Life cycle Upstream Emission Factors 2024

Database documentation

International Energy Agency

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Acknowledgements

This database has been compiled and developed by Pouya Taghavi under the guidance of Roberta Quadrelli and Nick Johnstone at the IEA Energy Data Centre.

Sara El Marzouki supported the work by completing the literature review and providing assistance with the harmonization corresponding to wind and solar PV generation. The natural gas and oil figures are from the World Energy Outlook team's modelling provided by Christophe McGlade, Jerome Hilaire and Tae-Yoon Kim. Additionally, the database benefited from data and feedback provided by colleagues across the Agency including Carlos Fernandez Alvarez and Eren Cam (coal), Jacob Tetter, Francois Briens and Laura Mari Martinez (renewables), Jeremy Moorhouse (biofuels) and Luca Lorenzoni (hydro). Arnau Risquez Martin and Juha Koykka has contributed to the work by reviewing the final output.

The IEA would like to thank the experts from the US National Renewable Energy Laboratory (NREL) namely Garvin Heath as this work has benefited from the Life Cycle Assessment Harmonization project carried out by NREL. The IEA is also grateful to the following reviewers from academia and industry, who kindly gave their time to provide input: Michael Wang and Zifeng Lu (Argonne National Laboratory), Claire Stentiford (Anthesis), Natalia Pascual (Agendi), John Dulac (Saint-Gobain), Alan Tarleton and Gavin Tivey (Ecoact) and Leigh Carter (UL).

1. CHANGES FROM LAST EDITION

Note: this section refers to changes of the database as compared to the 2023 pilot edition of the *IEA Life Cycle Upstream Emission Factors* database.

Database name change

Following the successful launch of a pilot version of the database last year, the database name has been revised from *IEA Life Cycle Upstream Emission Factors (pilot edition)* to *IEA Life Cycle Upstream Emission Factors*.

Timeseries expansion

With the objective to increase the relevance of the database, the coverage has been expanded to include data for timeseries starting in year 2015.

Inclusion of the historical data enhances the applicability of this database notably for greenhouse gas (GHG) footprint reporting purposes. As recommended by the Greenhouse Gas Protocol (GHG Protocol) Corporate Accounting and Reporting Standard, when changing accounting methodologies and/or sources, the change should be applied to both the reporting year and the base year. Hence, the expansion of the coverage allows using the IEA data as a harmonized dataset across the timeseries and minimizing inconsistencies in the reporting.

Change of the Global Warming Potential values

At the Conference of the Parties (COP) 26 there was an agreement for the global community to report greenhouse gas emission inventories using the IPCC 5th Assessment Report (AR5) published GWP100 figures starting from year 2024 (Decision 18/CMA.1). This choice supersedes the original guidance (Decision 24/CP.19), based on which non-CO_2 emissions were to be reported using the GWP 100 figures published by AR4.

However, the grid upstream emission factors published in this database are largely used for GHG footprint reporting purposes. Hence, to ensure alignment with the latest requirements from the European Sustainability Reporting (ESRS) and other major disclosure standards, the non-CO_2 emission intensities included in this edition of the database are now developed based on the AR6 metrics, as detailed in table below.

Type of GHG	Previous metrics : AR4 GWP100	New metrics: AR6 GWP100
CH_4	25	27
N_2O	298	273

LPG upstream intensity

In the pilot edition of the database, the LPG intensities used as inputs in the IEA life cycle model corresponded to oil-based extraction. In this edition of the database, the LPG intensities are updated to become weighted averages considering both oil-based and natural gas-based production. The weighted averages are derived using an estimated country-specific split of the two types of production routes. Please refer to section on fuel-cycle intensities corresponding to oil products for additional details.

2. DATABASE DESCRIPTION

This section contains a description of the data included in the 2024 edition of the *IEA Life Cycle Upstream Emission Factors* database. This database complements the IEA Emission Factors database which includes emission factors corresponding to direct combustion at the point of electricity generation. The product includes annual data for:

- countries: 149 countries and global aggregate (see section *Geographical coverage*);
- years: 2015 to 2022; and 2023 (provisional data for selected countries).

The database is published in an excel format and includes three main sheets with a set of life cycle emission factors corresponding to electricity generation. The factors are described below:

Total upstream emission factors (in CO2eq per kWh) (sheet Total upstream factors)
Correspond to the total upstream emissions intensity associated with the national electricity generation. The factors are computed using the overall life cycle footprint of the electricity generation technologies/fuels excluding direct emissions from combustion of the fuels at the generation point weighted by their respective shares in the generation mix.

Fuel-cycle emission factors (in CO2eq per kWh) (sheet Fuel-cycle factors)
Correspond to the fuel-cycle emissions intensity associated with the national electricity generation. The factors are computed using the life cycle emissions intensity corresponding to fossil fuels, uranium and biofuels fuel-cycles weighted by the respective shares of all fuels/technologies in the generation mix. The non-fuel cycle life cycle emissions and the direct emissions from combustion of the fuels at the generation point are excluded.

Note that the fuel-cycle emission factors are a sub-component of total upstream emission factors.

