Quantification of the carbon intensity of electricity produced and used in Europe

Applied Energy 305 (2022) 117901

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Quantification of the carbon intensity of electricity produced and used in Europe

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HIGHLIGHTS

- Carbon intensity of electricity produced and used is quantified.
- A Well-to-Wheel methodology considers all upstream and combustion emissions.
- Own electricity consumption, transmission and distribution losses in the grid are counted.
- Electricity trade impacts the carbon intensity of used electricity.
- Carbon intensity of electricity shows a clear reduction trend over the last years.

ARTICLE INFO

Keywords:
Electricity
Carbon intensity
Greenhouse gas emissions
Well-to-Wheel

ABSTRACT

The EU has a comprehensive legislation to facilitate the energy transition towards a low carbon energy system and achieve the EU's Paris Agreement commitments for reducing greenhouse gas emissions. The European Green Deal is an integral part of the EU strategy for a sustainable and climate neutral economy by 2050. The decarbonisation of the power generation is essential to achieve the goal of decarbonising the energy and transport sectors. This paper presents a study conducted to quantify the carbon emissions associated to the production of electricity produced and used in European countries, based on a comprehensive methodology developed for this purpose. A spreadsheet model has been developed that considers the various sources for electricity generation, the type of plants, conversion efficiencies, upstream emissions and emissions from power plant construction, as well as the electricity trade. The results show the greenhouse gas emissions from the production and use of electricity in all European countries, revealing significant variations between countries. The carbon intensity of electricity shows a clear reduction trend since 1990, for most of the European countries. In the European Union, carbon intensity of electricity used at low voltage degreased from 641 gCO2eq/kWh in 1990 to 334 gCO2eq/kWh in 2019, and this trend is expected to continue in the coming years.

1. Introduction

The global commitments to reduce GreenHouse Gas (GHG) emissions are not on track to achieve the temperature goals of the Paris Agreement to keep global warming well below 2 °C, and pursuing efforts to limit the increase to 1.5 °C. According to IEA [1], the consumption of fossil fuel at global level continues to grow and the associated energy-related GHG emissions increased by 1.7% in 2018, reaching a peak of 33.1 Gt CO_{2e}. While this happens at international level, GHG emissions were reduced in the European Union (EU) by 24% between 1990 and 2019. The most significant decline took place in sectors covered by the EU Emissions Trading System (EU ETS), in particular the power plants sector, while emissions excluded from the ETS (such as emissions from non-ETS industry, transport, buildings, agriculture and waste) remained stable for several years [2]. A similar trend occurred in the US, where the average carbon intensity was reduced by 21% from 2000 to 2015 [3].

The EU adopted a comprehensive legislation to facilitate the energy transition toward a low carbon energy system and achieve the EU's Paris Agreement commitments for reducing greenhouse gas emissions. The European Union policy for greening the energy system has a long history. In 1997, the White Paper for a Community Strategy and Action Plan, *Energy for the future: Renewable sources of energy* [4] set an

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https://doi.org/10.1016/j.apenergy.2021.117901
Received 15 April 2021; Received in revised form 6 August 2021; Accepted 16 September 2021
0306-2619/

important milestone for the European Union energy policy. This white paper proposed doubling the share of renewable energy in the EU gross energy consumption from 6% to 12% by 2010 and set technology specific targets for biomass, wind energy, photovoltaic energy, geothermal and hydro. As a result, significant progress has been achieved in the deployment of renewable energy sources and, although the indicative target of 12% renewable energy in gross energy consumption had been missed, some targets for renewable energies have been achieved or even exceeded. The Renewable Electricity Directive 2001/77/EC [5] set in 2001 a target of 21% of total electricity to be produced from renewable sources by 2010. A national indicative target was defined for electricity generation from renewable sources. As a result, the share of renewable electricity in the EU increased from almost 13% in 1997 to 19.5% in 2010, with significant progress in renewable electricity production from hydro, wind, biomass, solar and geothermal as well [6].

In 2006, the Green Paper *A European Strategy for Sustainable, Competitive and Secure Energy* [7] set down the EU baseline to develop a long-term and coherent energy policy. In 2007, the European Council adopted ambitious energy and climate change objectives for 2020: to reduce GHG emissions by 20%, to increase the share of renewable energy to 20% and to make a 20% improvement in energy efficiency compared to the baseline projection. The European Council has also made a long-term commitment to the decarbonisation of the economy, with a target to achieve from 80% to 95% reduction in CO_2 emissions by 2050. The integrated Energy and Climate Change package proposed by the European Commission included the commitment to combat climate change and increase the energy security and competitiveness and it also incorporated the energy and climate goals: *Energy policy for Europe* [8] and *Limiting Global Climate Change to 2 °C - The way ahead for 2020 and beyond* [9]. The *Renewable Energy Directive (RED)* 2009/28/EC *on the promotion of renewable energy sources* [10] required Member States (MS) to increase the share of renewable energy to 20% of gross final energy consumption and 10% renewable energy in transport by 2020.

The *Clean Energy for all Europeans* package [11] was proposed by the European Commission in 2016 to ensure a clean and fair energy transition and to accomplish the EU's Paris Agreement commitments for reducing GHG emissions. In order to foster the decarbonisation of the energy sector, the revised Renewable Energy Directive RED II [12] set the overall EU target for renewable energy consumption at 32% and at least 14% renewable energy in road and rail transport by 2030. RED II introduced caps and multipliers to promote the increased use of advanced biofuels and renewable electricity in transport. For example, renewable electricity will count 4 times its energy content towards the 14% renewable energy in transport target when used in road vehicles and 1.5 times when used in rail transport. The 2030 climate and energy framework [13] set the EU targets and policy objectives to 2030 to facilitate the transition away from fossil fuels towards cleaner energy and achieve the EU's Paris Agreement commitments for reducing greenhouse gas emissions: at least 40% reduction in GHG emissions (from 1990 levels); at least 32% share for renewable energy; at least 32.5% improvement in energy efficiency.

The *European Green Deal* [14] is an integral part of this EU strategy to implement the United Nation's 2030 Agenda for sustainable development [15]. It represents a new growth strategy aimed at a sustainable and climate-neutral economy by 2050. As part of the European Green Deal, the European Commission proposed in September 2020 to raise the GHG emission reduction target for 2030 to at least 55% compared to 1990 levels. Decarbonising the energy system is essential for climate neutrality, the main goal set in the European Green Deal. The European Commission has started the process of making legislative proposals, including increased energy efficiency and renewable energy, by June 2021, in order to achieve the increased target.

With the 2030 Climate Target Plan [16], the European Commission looked into different policy options to reach the 2030 GHG reduction target, reviewing a set of actions required across all sectors of the economy and launching the revisions of key legislative instruments. Achieving 55% GHG emissions reduction will require actions in all sectors: energy, transport, industry and agriculture. Renewable energy could reach a share of 38% to 40% of gross final consumption. By 2030, the share of renewable energy in the transport sector has to increase to around 24% through the electrification of transport, the use advanced biofuels and other renewable and low carbon fuels. The Commission proposed in the European Climate Law [17] a legally binding target of net zero GHG emissions by 2050 and set into law the goal set out in the European Green Deal to become a climate-neutral economy by 2050. It also includes the new EU target for 2030 of reducing GHG emissions by at least 55% compared 1990 levels.

To achieve climate neutrality, a 90% reduction in transport emissions is also needed by 2050 [14]. The electrification of transport is key to reach the decarbonisation of this sector. The Commission already adopted in 2016 a low-emission mobility strategy [18], identifying priority areas for actions. The envisaged measures include the deployment of low-emission alternative energy for transport, such as advanced biofuels, hydrogen and renewable synthetic fuels, plus the electrification of transport and the shift towards zero-emission vehicles.

The large variety of the electricity mix in the EU Member States has significant impact on the GHG emissions resulting from the production of electricity. This explains why the use of the average electricity mix at European Union (EU) level is not an adequate approach to assess the impact of the use of electricity in various fields, such as transport. The quantification of GHG from electricity generation and use is not widely available in literature. Moro and Lonza [19] provided the Well-to-Wheel (WTW) calculations on the electricity used at national level in the European context, taking into account upstream emissions and power losses in the electricity grid and trade to a certain extent. The European Environment Agency (EEA) provides a data set including average annual carbon emission intensity of electricity generation, per Member State and for the EU as a whole [20]. It is not clear, however, which emissions are included in the calculation (e.g. if only combustion emissions are included or if upstream emissions are also included). Tranberg et al (2019) [21] developed a method for real-time carbon accounting of electricity production and consumption based on flow tracing techniques that use power flows on the transmission network on an hourly basis, using CO_2 equivalent intensity per technology and country. The International Energy Agency (IEA) [22] provides annual time series of CO_2, CH_4 and N_2O emission factors from electricity generation, as well as correction factors for CO_2 emissions induced by electricity losses in the power grid and for CO_2 emissions induced by electricity trade for OECD countries. In the IEA data, upstream emissions or the emissions from the construction and decommissioning of electricity producing facilities are not considered.

Literature review shows a clear gap in the knowledge of the real GHG emissions associated with the production and the use of electricity with a severe impact of the assessment of different options for decarbonising the energy and transport sectors. In particular, in literature there is a lack of studies clearly addressing GHG emissions produced across the whole life cycle of electricity production and use, including upstream emissions, operational and use related emissions, etc. Additionally, few evaluation are available for the construction and decommissioning related emissions, of the electricity generation facilities.

