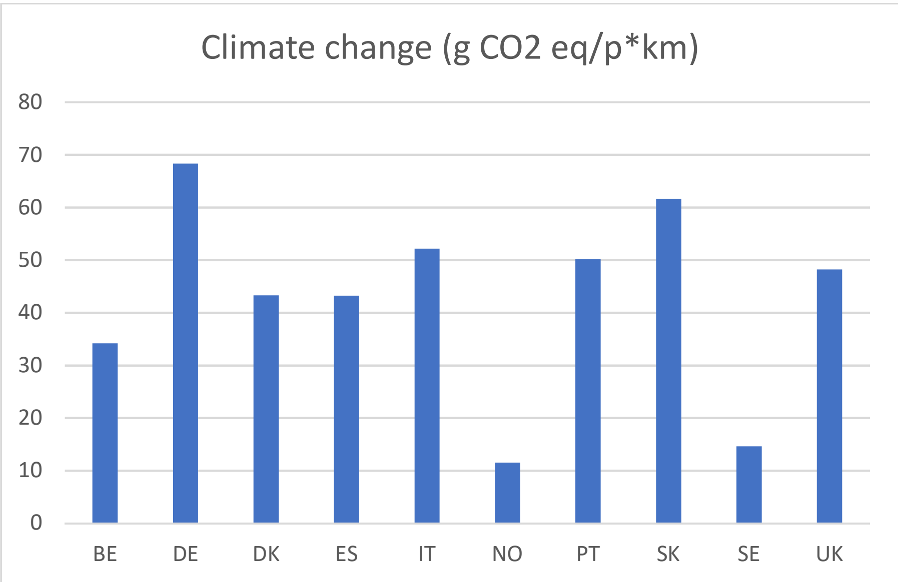


Figure 9. Global warming potential results (impact category Climate Change) for each country scenario of e-bus transportation

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

*Table 13. Environmental footprint of 1 person*km transport in an average e-bus, calculated for ten European countries. Characterization method EF v3.*

Impact category	Unit	BE	DE	DK	ES	IT	NO	PT	SK	SE	UK
Climate change	kg CO2 eq	3.42E-02	6.83E-02	4.33E-02	4.32E-02	5.22E-02	1.15E-02	5.02E-02	6.17E-02	1.46E-02	4.82E-02
Ozone depletion	kg CFC11 eq	7.00E-09	4.07E-09	2.94E-09	5.48E-09	7.61E-09	1.95E-09	3.87E-09	6.11E-09	4.30E-09	5.76E-09
Ionising radiation	kBq U-235 eq	4.14E-02	1.24E-02	7.22E-03	2.61E-02	7.33E-03	3.34E-03	4.77E-03	3.88E-02	4.45E-02	3.33E-02
Photochemical ozone formation	kg NMVOC eq	1.07E-04	1.45E-04	1.36E-04	1.98E-04	1.65E-04	7.39E-05	2.04E-04	1.95E-04	8.38E-05	1.49E-04
Particulate matter	disease inc.	3.16E-09	3.42E-09	3.41E-09	3.50E-09	3.63E-09	2.86E-09	3.55E-09	3.97E-09	3.06E-09	3.28E-09
Human toxicity, non-cancer	CTUh	1.17E-09	1.48E-09	1.35E-09	1.40E-09	1.28E-09	1.05E-09	1.37E-09	1.53E-09	1.11E-09	1.31E-09
Human toxicity, cancer	CTUh	3.62E-11	4.11E-11	4.02E-11	4.19E-11	4.00E-11	3.30E-11	4.00E-11	4.56E-11	3.49E-11	3.86E-11
Acidification	mol H+ eq	1.64E-04	2.71E-04	2.37E-04	4.06E-04	3.33E-04	1.20E-04	4.44E-04	4.76E-04	1.35E-04	2.52E-04
Eutrophication, freshwater	kg P eq	1.55E-05	9.27E-05	3.36E-05	2.34E-05	2.13E-05	1.12E-05	2.60E-05	8.14E-05	1.27E-05	1.87E-05
Eutrophication, marine	kg N eq	3.16E-05	5.94E-05	4.37E-05	6.29E-05	4.83E-05	1.83E-05	6.35E-05	7.25E-05	2.36E-05	4.61E-05
Eutrophication, terrestrial	mol N eq	3.31E-04	5.89E-04	5.00E-04	6.64E-04	6.03E-04	2.01E-04	6.77E-04	6.37E-04	2.49E-04	5.00E-04
Ecotoxicity, freshwater	CTUe	1.17E+00	1.40E+00	1.51E+00	1.38E+00	1.29E+00	8.85E-01	1.45E+00	1.38E+00	1.06E+00	1.34E+00
Water use	m3 depriv.	1.17E-02	5.29E-03	7.42E-03	2.55E-02	2.71E-02	4.76E-03	2.39E-02	1.53E-02	9.83E-03	3.98E-03
Resource use, fossils	MJ	1.16E+00	9.64E-01	6.11E-01	9.56E-01	7.98E-01	2.04E-01	6.80E-01	1.33E+00	7.74E-01	1.12E+00
Resource use, minerals and metals	kg Sb eq	1.29E-06	1.49E-06	1.30E-06	1.28E-06	1.33E-06	1.18E-06	1.26E-06	1.41E-06	1.21E-06	1.29E-06