This paper provides comprehensive estimations of these emissions, based on a new developed methodology, which enables an estimation of real emissions associated with the production and the use of electricity. The methodology proposed follows a Well-to-Wheel approach that considers all emissions that occur along the entire pathway, from fuel supply to the power plant, construction of the electricity generating facility, operational phase, plant decommissioning and waste management. Existing assessments ignore certain important phases in the electricity pathways that give only partial information about the real carbon intensity.

In addition, the new methodology takes into account the impact of electricity trade on the carbon intensity that can impact tremendously the carbon intensity of electricity used, but this is not considered so far in existing assessments of carbon intensity of electricity. The refined methodology considers all sources for electricity, including renewable energy sources, type of plant, conversion efficiencies, own electricity consumption in the power plant, as well as transmission and distribution losses in the grid. The new methodology enables an estimation of real emissions associated with the use of electricity that supports a meaningful comparison of the different options for decarbonising the energy and transport sectors.

The paper the provides the quantification of carbon intensities of both produced and used electricity in European countries along with a detailed analysis of the effect of the use of different sources for electricity production and use as well as electricity trade and the changes occurred between 1990 and 2019. After Introduction, Section 2 presents the methodology adopted to estimate the carbon intensity of produced and used electricity, including the input data and data sources. Section 3 focuses on the results in terms of electricity generation by country and carbon intensities of electricity generated and used in each country in 1990 and 2018. Conclusions are drawn in Section 4.

2. Materials and methods

This section describes in detail the main steps for the calculation of the carbon intensity of electricity produced and used at country level in Europe, employing the most recent and comprehensive set of statistical data available.

2.1. General methodological approach

For the calculation of the carbon intensity of electricity, the Well–To-Wheel approach has been chosen; the details of the methodology are presented in the JEC WTW report version 5 [23]. Compared to a comprehensive Life Cycle Assessment (LCA) approach, WTW can be described as a simplified LCA where the major impact category is the GHG emissions, expressed in gCO_{2eq}/MJ of fuel.

The approach followed in this JEC v5 study [23] allows quantifying the energy required and the GHG emissions resulting from the production, transport and distribution of conventional and alternative road transportation fuels (Well-To-Tank, WTT) - among others for electricity - and also to quantify the efficiency of different powertrains (Tank-To-Wheels, TTW) in converting those fuels. The GHGs taken into account are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), reported as gCO_{2eq}/MJ_{fuel}. In the WTW approach, emissions related to the hardware construction, maintenance and decommissioning of fuel and electricity producing facilities, including materials cycles, are not usually taken into account, due to the expected low contribution to the final emission values.

This study expands the boundaries of the WTW approach, by considering, for the purpose of calculating the carbon intensity of electricity generation, the emissions from the construction and decommissioning of power plants and upstream emissions. Therefore, the methodology for the carbon intensity calculation of electricity considers all the steps of the electric pathway: upstream emissions for providing fuel to power plants; emissions from the construction and decommissioning of electricity generation facilities; transmission and distribution losses in the electricity grid; losses in pump-storage; and the emissions from fuel combustion to produce electricity.

The GHG emissions from electricity generation depends on multiple factors, including conversion technology type, plant efficiency, fuel type and quality, fuel transport distance, local conditions (such as wind and solar resources) etc. Typically, GHG emissions decrease as the conversion efficiency and installed capacity of the power plant, among many factors, increase. The methodology developed in this study also considers the trade of electricity between countries that affects the carbon intensity of used electricity, depending on the carbon intensity of the electricity exchanged between trade partners. In this paper, the evaluation of life cycle CO_2 emissions from electricity generation includes the following:

- emissions from upstream processes of fuel supply and the provision of fuel to power plants: fuel mining, extraction or cultivation, fuel processing, transportation to electricity generation sites;
- emissions from plant construction: raw materials extraction, materials and equipment manufacturing, transportation from manufacturing facilities to construction sites and on-site construction;
- emissions from electricity generation: fuel combustion to generate electricity, operation and maintenance of electricity generation facilities;
- emissions from downstream processes: waste disposal, power plant decommissioning and land rehabilitation.

This methodology covers the main steps for the calculation of the carbon intensity of electricity throughout the stages of the electricity pathway: gross production, net production, electricity trade, supply post-trade and electricity used at high voltage, medium voltage and at low voltage.

2.2. Input data

2.2.1. Electricity production data

The methodology relies on a structured set of data, including detailed statistical data for primary energy consumption: the input for electrical energy production by power plants and power losses are from Eurostat and are reported for each European Union Member State [24]. Eurostat provides detailed information of the energy balances of energy products and their flow, from production to transformation and consumption in each Member State starting from 1990 [25]. For countries outside the European Union, the International Energy Agency provides data on the energy balances for coal, oil, natural gas and nuclear, as well as for renewable energy sources (wind, solar, geothermal, hydro, ocean, and biofuels and renewable wastes) and electricity generation in electricity only and CHP plants [26].

Input data on primary fuel consumption and energy production have been considered for the categories included in the energy balances of energy products and their flow in each Member State: solid fossil fuels, manufactured gases, peat and peat products, oil shale and oil sands, oil and petroleum products, natural gas, renewables and biofuels, non-renewable waste and nuclear. Renewables and biofuels include biofuels, renewable municipal waste, hydro, ocean, geothermal, wind, solar and heat pumps. As for any LCA based assessment, it has to be remarked that the accuracy of the results depend to a large extent on the quality of the input data. As a way to improve the accuracy of results, this study therefore proposes the use of a statistic based, coherent dataset of fuels, used for the electricity generation.

2.2.2. Electricity trade

Statistical data on the electricity trade is available from various sources, such as Eurostat that provides annual data on the imports of electricity and derived heat by partner country (online data code: NRG_TI_EH [27]) as well as exports of electricity and derived heat by partner country (online data code: NRG_TE_EH [28]). Most of the "unspecified" imports and exports could be assigned to particular importers or exporters on the basis of their declared exports or imports, or by verifying the electricity import and export data reported by partner countries. The few remaining minor discrepancies, between the exports country 'A' declared going to country 'B' and the imports country 'B' declared coming from country 'A', have been adjusted to achieve the balance of the trade matrix, with negligible effect on the results.

2.2.3. Upstream emission factors from fuel cycle and plant construction

Fuel upstream emissions refer to all the processes and phases required to make the fuel ready to supply the power production; they result from the extraction, refining and transport of the fuel used for electricity production. Fuel upstream emissions have been calculated by using the JEC WTW input data set [23]. Upstream emission factors are shown in the Table 1.

2.2.4. Transmission and distribution losses

Once produced, electric energy is distributed through transmission grids for consumption, usually located far away from the place of production; after long distance transmission, electric energy is delivered to the specific places of consumption, such as urban districts, buildings, factories, etc. at Medium Voltage (MV) and to individual private users at Low Voltage (LV). As electricity is transmitted through a grid from the power generation plant to the consumer, electricity losses occur in the electricity grid, depending on the voltage, distance of the lines and other factors. Total power losses were accounted on the base of national statistical data. However, the share of losses between the High Voltage (HV), Medium Voltage (MV) and Low Voltage (LV) sections of the electric grid have been calculated based on [29].

2.2.5. Emission factors from fuel combustion

The main GHG emissions from electricity production occur from the combustion of the primary fuel in the power plants. For the calculation of the GHG emissions from fuels combustion, the IPCC default emission factors for stationary combustion in the energy industries have been used [30]. GHG emissions are reported in units of carbon dioxide equivalent per unit of energy (e.g. gCO_{2eq}/MJ).

Gases other than CO_2 are converted to CO_{2eq} by multiplying their Global Warming Potential (GWP) relative to CO_2 over the 100-year time horizon as recommended in the IPCC Fourth Assessment Report 2007 [31] to account for the different impacts individual gases have on global warming. This reference was chosen in order to be consistent with the values mentioned in the methodology from REDII.

Because of their biogenic origin, CO_2 emissions from the combustion of biomass fuels are not accounted for; the CO_2 released does not alter the overall balance in the atmosphere, as carbon dioxide was previously absorbed during the growth of biomass. Besides CO_2 emissions, the use of biomass as fuel may result in emissions of CH_4 and N_2O into the atmosphere, and therefore the emission of these two greenhouse gases resulting from biomass combustion are accounted for. In addition, all the upstream emissions from the cultivation, harvesting, collection, processing and transport of biomass are considered.

When quantifying the emission related to the combustion of a waste stream, it is of utmost importance to consider the source of the carbon: the components of waste materials that are from fossil origins should be treated as a fossil fuel, as the carbon dioxide emissions from the combustion of waste result in a net positive emission into atmosphere. The CO_2 emissions from the combustion of peat are considered to be of fossil origin.

Table 1
Fuel upstream emission factors.

Fuel	Emission factor [g CO_{2eq}/MJ_{fuel}]
Hard coal[1]	16.0
Brown coal[2]	1.7
Coal gases	0
Petroleum Products	10.7
Natural gas	12.8
Solid biofuels	0.7
Liquid biofuels	46.8
Industrial Waste	0
Municipal waste	0
Biogases	14.9
Nuclear	1.4

Source: [23].
[1]Hard coal includes anthracite, coking coal and other bituminous coal.
[2]Brown coal includes sub-bituminous coal and lignite.

2.3. Detailed methodology for calculation of carbon intensity of electricity

The methodology developed for calculating the carbon intensity of the functional unit, defined in the kWh of electricity, considers all potential primary energy sources for electricity generation, type of plant, conversion efficiencies, own electricity consumption in the power plant, as well as transmission and distribution losses in the grid as well as electricity trade. For the calculation of the carbon intensity of electricity produced and used, a spreadsheet model has been developed, based on a new methodology described within this study. The methodology involves two main steps. In the first step, the carbon equivalent emissions, associated with the combustion and supply of the fuels used for electricity production, are calculated. This relies on the amount of different fuels used in the electricity production facilities and the emission factors from fuel combustion, upstream fuel emission factors and the and the emission factors associated plant construction and decommissioning along the entire lifetime. The second step in the methodology consists in the calculation of the carbon equivalent emissions associated to the electricity used at high, medium and low voltage, starting from the carbon intensity of electricity produced in each country, considering the losses in the electricity grid and the trade between countries. This enables an estimation of real emissions associated with the use of electricity, that supports a meaningful comparison of the different options for decarbonising the energy and the transport sectors.

2.3.1. Calculation of carbon intensity of electricity generation

The amount of fuels used for electricity generation is determined, for each country, on the basis of the electricity production and the conversion efficiency. In the case of Combined Heat and Power (CHP), part of the primary energy is used for electricity production and the rest is recovered for heat generation. The fuels associated with heat generation in CHP have been counted by considering alternative heat production with average efficiencies of 85% for coal, lignite, coke, peat, biomass and waste, and 90% for natural gas, biogas, petroleum gases and oil products, while the rest has been attributed to electricity generation.

For nuclear power plants, Eurostat [25] provides data on the transformation input to produce electricity as well as the electricity generated using nuclear heat. The conversion of the electric energy produced from nuclear energy into an equivalent primary energy can be done by using an average thermal efficiency for nuclear power plants of 33%. No fuels are associated with electricity production from renewables that include hydro, solar, wind and geothermal. Fig. 1 presents the calculations steps for the carbon intensity of electricity production.

The carbon emissions associated with electricity production include combustion emissions and upstream emissions (fuel upstream emissions and construction emissions).

$$e_{prod} = e_{up} + e_{constr} + e_{comb} \tag{1}$$

e_{prod} – CO_2 equivalent emissions from electricity production $[gCO_{2eq}]$

e_{up} – fuel upstream CO_2 equivalent emissions $[gCO_{2eq}]$

e_{constr} – CO_2 equivalent emissions from the construction of electricity facility $[gCO_{2eq}]$

e_{comb} – CO_2 equivalent emissions from fuel combustion $[gCO_{2eq}]$

The CO_2 equivalent emissions from electricity production include emissions from fuels use, which includes upstream fuel emissions and the emissions from fuels combustion, are calculated by multiplying fuel consumption and emission factors for stationary conversion (e.g. combustion) of the fuel used. The upstream emissions for supplying the fuel used are the JEC WTW v5 upstream emission factors [23], as shown in Table 1.

$$e_{prod} = \sum_{i=1}^{k}\left(\left(c_i^{ups} + c_i^{comb}\right)^* B_i\right) \tag{2}$$

c_i^{ups}– – fuel upstream CO_2 equivalent emission factors $\left[\frac{gCO_{2eq}}{MJ}\right]$

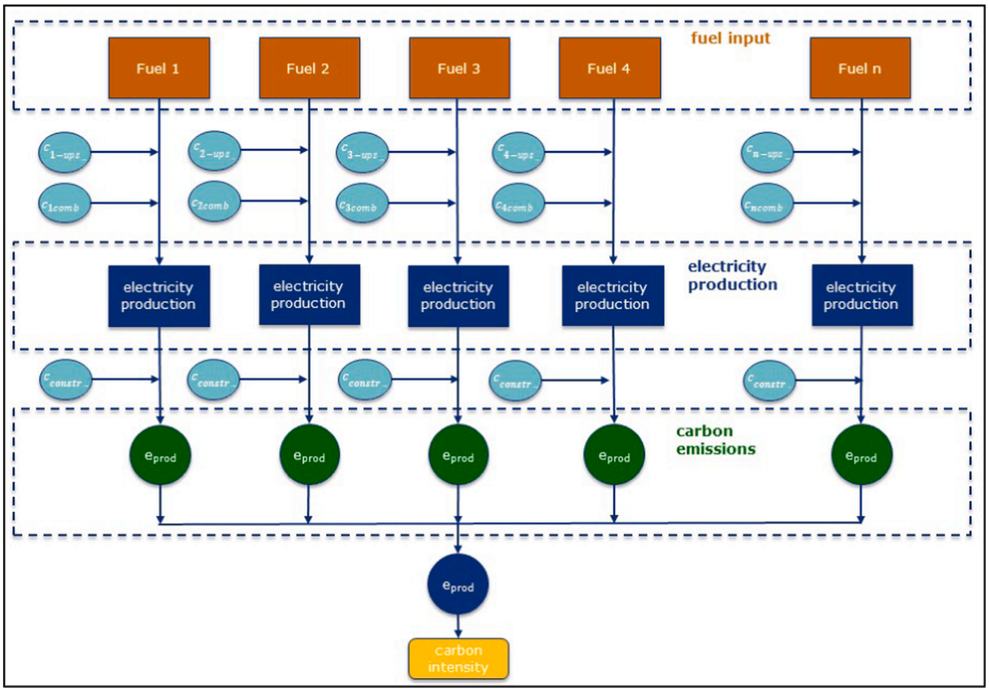


Fig. 1. Diagram of the calculation steps for carbon intensity of electricity production.

c_i^{comb} – CO_2 equivalent emission factors from fuels combustion $\left[\frac{gCO_{2eq}}{MJ}\right]$

B_i – fuel consumption for electricity generation $[MJ]$

$i = 1 \cdots k$ – fuels used for electricity production

The emissions associated with the construction and decommissioning of the power plant is calculated by multiplying the emission factor and the electricity produced:

$$e_{constr} = \sum_i^k \left(c_i^{constr} * E_i\right) \quad (3)$$

The carbon intensity of electricity produced was defined as the GHG emitted for producing or using a certain amount of electricity, as follows:

$$CI_{prod} = \frac{e_{CO_2}}{E} \quad (4)$$

where:

CI_{prod} - carbon intensity of electricity production $\left[\frac{gCO_{2eq}}{kWh}\right]$

$e_{CO_{2eq}}$ – CO_2 equivalent emissions $[gCO_{2eq}]$

E – electricity production $[kWh]$

2.3.2. Calculation of carbon intensity of electricity use

The emissions from the electricity used are calculated using the following formula:

$$e_{use} = e_{prod} - e_{pump} + e_i - e_e - e_{loss} \quad (5)$$

e_{use} – CO_2 equivalent emissions from electricity used $[gCO_{2eq}]$

e_{prod} - CO_2 equivalent emissions from electricity produced $[gCO_{2eq}]$

The carbon equivalent emissions are calculated in the model using the carbon intensity of electricity concerned and the amount of electricity, as follows:

$$e_{prod} = CI_{prod} * E_{prod} \quad (6)$$

e_{pump} - CO_2 equivalent emissions from electricity used for hydro pumping $[gCO_{2eq}]$

$$e_{pump} = CI_{prod} * E_{pump} \quad (7)$$

e_{loss} - carbon emissions from transmission and distribution losses $[gCO_{2eq}]$

$$e_{loss} = CI_{use} * E_{loss} \quad (8)$$

e_i - CO_2 equivalent emissions from electricity from import $[gCO_{2eq}]$

e_e – CO_2 equivalent emissions from electricity exported $[gCO_{2eq}]$

The amount of electricity used is determined by the domestic electricity production (gross and net electricity production, respectively), the electricity losses in pump storage and in transmission and distribution losses as well as the electricity trade.

$$E_{use} = E_{prod} - E_{pump} + E_i - E_e - E_{loss} \quad (9)$$

where: E_{use} – electricity use $[kWh]$

E_{prod} – electricity production $[kWh]$

E_{pump} – electricity for pumping $[kWh]$

E_i – electricity from import $[kWh]$

E_e – electricity to export $[kWh]$

E_{loss} – transmission and distribution losses in the electricity grid $[kWh]$

The trade of electricity changes the carbon intensity of the electricity used in a country. The importing country receives CO_2 equivalent emissions with imported electricity to add to its own emissions from electricity generation. The exporting country also "exports" CO_2 equivalent emissions with exported electricity that will be deducted from the CO_2 equivalent emissions of the electricity used. However, part of the electricity exported by a certain country comes from imported electricity to that country, thus having a different carbon intensity (Fig. 2). To establish the carbon intensity of the consumed electricity, the balance of the CO_2 equivalent emissions between domestic and traded electricity is divided by the electricity used. This results in the carbon intensity of the used electricity, which is established by a number of iterations until the convergence of calculations is achieved. Finally, the carbon intensity attributed to exports is equal to the domestic carbon intensity of electricity distributed and used inside the exporting country. Please see Box 1 for more detailed information on the calculation of

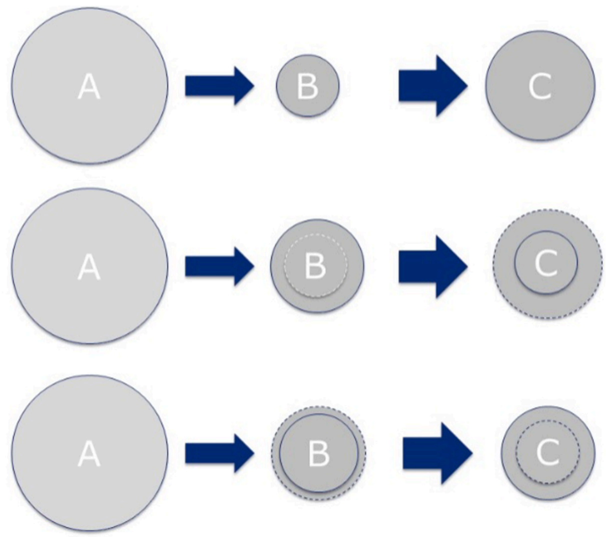


Fig. 2. Changes in carbon electricity with trade.

carbon emissions induced by the electricity trade.