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

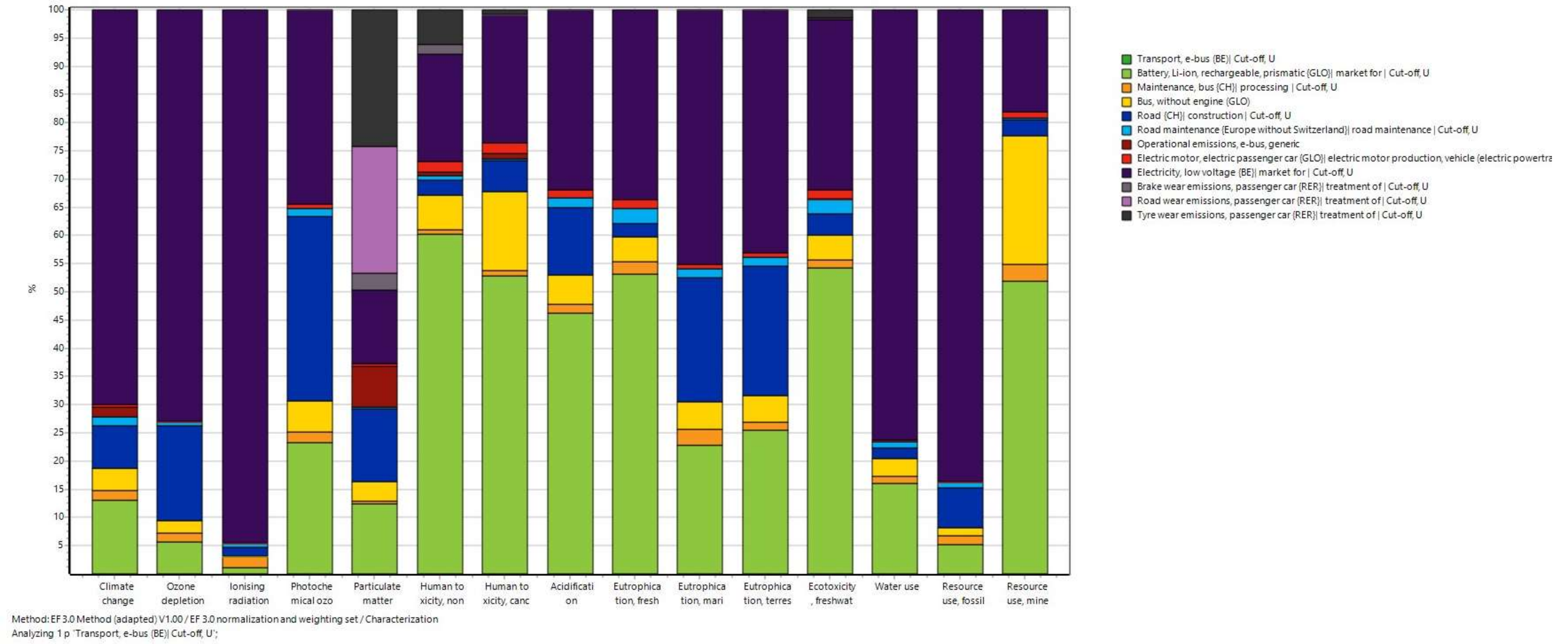


Figure 10. Contribution analysis of the main processes responsible of the environmental footprint of a passenger transportation with an e-bus (specific results of the country scenario Belgium).

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

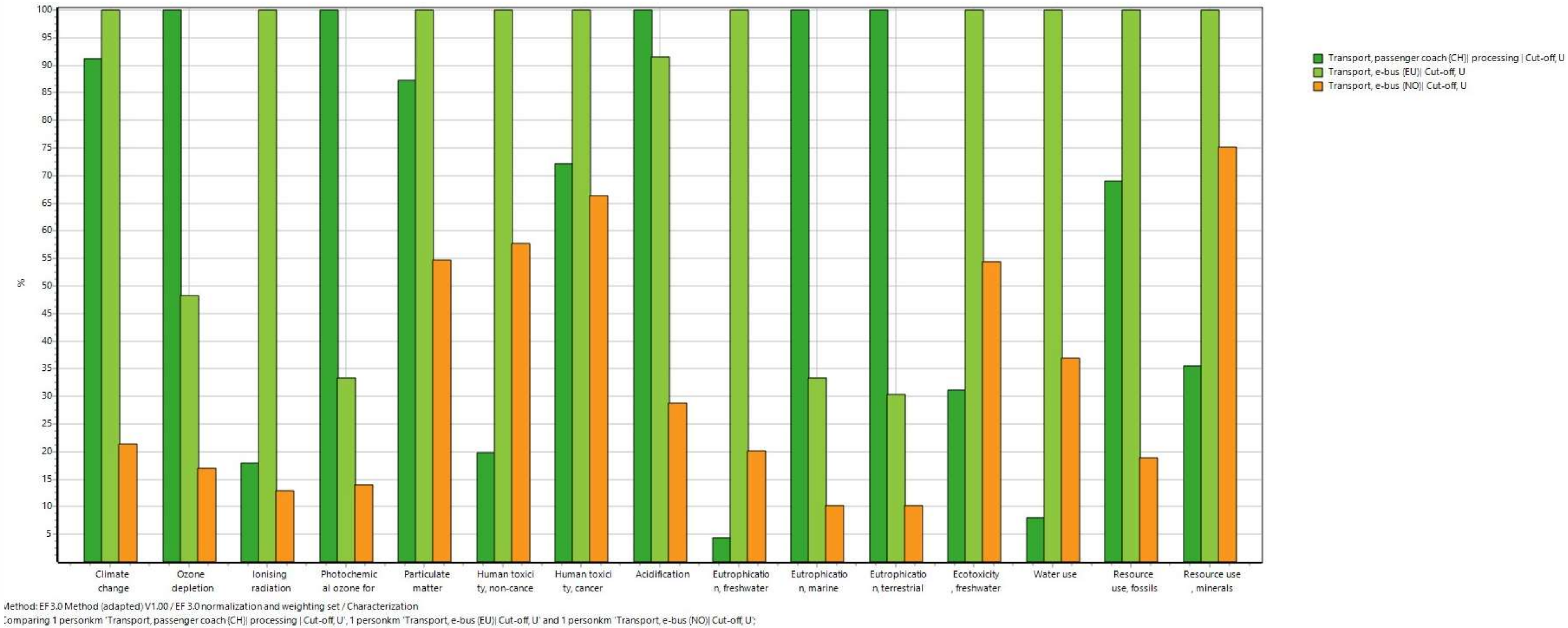


Figure 11. Comparison of different public bus transport options. Dark green a conventional diesel coach; Light green: the modelled e-bus (average EU electricity supply mix); Orange: modelled e-bus transportation in Norway (best case scenario).

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

In Figure 10 the process contribution analysis is shown for the e-bus transportation (Belgium case), where it can be seen that the electricity input to charge the battery and the battery itself are the main drivers of almost all environmental impacts.

In Figure 11 a comparison of the environmental performance of three different public bus transportation alternatives is shown. There it can be seen the criticality of the energy mix and the emissions and impacts embodied in the electricity consumption for the battery charge of an electric bus. In this figure, we compare the environmental performance of a conventional diesel coach with a EU-average e-bus (same e-bus as described above, with the average EU electricity mix as input) and a best-case e-bus transportation represented by Norway, whose electricity production is mainly based in RES (especially hydro power). According to this analysis, an e-bus fed with an EU-average electricity would perform worse in most impact categories (Climate Change, Ionising radiation, Particulate Matter, Toxicity, Freshwater Eutrophication, Water use and Resource use) than the diesel counterpart (performing worse for the impact categories of Ozone Depletion, Photochemical Ozone formation, Acidification, Eutrophication – marine & terrestrial). The Norwegian e-bus case demonstrates the importance of increasing the RE share into the European electricity markets, if the electrification of the transport sector is to yield significant environmental benefits. This good case example only showed a worse environmental performance than the diesel coach transportation for the impact categories of Resource use (minerals and metals), Freshwater Eutrophication, Water use and Toxicity (human, non-cancer diseases and eco-toxicity).

3.5 Heat pumps

For this final LCA screening of the good practice cases for heating technologies, two different types of heat pumps for household applications were considered: borehole and air-water heat pumps of 10 kW capacity each. The datasets represent the production of heat with these two heat pumps for an average single-family house in Europe. Switzerland is assumed to represent an average climatological and geological location in Europe.

The air-water heat pump has a Seasonal Performance Factor (SPF) of 2.8 (year 1998 data). The SPF values rose continuously until 1995 but then have remained rather constant, according to measurements of Roth 2001. The estimation of the SPF of the borehole heat pump is based on

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

a COP (Coefficient of Performance) value range of 3.47 to 4.84, which averaged it amounts to 3.83.

For the borehole heat pump, a system with a heating output of 10,25 kW (at a supply temperature of 40°C), a mean cooling capacity of 8,25 kW (to dimension the borehole heat exchanger) and an extraction performance of 55 W/m, taken as in Ecoinvent 3.6. The system is assumed to be operated without an auxiliary heating system.

Finally, a small-scale heat pump was also considered for bigger space applications like a municipal building or a small industry. The modelled heat pump has a capacity of 30 kW and it is installed at a 160 kW cogeneration unit. This setup makes this heat pump type the most efficient of the modelled heating systems, as it can be seen by comparing the Carbon Footprint results depicted in **Figure 12** to **Figure 14**. The full environmental footprint numeric results for all the impact categories and all the countries considered can be seen in **Table 14** to **Table 16**, presented after the Figures.

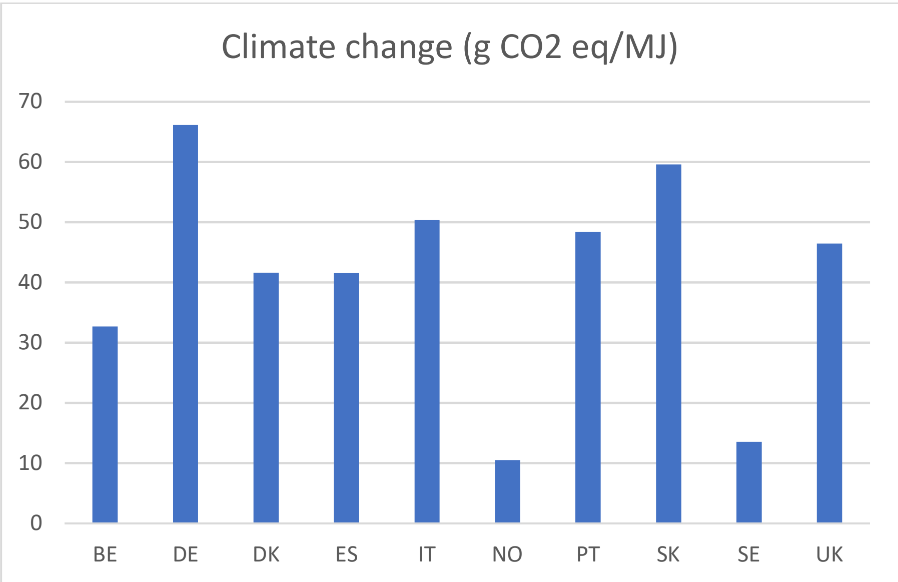


Figure 12. Global warming potential results (impact category Climate Change) for each country scenario of heat production with an air-water heat pump