The CO_2 equivalent emissions from electricity related to import is determined by the amount of electricity imported as well as the carbon intensity of the electricity of the country of origin.

$$e_i = \sum_{k=1}^{p} \left(CI^k_{cons} * E^k_i \right) \tag{10}$$

The CO_2 equivalent emissions from electricity exported is determined by the amount of electricity exported and the carbon of electricity produced domestically. In a first iteration, it can be considered that the carbon intensity of exported electricity is equal to that of the electricity produced domestically. The carbon intensities of exported electricity is then established taking into consideration the imported electricity in several iterations until the convergence in calculations is achieved (Fig. 3).

$$e_e = CI_{cons} * E_e \tag{11}$$

3. Results and discussion

3.1. Electricity generation

According to Eurostat data for 2019 [32], in EU27, 42.8% of electricity production relies on conventional thermal power plants and 26.7% on nuclear plants while the rest is comes from renewable sources. Several countries display significant contributions from nuclear plants in their mix, in particular France (69.9%), Slovakia (55.3%), Hungary (48.3%) and Belgium (47.6%). Among renewable sources, wind energy represents 13.3%, almost the same share of hydro energy (12.3%). Solar accounts for 4.4%, followed by geothermal and other sources with 0.5%. It is interesting to note that according to IEA [33] in the first quarter of 2020, when many countries were under lockdown, the total share of renewables accounted for 40–42%, while nuclear for 28%; traditional gas and coal sector faced the stronger reduction, representing the lower share in the mix: 12.3 and 12.7% respectively.

Fig. 4 shows the electricity mix in European countries, in 1990 and in 2019, as derived from statistics. It is interesting to note the remarkable change in the electricity mix in major countries, with a large decrease in the share of electricity from the use of solid fossil fuels or oil products and the increase in the shares of low carbon electricity (wind, solar, biomass and biogas) in most European countries.

Fig. 5 shows the evolution of the electricity production sector in the EU27, during the past two decades. There are some clear general trends that emerge from the data. Some fluctuations have occurred around these trends, mainly in relation to specific circumstances, such as the aftermath of the 2008 financial crisis. In general, a progressive reduction in the use of solid fossil fuels, accompanied by oil products, is noticeable. A less clear, but still visible reduction has occurred in the use of nuclear energy. The electricity generation from the use of natural gas shows, however a clear increasing trend, with some notable variations. These variations can be partially explained by the fact that the growth in the renewable share has led to an increasing need of grid balancing, which is usually performed by gas turbine plants, almost entirely fed with natural gas. With regards to renewables, there is a clear increase in the share of electricity produced by wind, solar, biomass and waste and from biogas, while hydropower kept a relatively constant share in electricity production. After hydro power, wind represents the major player, followed by biomass and solar, respectively.

Box 1

Let's consider the following scenario: a country B generating electricity with low carbon intensity, importing electricity with high carbon intensity from country A and exporting electricity to a country C with a higher carbon intensity. In a first step, the exports were given the carbon intensity of the exporting country B emissions. After trade, the low carbon intensity emissions from country B are largely passed on to country C and country B received high emissions from country A. The result is that now B apparently has a larger carbon intensity than C, but is exporting cleaner energy. The problem is that part of the exports from B probably came from the electricity country B imported from A.The best assumption we can make is that the carbon intensity attributed to B exports is the same as the electricity used within country B itself (thus considering domestic production and imports from country A). A recalculation of the trade effects has now somewhat decreased the carbon intensity of the electricity used in country B because some of the high emissions from country A have been exported to country C. This requires a new recalculation of the carbon intensity in country B, replacing the previous carbon intensity of its exports with the new estimate of the carbon intensity of used electricity. Several iterations for calculating carbon intensity might be needed until the variations of the carbon intensity of the electricity used in country B, compared to the previous iterations, decreases below a certain limit.The size of the circler are indicative for the carbon intensity of the electricity in a country. As result of imported/exported electricity, the carbon intensity change is reflected by the different size of the circle in this figure. In the first row, there is the initial situation with the electricity trade between countries A, B and C. In row two, after the trade, the carbon intensity of country B increases; the carbon intensity of country C decreases, as a result of the carbon received with electricity; the carbon intensity of country C becomes even lower than that of country B. In row three, the carbon intensity of country B further increases and the carbon intensity of country C increases as well due to the carbon received.

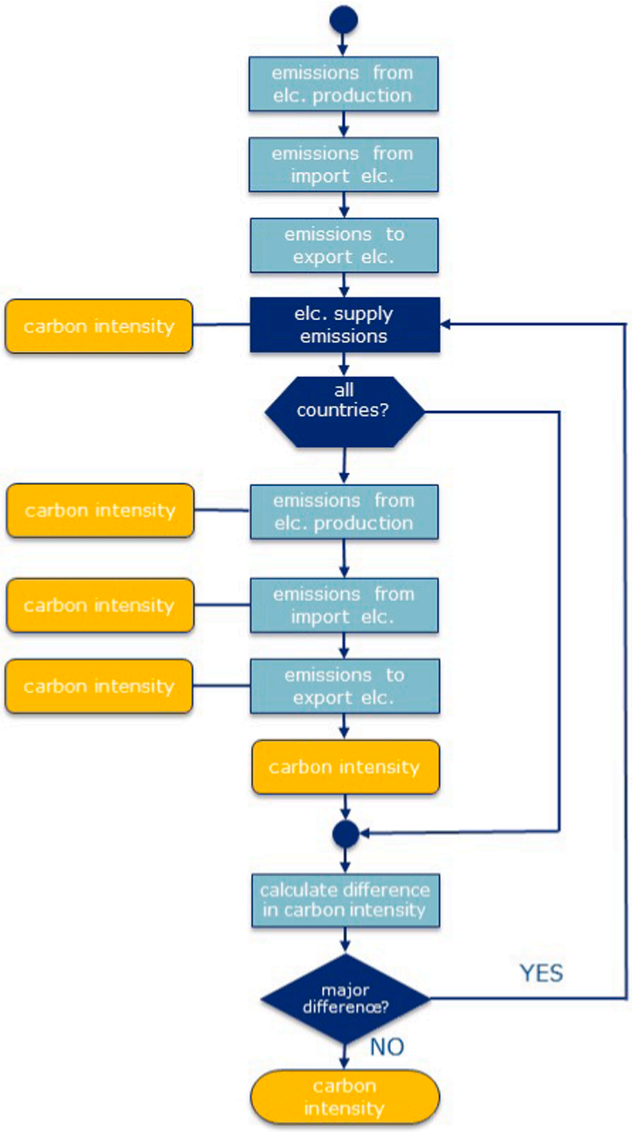


Fig. 3. Diagram for the calculation of the carbon intensity of electricity used.

3.2. *Emissions from construction and decommissioning*

The *emissions from the construction and decommissioning* of electricity producing facilities may be significant at the entry into service of an electricity generation plant, as well as during waste disposal at the end of life. They include emissions from material production and processing, transport, assembly and installation, building construction and the equipment production and decommissioning. These emissions are expressed in terms of electricity produced along the full lifetime of the plant.

In the case of renewable energy (hydropower, solar, wind, geothermal, ocean), the operational emissions (from fuel use, maintenance, repairs, etc.) are zero or negligible. Thus, the emissions from the construction and decommissioning represent the highest fraction of the total life cycle emissions of the produced renewable electricity. In comparison, the operation emissions from fossil-based electricity production are the most important, as the construction emissions have little impact on the unit output, due to the typical production capacity of such plants along their entire lifetime. For consistency reasons, the emissions from electricity facility construction should include emissions from fossil fuel electricity and from renewable energy (hydropower, solar PV, wind, geothermal, ocean and bioenergy) related emissions.

Large variations could occur in GHG emission estimations, due to the use of different LCA methods, assumptions and system boundaries [34–36]. The emissions from the construction reported in the literature are rather small and present quite large variations, depending on the energy consumption and energy mix used in the production, local resources (such as solar or wind), technology employed, type of plant (for example run-off river or reservoir hydro plant), conversion efficiency, plant size, plant lifetime, etc. and other aspects ([37–41]). The US National Renewable Energy Laboratory (NREL) carried out the Life Cycle Assessment Harmonization Project [42] to review and harmonise the ranges of inconsistent and conflicting estimates of the GHG emissions for electricity production from various sources and reduce the uncertainty of the estimates. This study reduced the range of life cycle GHG emission estimates by harmonising the main assumptions from the LCA studies, such as system boundaries, operating lifetime, key performance parameters (e.g., capacity factor, thermal efficiency), etc.

When renewable energy sources are used for electricity production, many new challenges need to be addressed to determine their GHG performances. *Wind* energy offers the potential for significant GHG emissions reduction. The emissions produced in the manufacture, transport, installation, operation and decommissioning of wind turbines are small compared to other energy options. GHG emission variations can be attributed to, for example, local resources, system designs, technology performances, capacity factor, etc. as well as LCA methods and assumptions [37–40,43–45]. The wind lifecycle GHG estimates show a median value of 11 gCO_{2eq}/kWh, with the estimates ranging between about 8 gCO_{2eq}/kWh and 20 gCO_{2eq}/kWh, with maximum estimates reaching 44 gCO_{2eq}/kWh. Wind offshore shows some narrow ranges for GHG emissions between 9 gCO_{2eq}/kWh and 16 gCO_{2eq}/kWh and maximum values of 24 gCO_{2eq}/kWh. Wind onshore shows a wider variation of GHG emissions, between 8 and 20 g CO_{2eq}/kWh and maximum values of 44 CO_{2eq}/kWh [46,47].