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

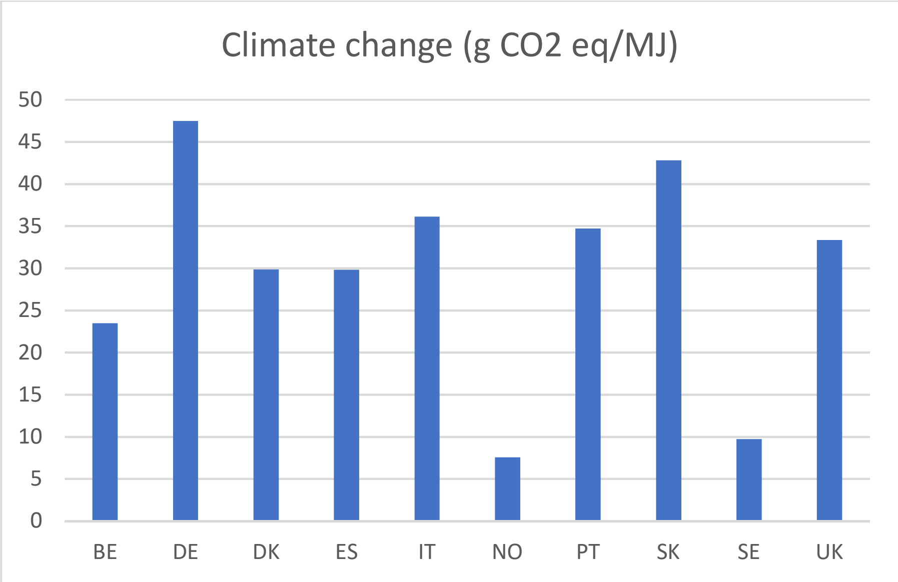


Figure 13. Global warming potential results (impact category Climate Change) for each country scenario of heat production with a borehole heat pump

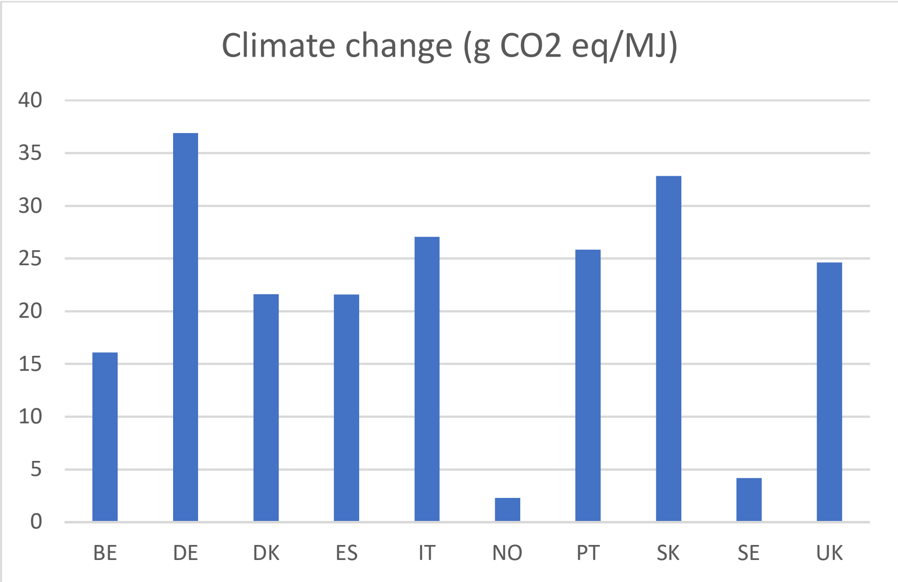


Figure 14. Global warming potential results (impact category Climate Change) for each country scenario of heat production with a centralised 30 kW heat pump coupled to a 160 kW cogeneration unit

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

Table 14. Environmental footprint of 1 MJ heat production from an air-water heat pump in ten European countries. Characterization method EF v3.

Impact category	Unit	BE	DE	DK	ES	IT	NO	PT	SK	SE	UK
Climate change	kg CO2 eq	0.032682	0.066139	0.041596	0.041545	0.050306	0.010497	0.048343	0.059597	0.013524	0.046432
Ozone depletion	kg CFC11 eq	1.1E-08	8.11E-09	7E-09	9.49E-09	1.16E-08	6.03E-09	7.91E-09	1.01E-08	8.33E-09	9.76E-09
Ionising radiation	kBq U-235 eq	0.038479	0.010154	0.005052	0.02355	0.005163	0.001253	0.002656	0.035991	0.04151	0.030608
Photochemical ozone formation	kg NMVOC eq	4.38E-05	8.16E-05	7.26E-05	0.000133	0.000101	1.16E-05	0.000139	0.00013	2.12E-05	8.54E-05
Particulate matter	disease inc.	4.88E-10	7.48E-10	7.34E-10	8.23E-10	9.57E-10	2.01E-10	8.77E-10	1.29E-09	3.97E-10	6.11E-10
Human toxicity, non-cancer	CTUh	4.49E-10	7.58E-10	6.26E-10	6.79E-10	5.62E-10	3.35E-10	6.49E-10	8.01E-10	3.87E-10	5.89E-10
Human toxicity, cancer	CTUh	1.35E-11	1.84E-11	1.75E-11	1.91E-11	1.73E-11	1.05E-11	1.72E-11	2.28E-11	1.23E-11	1.59E-11
Acidification	mol H+ eq	7.69E-05	0.000182	0.000149	0.000314	0.000243	3.44E-05	0.000352	0.000383	4.88E-05	0.000164
Eutrophication, freshwater	kg P eq	8.04E-06	8.36E-05	2.58E-05	1.58E-05	1.37E-05	3.86E-06	1.83E-05	7.25E-05	5.34E-06	1.11E-05
Eutrophication, marine	kg N eq	1.63E-05	4.35E-05	2.82E-05	4.7E-05	3.27E-05	3.36E-06	4.75E-05	5.63E-05	8.49E-06	3.06E-05
Eutrophication, terrestrial	mol N eq	0.000168	0.000421	0.000334	0.000494	0.000434	4.05E-05	0.000507	0.000467	8.77E-05	0.000333
Ecotoxicity, freshwater	CTUe	0.569457	0.789151	0.898924	0.77118	0.686192	0.287662	0.841751	0.769833	0.454829	0.729946
Water use	m3 depriv.	0.009536	0.003216	0.005297	0.023028	0.02456	0.002693	0.021397	0.013	0.007658	0.00193
Resource use, fossils	MJ	0.980322	0.78447	0.438155	0.775973	0.621353	0.040093	0.505916	1.144016	0.59823	0.938053
Resource use, minerals and metals	kg Sb eq	3.79E-07	5.71E-07	3.91E-07	3.67E-07	4.22E-07	2.71E-07	3.51E-07	4.95E-07	2.97E-07	3.76E-07

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

Table 15. Environmental footprint of 1 MJ heat production from a borehole (air-brine water) heat pump in ten European countries. Characterization method EF v3.

Impact category	Unit	BE	DE	DK	ES	IT	NO	PT	SK	SE	UK
Climate change	kg CO2 eq	0.023469	0.047482	0.029867	0.02983	0.036118	0.007546	0.03471	0.042787	0.009718	0.033338
Ozone depletion	kg CFC11 eq	7.44E-09	5.38E-09	4.59E-09	6.37E-09	7.87E-09	3.89E-09	5.24E-09	6.81E-09	5.54E-09	6.57E-09
Ionising radiation	kBq U-235 eq	0.027655	0.007325	0.003663	0.01694	0.003743	0.000936	0.001943	0.025869	0.029831	0.022006
Photochemical ozone formation	kg NMVOC eq	3.82E-05	6.54E-05	5.89E-05	0.000102	7.92E-05	1.51E-05	0.000106	1E-04	2.21E-05	6.81E-05
Particulate matter	disease inc.	4.79E-10	6.66E-10	6.56E-10	7.2E-10	8.15E-10	2.73E-10	7.58E-10	1.05E-09	4.13E-10	5.67E-10
Human toxicity, non-cancer	CTUh	3.12E-10	5.35E-10	4.4E-10	4.78E-10	3.93E-10	2.31E-10	4.56E-10	5.65E-10	2.68E-10	4.13E-10
Human toxicity, cancer	CTUh	9.7E-12	1.32E-11	1.25E-11	1.37E-11	1.24E-11	7.49E-12	1.23E-11	1.63E-11	8.84E-12	1.14E-11
Acidification	mol H+ eq	5.95E-05	0.000135	0.000111	0.00023	0.000179	2.9E-05	0.000257	0.000279	3.93E-05	0.000122
Eutrophication, freshwater	kg P eq	5.68E-06	5.99E-05	1.84E-05	1.12E-05	9.75E-06	2.68E-06	1.3E-05	5.2E-05	3.75E-06	7.91E-06
Eutrophication, marine	kg N eq	1.39E-05	3.34E-05	2.25E-05	3.6E-05	2.57E-05	4.6E-06	3.63E-05	4.26E-05	8.29E-06	2.41E-05
Eutrophication, terrestrial	mol N eq	0.000144	0.000326	0.000263	0.000378	0.000335	5.29E-05	0.000388	0.000359	8.67E-05	0.000263
Ecotoxicity, freshwater	CTUe	0.402795	0.560478	0.639267	0.54758	0.48658	0.200538	0.598232	0.546613	0.320521	0.517984
Water use	m3 depriv.	0.006961	0.002425	0.003919	0.016645	0.017744	0.002049	0.015474	0.009447	0.005613	0.001502
Resource use, fossils	MJ	0.714855	0.574284	0.325719	0.568186	0.457208	0.040013	0.374355	0.832346	0.440612	0.684517
Resource use, minerals and metals	kg Sb eq	2.67E-07	4.04E-07	2.76E-07	2.58E-07	2.97E-07	1.89E-07	2.47E-07	3.5E-07	2.08E-07	2.65E-07

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

Table 16. Environmental footprint of 1 MJ heat production from a central, small-scale (30 kW) heat pump in ten European countries. Characterization method EF v3.