Life cycle GHG emission studies for *solar photovoltaic* (PV) electricity generation provide a wide range of estimates for different systems, depending on plant location (e.g. solar irradiance), technology (monocrystalline, poly crystalline, amorphous silicon cadmium telluride, etc.), technological performance (e.g., efficiency) in addition to the variety of LCA assumptions, system boundaries, etc. [37–40,43–45,48–51]. Efforts to harmonise the methods and assumptions of LCA studies carried by NREL provide more reliable estimates of GHG emissions. The majority of life cycle studies provide GHG emission estimates between 35 gCO_{2eq}/kWh and 50 gCO_{2eq}/kWh, with a median value of 41 gCO_{2eq}/kWh, while reaching maximum values of 180 gCO_{2eq}/kWh [52]. Fewer studies are available for *Concentrating Solar Power (CSP)* systems to produce high-temperature heat, which is used for electricity generation. Life cycle GHG emissions for CSP appear to have a smaller range of variations, reflecting solar irradiance, plant efficiency, plant lifetime, as well as LCA assumptions and boundaries. LCA estimates give a median value of 24 gCO_{2eq}/kWh, with a range between 14 gCO_{2eq}/kWh and 32 gCO_{2eq}/kWh and a maximum value of 84 gCO_{2eq}/kWh [37,53].

The life cycle GHG emissions from *hydropower* production originate at construction stage, production and transportation of materials for construction, production of equipment and the use of civil work equipment and materials for plant construction. Land use change induced by reservoir creation can also lead to GHG emissions [37–40,43,54]. GHG emissions from the operation and maintenance activities are rather negligible. However, some methane emissions might occur in reservoirs from the decomposition of organic material, depending on reservoir type and size, vegetation flooded and climate. LCA GHG emission estimates for hydropower range between 6 gCO_{2eq}/kWh and 36 gCO_{2eq}/kWh, with the highest emissions from reservoir hydropower of 164 gCO_{2eq}/kWh. Run-of-river systems displays much lower GHG emission levels, between 6 gCO_{2eq}/kWh and 9 gCO_{2eq}/kWh [55].

GHG emissions from *geothermal* power plants are related to the construction, operation and decommissioning of the plant and depend

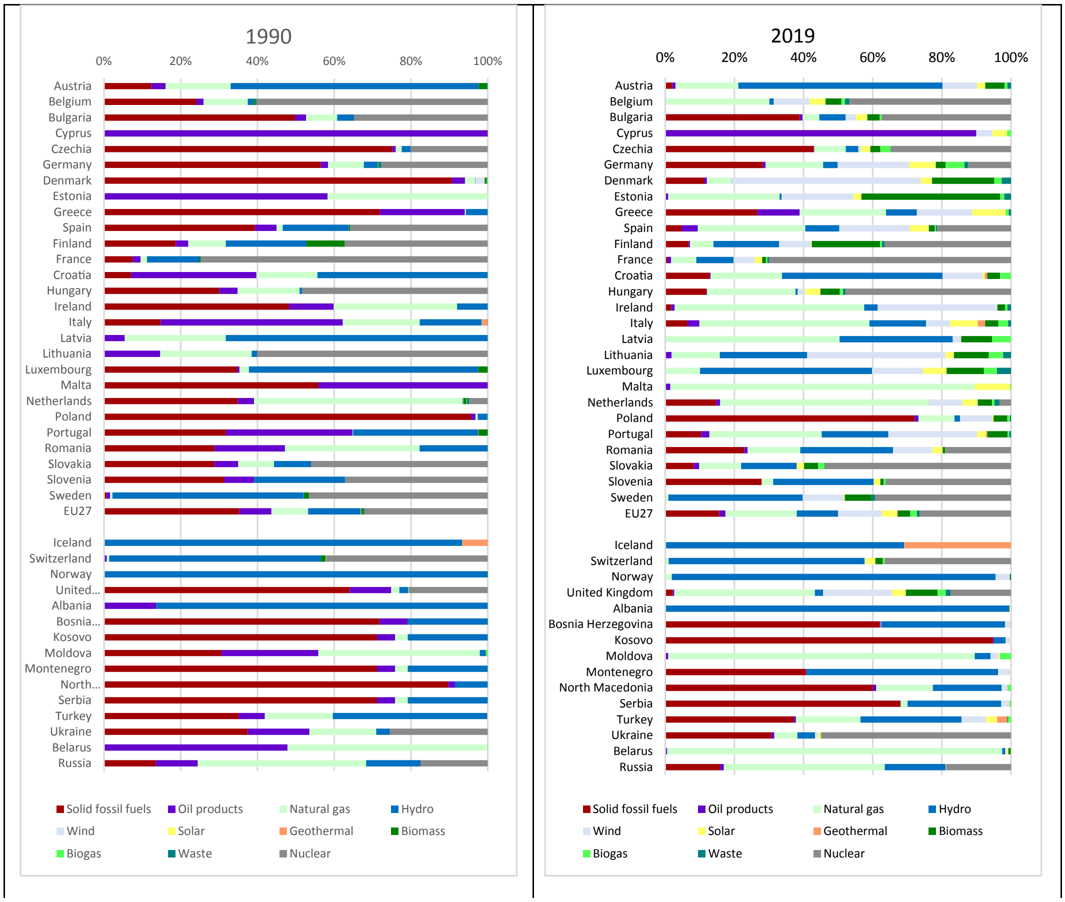


Fig. 4. The share of electricity production in European countries, by source: 1990 (left) and 2019 (right).

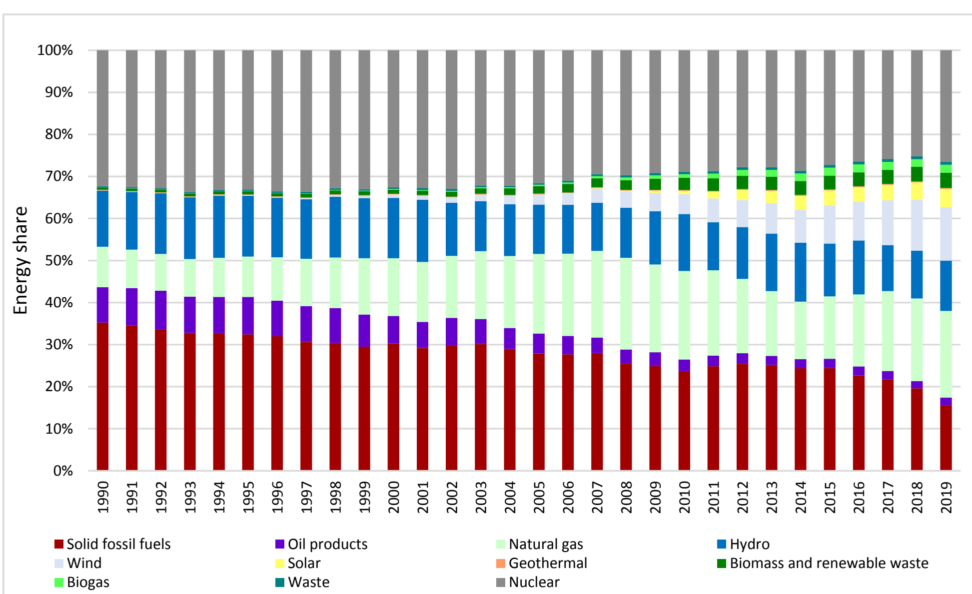


Fig. 5. Changes in the share of electricity production in European in the EU27.

on the location, well depth, temperature and technology employed (Enhanced Geothermal Systems -EGS) binary, HydroThermal - HT flash, and HT binary). Operational emissions occur mostly from geothermal flash plants and vary widely in relation to system characteristics (e.g. local geology, well depth and resource temperature). GHG emissions from geothermal systems show a wide spread [37,38,56]. The NREL Life Cycle Assessment (LCA) Harmonization study provides more narrow estimates, between 22 gCO_{2eq}/kWh and 52 gCO_{2eq}/kWh, while the maximum values can reach 245 gCO_{2eq}/kWh [57,58].

All *ocean* energy technologies, including wave energy, tidal and ocean currents technologies, are at an early stage of development and all are pre-commercial. GHG emissions from ocean energy systems occurring from the raw material extraction, component manufacturing, plant construction, maintenance and decommissioning [38]. Very few studies have been conducted on wave and tidal plants to determine whether there are any significant differences between them in terms of GHG emissions. The performance of ocean energy technologies is anticipated to improve over time. Life cycle GHG emissions from ocean energy (wave and tidal) systems range between 2 gCO_{2eq}/kWh and 23 gCO_{2eq}/kWh, with a median estimate of 8 gCO_{2eq}/kWh. Further LCA studies are needed to increase the number of estimates for all ocean energy technologies [59].