Impact category	Unit	BE	DE	DK	ES	IT	NO	PT	SK	SE	UK
Climate change	kg CO2 eq	0.016076	0.036886	0.021621	0.021589	0.027038	0.002278	0.025817	0.032817	0.004161	0.024629
Ozone depletion	kg CFC11 eq	3.43E-09	1.65E-09	9.58E-10	2.51E-09	3.8E-09	3.56E-10	1.52E-09	2.89E-09	1.79E-09	2.68E-09
Ionising radiation	kBq U-235 eq	0.023909	0.006291	0.003118	0.014624	0.003187	0.000756	0.001628	0.022362	0.025795	0.019014
Photochemical ozone formation	kg NMVOC eq	2.48E-05	4.83E-05	4.27E-05	8.03E-05	6.04E-05	4.79E-06	8.39E-05	7.83E-05	1.08E-05	5.07E-05
Particulate matter	disease inc.	2.68E-10	4.31E-10	4.22E-10	4.77E-10	5.6E-10	9.03E-11	5.1E-10	7.66E-10	2.12E-10	3.45E-10
Human toxicity, non-cancer	CTUh	1.88E-10	3.8E-10	2.98E-10	3.31E-10	2.58E-10	1.17E-10	3.13E-10	4.07E-10	1.5E-10	2.75E-10
Human toxicity, cancer	CTUh	6.55E-12	9.56E-12	9E-12	1E-11	8.88E-12	4.64E-12	8.85E-12	1.23E-11	5.81E-12	8.01E-12
Acidification	mol H+ eq	3.93E-05	0.000105	8.42E-05	0.000187	0.000143	1.29E-05	0.00021	0.00023	2.18E-05	9.32E-05
Eutrophication, freshwater	kg P eq	4.04E-06	5.1E-05	1.51E-05	8.85E-06	7.57E-06	1.45E-06	1.04E-05	4.42E-05	2.37E-06	5.97E-06
Eutrophication, marine	kg N eq	9.53E-06	2.65E-05	1.69E-05	2.86E-05	1.98E-05	1.48E-06	2.9E-05	3.44E-05	4.67E-06	1.84E-05
Eutrophication, terrestrial	mol N eq	9.67E-05	0.000254	0.0002	0.000299	0.000262	1.76E-05	0.000308	0.000283	4.69E-05	0.000199
Ecotoxicity, freshwater	CTUe	0.278449	0.415093	0.483369	0.403916	0.351055	0.103179	0.447809	0.403078	0.207153	0.378269
Water use	m3 depriv.	0.005793	0.001862	0.003156	0.014185	0.015137	0.001537	0.01317	0.007947	0.004625	0.001062
Resource use, fossils	MJ	0.605422	0.483607	0.268207	0.478322	0.382152	0.020622	0.310353	0.707236	0.36777	0.579132
Resource use, minerals and metals	kg Sb eq	1.85E-07	3.04E-07	1.92E-07	1.77E-07	2.11E-07	1.17E-07	1.67E-07	2.57E-07	1.34E-07	1.83E-07

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

4. Discussion and Conclusions

The present deliverable represents the first round of LCA results and LCA datasets of renewable energy (RE) technologies that will be progressively built and gradually extended during the rest of the project. The presented analysis covers three major renewable energy sources (RES): hydro, wind, solar, and it focused on one specific technology for each RES: run-of-river hydro power, onshore wind power and multi-crystalline Si-cell photovoltaic (PV) power. Additionally, the performed LCA screening also assessed the environmental footprint of generic electric vehicles (EV) (electric cars and buses) and heat pumps (air-water, borehole and central), given their presence in some European public tenders. The performed LCA screening and construction of first LCA datasets are therefore linked to some green public procurement tenders that were identified during the TED database screening.

Some of the RE technologies assessed rely on large infrastructures requiring a considerable initial investment in terms of resource consumption and environmental interventions. The LCA screening results showed that the main infrastructures (hydropower plant construction; wind turbine manufacturing and installation; solar PV panels) were indeed responsible of most of the environmental burden of the assessed RE technologies and, consequently, their delivered power. The specific results are highly sensitive to the primary data utilized in such infrastructure inventories.

For the case of run-of-river electricity, the hydropower plant construction data refers to a mix of dams built between 1945 and the beginning of the 1980s. The technological and temporal representativity of such plants might differ substantially from more modern plants, especially for an individual type and for the smallest-scale run-of-river plants that work without dams. Due to lack of data, it was not possible to adapt the generic results to each country, taking into account the different water availabilities (hence the productivity) of each region. Acquiring first-hand, updated, and geo-spatialized data will be of primary importance for a reliable and robust LCA of such RE electricity.

For the case of wind power, the manufacturing and installation data of the considered 2 MW wind turbine (metals consumptions, concrete use for foundation, fiberglass for blades, etc.) seem

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

more recent, completer and more reliable, and therefore more representative of modern turbines. The LCA results for the best countries (UK and NO) showed a similar environmental footprint of the power delivered as that of the generic run-of-river plant. The LCA results presented seemed also in line with other LCA studies of similar wind turbines, although another recent study that carried out a statistical life-cycle inventory analysis for Danish wind power showed that previous LCA studies might overestimate the environmental performance of wind turbines (Sacchi et al., 2019). In their analysis, an average of 17.8 g CO2 eq/kWh was found, about the double of our estimate and previous literature.

In the analysed cases of solar PV panels, Si-cell and wafer production data, as well as cell efficiency should be further updated (study from 2012, older manufacturing data), since the environmental footprint largely relies on them. The produced LCA results seem in line with other studies (three to five-fold impacts per kWh, compared to wind power). Ideally, actual maintenance (operations, replacements, etc.) and decommissioning data from real case studies could shed some light regarding the uncertainties involved in these necessary assumptions and coarse-resolution values (e.g. global average data and inventories for wafer manufacturing).

For the case of EVs, the Li-ion (LMO) battery component (its material content and manufacturing data) resulted a key process for the overall performance of the transport service provided by electric cars and e-buses. Consulting recent literature and specialized industry information, it was found out that LMO batteries are being phased out to a large extent in the automotive sector. LMO batteries are nowadays replaced by higher power density NMC batteries, which are also based in Lithium but contain other metals in the cathode like Nickel and Cobalt. No manufacturing data for these materials nor the batteries themselves could be found, and this battery module cannot be found either in the Ecoinvent 3.6 database. Thus, the presented LCA screening results are considered to be approximative of the potential environmental impacts of such transportation services. The inventory of LMO batteries were combined with a trolleybus operation dataset (for the consumption and emission data during the use phase) and with a normal coach manufacturing dataset, in order to obtain the environmental footprint of e-bus transportation. With these assumptions and simplifications, it was found that such e-buses would perform worse for many impact categories than conventional diesel coaches. Only when the

This project has received funding from the European Union's Horizon 2020
Research and Innovation programme under Grant Agreement No 857831

electricity input derives from country-mixes with high shares of RE like that of Norway, the e-bus would perform significantly better than the diesel one.

Finally, the environmental performance of heat pumps too is directly related to the country where they are installed in. This relationship is even stronger than in the case of EVs (whether e-cars or e-buses), since there are no batteries involved in this technology. Besides the efficiency of the machines themselves (so-called SPF, similar to the COP of cooling systems), the electricity consumption and the related LCA dataset covering the technology/energy mix of each country is therefore crucial for their environmental performance.

For some partner countries where the RE technologies were simulated to be implemented, the actual productivity and availability of certain RES varies significantly across and within countries, e.g. solar irradiation. The presented results for solar PV electricity rely on the solar irradiation figures take from the PVGIS tool, while the wind power results depend on the wind distribution and mean speed, taken as a country average from the Global Wind Atlas. For the future case studies, the specific location will be known so the uncertainty related to average country-values will be surmounted, as the site-specific RES (water, wind, sun) availability will be utilized.

This project has received funding from the European Union's Horizon 2020
Research and Innovation programme under Grant Agreement No 857831

Critical parameters

Since the estimated power production of a RE technology goes in the denominator (to amortize the infrastructure-related emissions over the lifetime electricity output), the higher the estimated productivity, the lower it becomes the environmental footprint. In Table 17 we present a summary of the critical parameters and assumptions for the LCA results (thus the environmental performance) of RE technologies. The authorities preparing GPP tenders could focus on these critical parameters and define targeted criteria for them. The criteria could be qualitative – regarding a data quality analysis, data/performance verification requirements, repairability, etc. – and/or quantitative – setting for instance minimum thresholds for efficiency, durability/lifetime, or recycled material content.

Table 17. Summary table that gathers the key critical parameters and assumptions of the LCA models. The LCA results, and the environmental performance of RE technologies in general, are highly sensitive to them

RE technologies	Critical parameters	Critical assumptions
Hydro, run-of-river	Capacity or load factor (location) Inventory of plant construction (manufacturer) Type of turbine and plant configuration (installation)	**Lifetime expectancy** (or operational lifetime until decommissioning) **End of Life** processes for main components and materials
Wind power	Capacity or load factor (location) Mean windspeed (location) Weibull parameter (location) Wind turbine and foundation inventory (manufacturer)	
Solar PV	Solar incidence angle on panels (orientation, tracking system: installer) Annual solar irradiation (location) PV cell efficiency (manufacturer) Wafer & cell production inventory (manufacturer)	
Electric Vehicles	Type of battery (power density, lifetime, weight) Inventory data for battery production (manufacturer) Type of EV (size, weight, lifetime) Electricity input (energy mix)	
Heat pumps	Electricity input (energy mix)	

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

	SPF (manufacturer)	

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

5. References

Aegerter A.m Bosshardt O. (1954), Das Kraftwerk Birsfelden Wassern und Energiewirtschaft Vol. 46 Issue number: 5-7.

Baumann J. (1949) Kraftwerk Rupperswil Auenstein.

Bódis, K., Monforti, F., & Szabó, S. (2014). Could Europe have more mini hydro sites? A suitability analysis based on continentally harmonized geographical and hydrological data. *Renewable and Sustainable Energy Reviews*, *37*, 794–808. https://doi.org/10.1016/j.rser.2014.05.071

Bonou, A., Laurent, A., & Olsen, S. I. (2016). Life cycle assessment of onshore and offshore wind energy-from theory to application. *Applied Energy*, *180*, 327–337. https://doi.org/10.1016/j.apenergy.2016.07.058

Dwivedi, P., Khanna, M., & Fuller, M. (2019). Is wood pellet-based electricity less carbon-intensive than coal-based electricity? It depends on perspectives, baselines, feedstocks, and forest management practices. *Environmental Research Letters*, *14*(2). https://doi.org/10.1088/1748-9326/aaf937

Elsam Engineering A/S. (2004). Life Cycle Assessment of offshore and onshore sited wind farms. *Engineering*.

European Commission. (2000). Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 - Establishing a framework for Community action in the field of water policy. *Official Journal of European Union*, 72.

European Commission. (2009). Directive 2009/28/EC of the European Parliament and of the Council on the promotion of the use of energy from renewable sources. *Official Journal of the European Union*, *140*(16), 16–62. https://doi.org/10.3000/17252555.L_2009.140.eng

European Commission. (2013). Building the Single Market for Green Products - Facilitating better information on the environmental performance of products and organisations. *Publications Office of the European Union*, *1*, 13. https://doi.org/10.1007/s13398-014-0173-7.2

Eurostat. (2019). *Energy, Transport and environment statistics. 2019 edition*. https://doi.org/10.2785/660147

Fargione, J., Hill, J., Tilman, D., Polasky, S., & Hawthorne, P. (2008). Land clearing and the biofuel carbon debt. *Science (New York, N.Y.)*, *319*(5867), 1235–1238. https://doi.org/10.1126/science.1152747

Guezuraga, B., Zauner, R., & Pölz, W. (2012). Life cycle assessment of two different 2 MW class wind turbines. *Renewable Energy*, *37*(1), 37–44. https://doi.org/10.1016/j.renene.2011.05.008

Hsu, D. D., O'Donoughue, P., Fthenakis, V., Heath, G. A., Kim, H. C., Sawyer, P., Choi, J. K., & Turney, D. E. (2012). Life Cycle Greenhouse Gas Emissions of Crystalline Silicon Photovoltaic Electricity Generation: Systematic Review and Harmonization. *Journal of*

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

Industrial Ecology, *16*(SUPPL.1). https://doi.org/10.1111/j.1530-9290.2011.00439.x

Jungbluth, N., & Stucki, M. (2012). Life cycle inventories of photovoltaics. *ESU-Services Ltd., …*, *17*, 250.