GHG emissions from *nuclear* electricity are generated from mining, fuel conversion, enrichment, nuclear power plant construction, decommission, operation and waste disposal. GHG emissions show large variations, depending on various assumptions in the LCA studies, including technology type, uranium enrichment method, uranium ore grade, thermal efficiency, plant capacity, reactor lifetime, capacity factor, waste storage, as well as primary source energy mix used etc. [37–39,44,60,61]. A review and harmonisation of life cycle GHG emissions of nuclear electricity generation technologies was done to reduce variability in estimates. The GHG emissions range between 10 gCO_{2eq}/kWh and 39 gCO_{2eq}/kWh with a maximum value of 110 gCO_{2eq}/kWh [62]. Conversely to other renewable sources, for nuclear energies the induced effects, when considering the energy sector decarbonisation could significantly change the picture, if carefully modelled. Fig. 6 presents the results of the analysis of the GHG emission factors from the construction and decommissioning of electricity producing facilities from renewable energy sources and nuclear electricity

3.3. Electricity trade and impact on carbon intensity of electricity

Electricity trade plays a significant role in electricity supply, allowing exchange between countries to enable demand to meet supply, as shown in Fig. 7. According to the proposed methodology, the carbon intensity of the electricity used in a country depends, in addition to the carbon intensity of electricity produced domestically, on the carbon intensity and the amount of electricity traded with other countries.

Electricity produced in a country embeds the GHG resulting from its production, including the emissions from the extraction, refining and transport of the fuel used to the power plant and the emissions from the combustion of the fuel in the power plant. The fuel mix used for the production of electricity, technological level and plant efficiencies differ from one country to another. Therefore, the carbon intensity of electricity produced in one country can vary significantly to that of another country.

Even in the case of near zero net trade between two countries, if the carbon intensity of their produced electricity differs, the impact of electricity exchange between them might have a large impact on the carbon intensity of used electricity. This is because one country might export electricity with low carbon intensity from domestic production, but importing, in another period of the same year, electricity with higher carbon intensity.

The calculations of the carbon intensity of the electricity used in a country should consider this trade effect, as proposed in this work. The importing country receives CO_2 equivalent emissions with imported electricity to add to its own emissions from electricity generation (Fig. 8). Through exporting electricity, the country passes on to the importing country CO_2 equivalent emissions with exported electricity to add to its own emissions from domestic electricity generation.

The average carbon intensity of the used electricity is determined by dividing the associated emissions of domestic and traded electricity by the electricity used in that country. This results in a new estimate of the domestic carbon intensity of each country that reflects the electricity trade. This first estimate is then used in a second iteration for the calculation of the carbon intensity of the export electricity for each country. The process is repeated until the carbon intensity of each country converges on a value that remains steady during future iterations. Finally, the carbon intensity attributed to exports is equal to the domestic carbon intensity of electricity distributed inside the exporting country.

3.4. Carbon intensity of electricity

In order to get realistic estimates of GHG emissions from electricity generations, fuel upstream emissions, combustion emissions as well as emissions from the construction and decommissioning of power plants were taken into account. Fig. 9 provides the results of the calculations of the averaged GHG emissions in the EU27 from various electricity sources, considering the emissions from mining, as well as the emissions from fuel processing, transportation and facility construction, combined with the combustion emissions from the existing plants, thus considering the conversion efficiency to electricity.

This figure shows the differences in the emissions from electricity produced from fossil fuels (solid fuels, oil and natural gas) in comparison to the emissions from low carbon electricity (renewables and nuclear). It

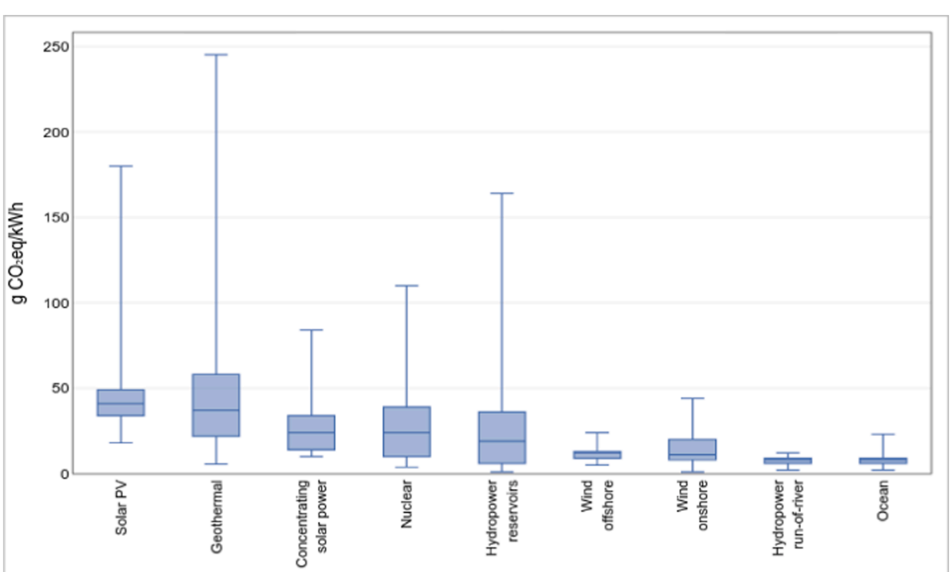
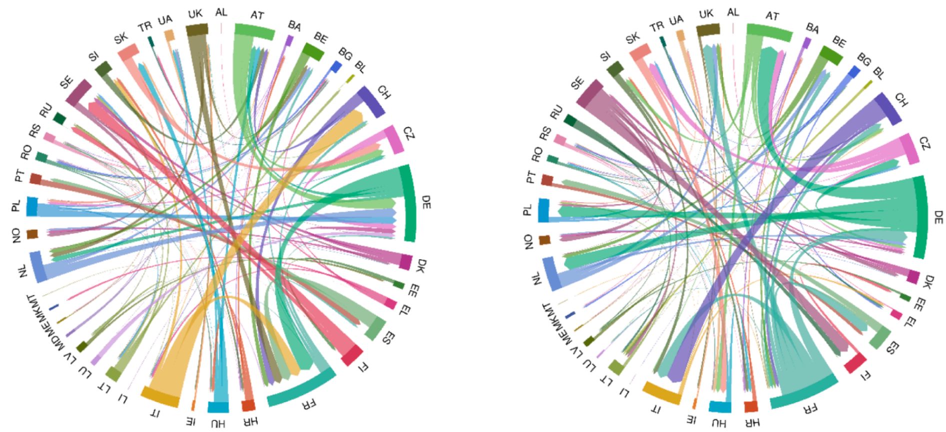
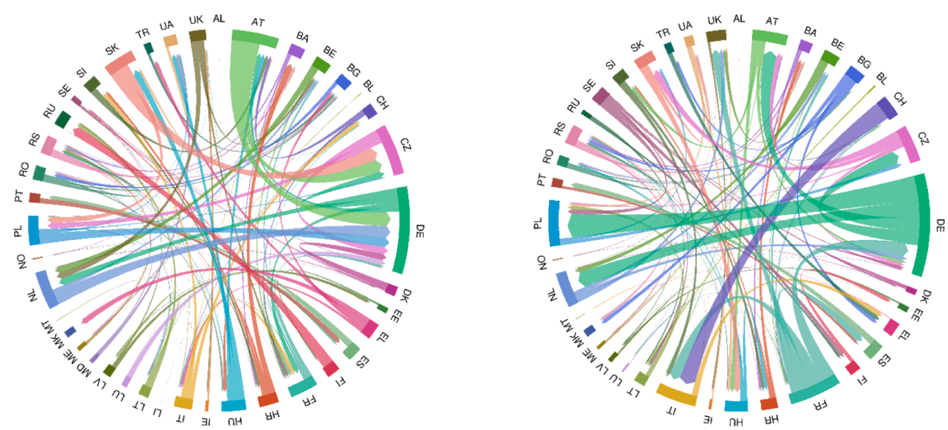


Fig. 6. GHG emissions from plant construction and decommissioning from renewables and nuclear electricity.



electricity import [GWh] electricity import [GWh]

Fig. 7. Electricity trade between European countries in 2019.



CO_2 import with electricity [tonnes CO_2] CO_2 export with electricity [tonnes CO_2]

Fig. 8. Trade of carbon dioxide with electricity between European countries in 2019.

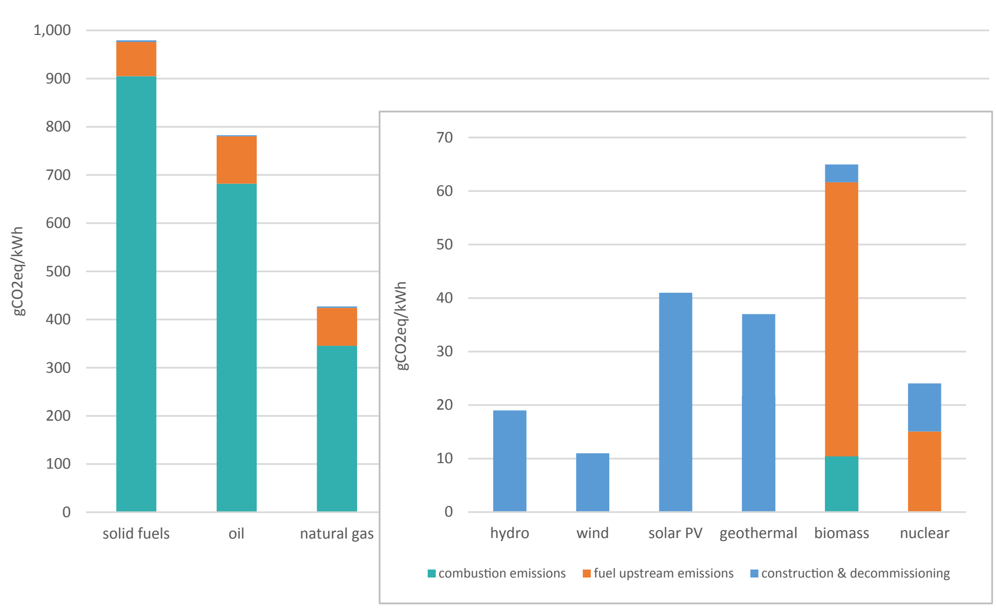


Fig. 9. GHG emissions factors from the construction and decommissioning of electricity producing facilities.

also shows that the combustion emissions dominates for fossil electricity, the contribution of fuel upstream emissions are low and the emissions from construction and decommissioning, although considered in this study for fossil electricity production, are rather negligible. The real data show that the situation is quite different for low carbon electricity, where construction and decommissioning emissions, although small, are the majority of emissions. In this case, some emissions are associated with upstream fuel emissions (biomass, nuclear) of some operation emissions (geothermal). Emissions from biomass are dominated by the fuel upstream emissions from the cultivation and supply of raw material, with some smaller contribution from combustion in the form of methane or nitrous oxide emissions, while biogenic carbon emissions are not considered, as explained above. This Fig. 9 shows that renewables are able to provide significant advantages, in terms of GHG emission saving, in comparison to fossil energy, even when upstream emissions are considered. In addition, due consideration of all emissions are a must to have the real picture of the GHG emission savings offered by different options.