Lakhani, R., Doluweera, G., & Bergerson, J. (2014). Internalizing land use impacts for life cycle cost analysis of energy systems: A case of California's photovoltaic implementation. *Applied Energy*, *116*(2014), 253–259. https://doi.org/10.1016/j.apenergy.2013.11.038

Lapola, D. M., Schaldach, R., Alcamo, J., Bondeau, A., Koch, J., Koelking, C., & Priess, J. a. (2010). Indirect land-use changes can overcome carbon savings from biofuels in Brazil. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(8), 3388–3393. https://doi.org/10.1073/pnas.0907318107

McKechnie, J., Colombo, S., Chen, J., Mabee, W., & MacLean, H. L. (2011). Forest bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels. *Environmental Science & Technology*, *45*(2), 789–795. https://doi.org/10.1021/es1024004

Pachauri, R. K., Meyer, L., Van Ypersele, J.-P., Brinkman, S., Van Kesteren, L., Leprince-Ringuet, N., & Van Boxmeer, F. (2014). IPCC AR5 Synthesis Report. In *Russian Federation), Hoesung Lee (Republic of Korea) Scott B. Power (Australia) N.H. Ravindranath (India)*. IPCC, Geneva, Switzerland.

Plevin, R. J., Jones, A. D., Torn, M. S., Group, R., Division, E. S., & Berkeley, L. (2010). The greenhouse gas emissions from indirect land use change are uncertain, but potentially much greater than previously estimated. *Environmental Science & Technology.*, *44*(21), 8015–8021.

Premalatha, M., Tabassum-Abbasi, Abbasi, T., & Abbasi, S. A. (2014). A critical view on the eco-friendliness of small hydroelectric installations. *Science of the Total Environment*, *481*(1), 638–643. https://doi.org/10.1016/j.scitotenv.2013.11.047

Sacchi, R., Besseau, R., Pérez-López, P., & Blanc, I. (2019). Exploring technologically, temporally and geographically-sensitive life cycle inventories for wind turbines: A parameterized model for Denmark. *Renewable Energy*, *132*, 1238–1250. https://doi.org/10.1016/j.renene.2018.09.020

Saez de Bikuña, K., Hauschild, M. Z., Pilegaard, K., & Ibrom, A. (2017). Environmental performance of gasified willow from different lands including land-use changes. *GCB Bioenergy*, *9*(4), 756–769. https://doi.org/10.1111/gcbb.12378

Steer Davies Gleave. (2016). *Comprehensive Study on Passenger Transport by Coach in Europe*. *April*. https://ec.europa.eu/transport/sites/transport/files/modes/road/studies/doc/2016-04-passenger-transport-by-coach-in-europe.pdf

Treyer, K., & Bauer, C. (2016). Life cycle inventories of electricity generation and power supply in version 3 of the ecoinvent database—part I: electricity generation. *International Journal of Life Cycle Assessment*, *21*(9), 1236–1254. https://doi.org/10.1007/s11367-013-0665-2

Vidal-Legaz, B., Sala, S., Antón, A., Souza, D. M. De, Nocita, M., Putman, B., & Teixeira, R. F. M. (2016). *Land-use related environmental indicators for life cycle assessment - Analysis of key aspects in land use modelling - Study*. https://doi.org/10.2788/905478

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

Wiedmann, T. O., Suh, S., Feng, K., Lenzen, M., Acquaye, A., Scott, K., & Barrett, J. R. (2011). Application of hybrid life cycle approaches to emerging energy technologies - The case of wind power in the UK. *Environmental Science and Technology*, *45*(13), 5900–5907. https://doi.org/10.1021/es2007287

Withey, P., Johnston, C., & Guo, J. (2019). Quantifying the global warming potential of carbon dioxide emissions from bioenergy with carbon capture and storage. *Renewable and Sustainable Energy Reviews*, *115*, 109408. https://doi.org/10.1016/J.RSER.2019.109408

Wong, J. H., Royapoor, M., & Chan, C. W. (2016). Review of life cycle analyses and embodied energy requirements of single-crystalline and multi-crystalline silicon photovoltaic systems. In *Renewable and Sustainable Energy Reviews* (Vol. 58, pp. 608–618). Elsevier. https://doi.org/10.1016/j.rser.2015.12.241

Zanchi, G., Pena, N., & Bird, N. (2012). Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *GCB Bioenergy*, *4*(6), 761–772. https://doi.org/10.1111/j.1757-1707.2011.01149.x

Nordostschweizerische Kraftwerke AG (1956), Das Kraftwerk Wildegg Brugg - Schweizerische Bauzeitung Volume 74.

TheWindPower (2014) Wind turbines and wind farms database. www.thewindpower.net

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 857831

@xpress-project · www.xpress-h2020.eu

APRE Agenzia per la Promozione della Ricerca Europea

eambiente

University of York

elementenergy

DIW BERLIN

NTNU Norwegian University of Science and Technology

ovgroup green economy industry

Linnæus University

LOBA CUSTOMER EXPERIENCE DESIGN

INSME LOCAL STRENGTH • GLOBAL REACH International Network for SMEs

circe RESEARCH CENTRE FOR ENERGY RESOURCES AND CONSUMPTION

European Green Cities

Alleanza per il Clima Italia onlus

Climate Alliance

SLOVENSKÝ ŽIVNOSTENSKÝ ZVÄZ

eurada

XPRESS