The estimates of the carbon intensity of electricity show that in the EU27, the emissions associated with gross electricity production reached 296 gCO_{2eq}/kWh electricity, of which 251 gCO_{2eq}/kWh are related to fuel combustion, 36 gCO_{2eq}/kWh are related to upstream fuel supply and 9 gCO_{2eq}/kWh electricity are related to the construction and decommissioning of electricity plants. Carbon emissions from gross electricity production in different European countries in 2019 are shown in Fig. 10, differentiated between combustion emissions, upstream fuel emissions and the emissions from the construction of the electricity generation plants. The differences between countries reflect the differences in the fuel sources and the conversion efficiencies to electricity or the plant types (electricity only, or cogeneration). Although rather small for many countries, fuel upstream emissions vary between 7 and 122 gCO_{2eq}/kWh, depending on the type of fuel used (solid fossil fuels, oil, biomass fuels, etc.) and the conversion efficiency to electricity. Fig. 10 also shows that the emissions associated with the construction and decommissioning of electricity plants are quite low in comparison to combustion emissions, between 3 and 19 gCO_{2eq}/kWh, but in some countries their relative share in total carbon emissions from electricity production might be important, especially in countries with a very large share of electricity from renewables and nuclear.

The carbon emissions associated to the production and use of electricity in EU27 (thus including own energy consumption, energy losses in transmission and distribution grids and the effects of EU27 trade with third countries) reached 334 gCO_{2eq}/kWh electricity at low voltage in 2019. Table 2 presents the carbon intensity of electricity produced and used in European countries in 2019.

Fig. 11 shows the carbon intensities of both produced and used electricity by European countries in 2019 expressed in gCO_{2eq}/kWh on the y-axis and the country share of low carbon electricity (that includes renewables and nuclear electricity) on the x-axis. A high share of low carbon electricity generally results in lower carbon intensities of electricity. The major factor in the differences between the carbon intensity of produced and used electricity includes trade between countries; transmission and distribution losses have a limited contribution.

The changes of the carbon intensity of net electricity production in European countries is presented in Fig. 12, which compares 2019 figures with values for 1990. The general trend of decreasing emissions appears to be more evident in some countries (such as Denmark, Malta, Greece, Romania, United Kingdom, etc.), compared to others (e.g. Kosovo, Bosnia and Herzegovina). EU27 countries, especially the ones with higher carbon intensity, are generally the ones that registered the highest decline in their carbon intensities in almost the past 30 years as a result of the policies supporting renewables adopted by the EU. The significant changes in the carbon intensity of electricity in different countries are related to the changes in the fuel mix used for electricity generation (as seen in Fig. 4), but by comparing Fig. 4 and Fig. 12 it is obvious that in many cases, the changes in the efficiency of electricity conversion played a major role.

In particular, Fig. 13 shows the evolution of the carbon intensity associated with electricity production in EU27. The impressive reduction trend followed a clear downward trajectory, which is expected to continue in the coming years. The new Green Deal is likely to push for further reductions in all the relevant sectors, which would accelerate the ongoing decarbonisation of EU economy.

4. Conclusions

As stated in the European Green Deal, decarbonising the EU's energy system is critical to reach the climate objectives. Decarbonising power generation is essential to decarbonising the energy sector. The paper presented a methodology developed for the calculation of carbon intensity of electricity used, using Life Cycle Assessment (LCA) based approach and a structured set of data. The proposed methodology enables the calculation of the carbon intensity of electricity produced and consumed in each country, by using input data from national statistics, for the primary fuel used as well as for the transmission and distribution losses in electricity grids as well as the electricity trade between countries. The paper provides detailed data on the carbon intensity of electricity produced and use for all European countries, with a comparison

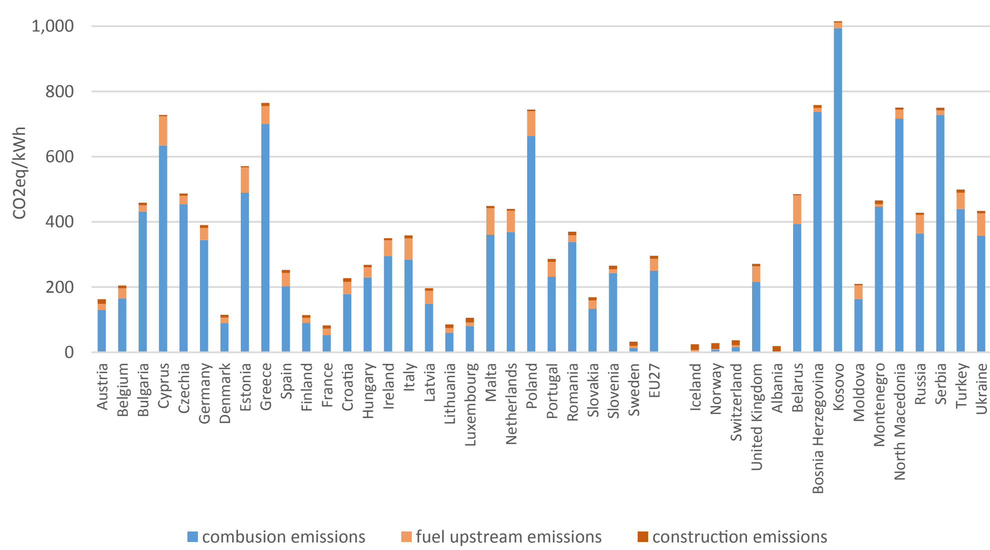


Fig. 10. Carbon emissions from gross electricity production in European countries in 2019.

Table 2
Carbon Intensity (CI) of electricity produced and used in European countries in 2019.

	CI gross electricity production (gCO_{2eq}/kWh)	CI net electricity production (gCO_{2eq}/kWh)	CI consumed electricity low voltage (gCO_{2eq}/kWh)
Austria	163	170	264
Belgium	205	213	230
Bulgaria	459	504	544
Cyprus	728	762	791
Czechia	487	529	564
Germany	390	410	422
Denmark	115	118	158
Estonia	571	659	472
Greece	765	785	780
Spain	253	262	279
Finland	114	119	141
France	82	86	98
Croatia	228	237	372
Hungary	268	286	338
Ireland	350	358	384
Italy	358	371	356
Latvia	197	212	325
Lithuania	86	91	321
Luxembourg	106	108	338
Malta	449	462	463
Netherlands	440	453	450
Poland	744	807	805
Portugal	286	292	324
Romania	370	400	464
Slovakia	169	182	346
Slovenia	265	281	307
Sweden	33	33	40
EU27	296	310	334
Iceland	25	25	26
Norway	28	28	31
Switzerland	37	40	78
United Kingdom	271	282	304
Albania	19	19	24
Bosnia Herzegovina	758	809	831
Kosovo	1,015	1,101	1,101
Moldova	210	252	488
Montenegro	466	484	663
North Macedonia	751	801	974
Serbia	750	816	900
Turkey	499	524	588
Ukraine	434	461	492
Belarus	485	485	516
Russia	428	455	489

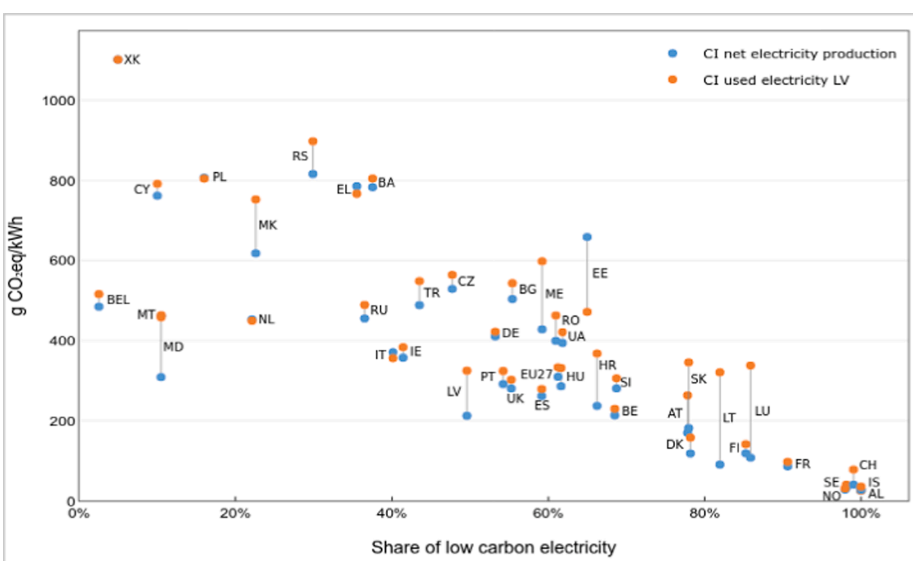


Fig. 11. Carbon intensity of electricity produced and used in European countries in 2019.

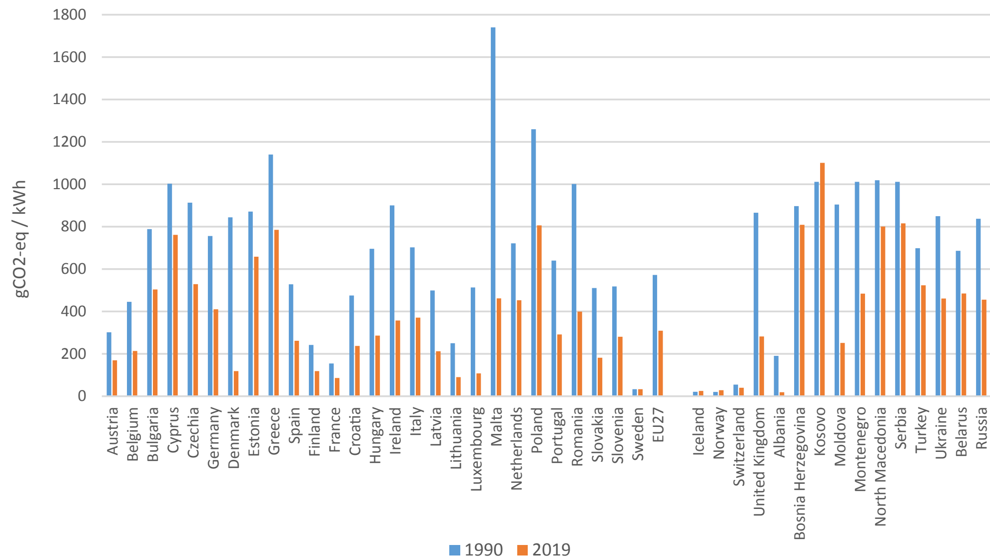


Fig. 12. Changes in carbon intensity of net electricity production in European countries between 1990 and 2019.

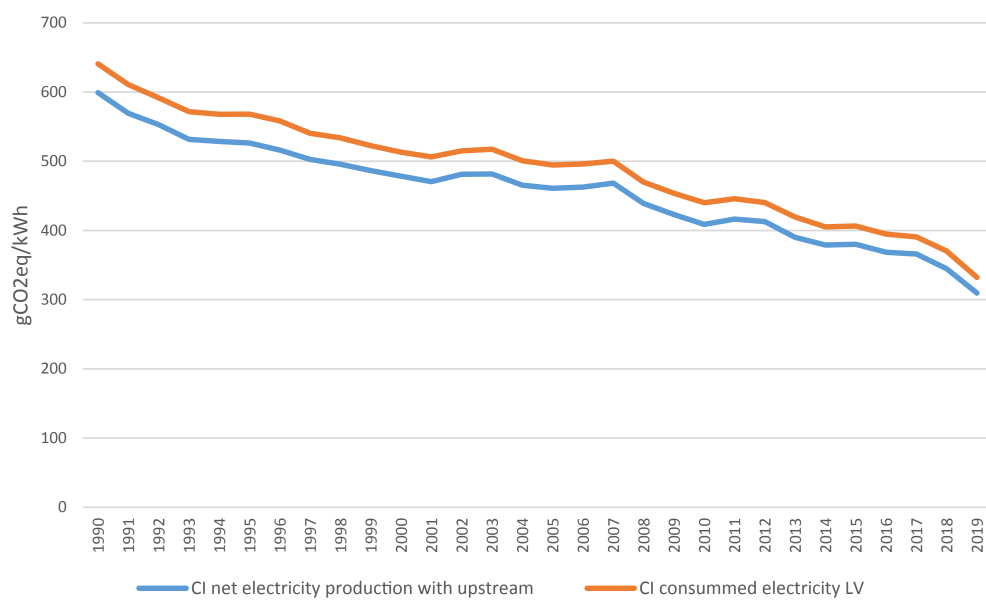


Fig. 13. Evolution of the carbon intensity of electricity in the EU27.

of the carbon emissions in 1990 and 2019. The results show that, over the past decades, there was a clear decrease in the carbon intensity of electricity in most European countries, mainly related to the increase in the use of renewables such as wind, solar, biomass and biogas. This trend is expected to continue, driven by the policies targeting the decarbonisation of the energy sector.

Electrification is at the core of the vision for decarbonising transport and reduce pollution in cities. The contribution of electricity to the decarbonisation of the transport sector depends on the carbon intensity of the electricity used. This is particularly relevant when weighing up fuel options (sustainable biofuels, electrofuels, hydrogen, etc.), where electricity plays a major role in their production process. The calculation of the carbon intensity of electricity used in each country is a prerequisite, particularly for a proper comparison of the greenhouse gas emissions performances of different powertrains that includes the use of electricity in electric vehicles, the use of grid electricity for hydrogen production or for the production of electrofuels.

Although the combustion of fuels generates most of the greenhouse gas emissions from electricity generation, upstream emissions from fuel supply and from the construction of electricity generation facilities might be important as well. The consideration of upstream emissions and emissions from plant construction and decommissioning is necessary to form a fair basis for the comparison of the different options for electricity generation, including renewable or nuclear electricity. Moreover, these emissions need to be properly accounted for as to avoid promoting initiatives that may impact the environment with indirect effects (e.g. water management and biodiversity preservation for large hydro plants, etc.).

While operational greenhouse gas emissions from fuel combustion are important in thermal power plants, in the case of renewable energy, the most relevant contribution to greenhouse gas emissions comes from material processing, production of the components and equipment, construction (e.g. dams for hydropower plants), transport and installation, and decommissioning.

For decarbonising the transport sector, a fair comparison of the different powertrains from the point of view of greenhouse gas emission savings is needed. For this purpose, the emissions from the raw materials extraction and processing, manufacturing equipment, batteries production, transportation, plant operation, end of life with waste disposal and material recycling needs to be considered. A detailed analysis of these impacts are out of the scope of this paper, but a detailed evaluation can be found in recent studies, such as [63].

The work presented clearly highlights the significant impact electricity trade has on the carbon intensity of electricity used, in particular if imports and exports account for a large proportion of the electricity mix. At EU27 level, there are a few cases where trade can be neglected and the carbon intensity is determined by the emissions associated with electricity generation. However, the carbon intensity of imported electricity may differ greatly from the carbon intensity of domestic generation mix, and therefore this is a relevant point to consider in a detailed analysis.

The methodology proposed in this work allows to consider all the relevant emissions related to the production and use of electricity, thus providing a fair ground for the assessment of GHG emissions performance in all sectors that involve the use of electricity. It is worth to emphasise that renewable energy sources are able to provide significant advantages, in terms of GHG saving, even when upstream emissions are considered. The carefully analysis of the upstream emissions, here proposed, allows performing a scientifically sound comparison of the existing options, clearly showing that the increase in the renewables energy penetration remains the most effective way to cut Greenhouse Gases emissions.

The approach proposed was able to provide the calculation of the real carbon emissions associated to the use of electricity that considers all factors that contribute to carbon equivalent emissions. The results of this study is expected to have a significant impact on real applications, since these emissions are essential for the calculation of the greenhouse gas emission from electricity production and use and for the quantification of the decarbonisation of the power sector as well as of the transport sector, which relies on a great extent on the electrification of transport.

The limitations of the proposed approach for the calculation of carbon intensity of electricity derive from the quality of data available for each country. The accuracy of estimations depend thus on the availability of data and the level of details of the fuel used, conversion efficiency for each type of fuels and plants in each country, as well as associated emissions from each fuel type. For the European Union, detailed information is available from the energy balances of energy products and their flow, from production to transformation and consumption in each Member State. The accuracy of the calculations will diminish if the calculation is based on the fewer fuel categories, whenever not complete data is available. While this study use average values for the GHG emission factors from renewable electricity generation, for a study at continental level, the accuracy of results could be improved by considering local emission factors for solar, wind, geothermal, etc. that are depending on high extent on local resources and local circumstances.

The carbon intensity of electricity consumed also depends on the power losses at high voltage, medium voltage and low voltage. Total power losses in the national grid were accounted on the base of national statistical data. More detailed info, at country level, on the share of losses between the high voltage, medium voltage and low voltage sections of the electric grid could be beneficial for the improvement of the accuracy of results.

For the calculation of the carbon intensity of electricity consumed, this paper consider the annual data on the import and export of electricity; the values reported thus represent average annual values. At one point in time in a year, the actual values of the carbon intensity of electricity consumed might differ from the average annual values, due to the different values of electricity used from domestic production and import. Future work can improve the estimations, by providing real-time data on carbon intensity of electricity used, considering the actual electricity traded at a low time step (for example 15 min), provided that this info is available.

5. Disclaimer

The views expressed are purely those of the authors and may not, under any circumstances, be regarded as an official position of the European Commission.

CRediT authorship contribution statement

Nicolae Scarlat: Conceptualization, Methodology, Investigation, Supervision. **Matteo Prussi:** Methodology, Validation, Investigation. **Monica Padella:** Methodology, Validation, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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