Life cycle adjustment factors for transmission and distribution losses (in CO2eq per kWh) (sheet Life cycle T&D factors)
Include the emission intensities associated with the transmission and distribution losses of electricity in the grid developed from a life cycle perspective.

Note that these adjustment factors are not included in the above emission factors and can be added to the above to derive a closer intensity figure at the final consumption point.

3. SCOPE AND OBJECTIVE

The energy sector accounts for about three quarters of total greenhouse gas (GHG) emissions globally, hence addressing the clean energy transition is central in achieving climate mitigation objectives. Electricity is central to many parts of life in modern societies and power generation is currently the largest source of carbon dioxide emissions globally. Additionally, with significant potential to mitigate emissions and decarbonise energy supply chains, electrification is an important strategy to reach climate and clean air objectives. Most climate mitigation scenarios entail electrification of energy end uses and a substantial increase of the share of electricity in total final energy consumption.

Low carbon generation technologies generally do not correspond to any direct emissions at the point of generation; however, they do emit GHG emissions over their life cycle. Considering the climate impacts over the life cycle provides a better understanding of the emission reduction benefits from electrification and how penetration of low carbon generation sources may contribute to decarbonization goals. Life cycle assessment (LCA) of electricity systems is critical to identify potential problem-shifting along supply chains and technology life cycles.

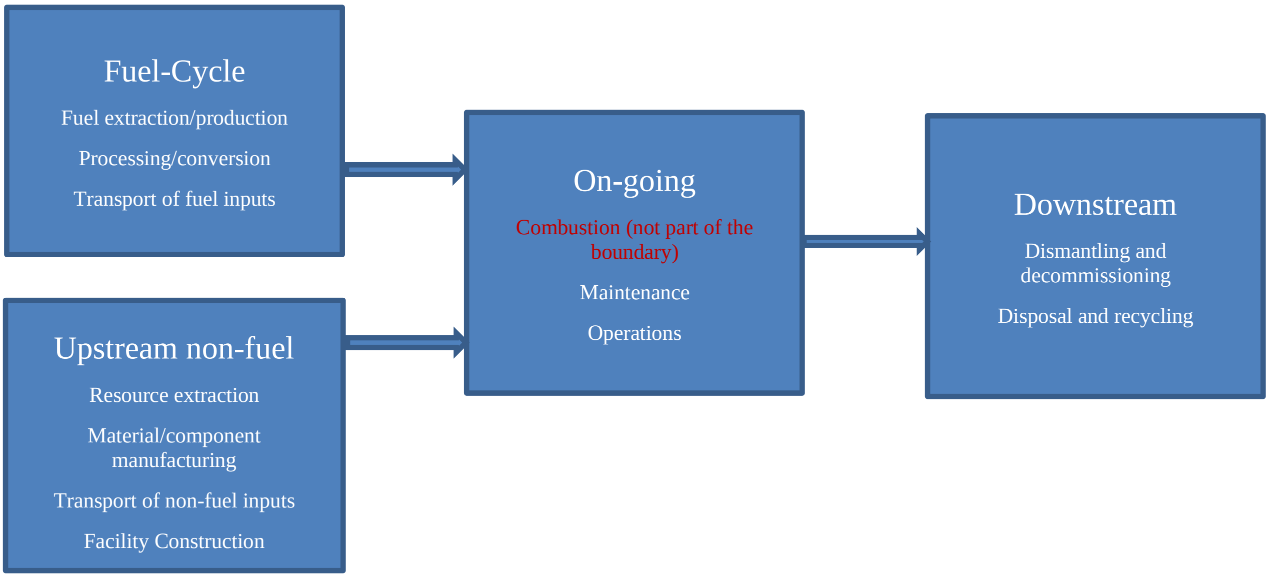
The *IEA Emission Factors* database currently includes the emission factors at the point of electricity generation (combustion only, including energy used by the plant). These factors reflect annual average intensities of the national grid and can be used for the estimation of location-based Scope 2 emissions corresponding to consumption of purchased electricity under the WRI *Greenhouse Gas Protocol (GHG Protocol)*. The database also provides adjustment factors for emissions associated with transmission and distribution losses of electricity in the grid, as well as electricity trade between countries (data available for selected countries). These adjustments can be added to the default factors, as required, to obtain a closer estimate of emission at the point of final consumption. However, the product does not account for the life cycle upstream emission factors required for a complete Scope 3 reporting under the GHG Protocol.

The IEA is disseminating new database including the life cycle emission factors corresponding to national electricity grids. The database assesses and compiles reliable data to provide a global harmonized database on an annual basis. As it has been detailed in the *Methodology* section, this database has been developed by merging data from multiple sources namely the IEA statistics, IEA modelling work, IEA performed LCA harmonization alongside a life cycle assessment project carried out by the US National Renewable Energy Laboratory (NREL). The results from the IEA performed harmonization of the latest LCA studies corresponding to wind and solar PV generation, largely match the harmonized central tendencies published by the NREL project. It is deemed unlikely that a new review based on the latest published LCA studies corresponding to fossil-based, nuclear and hydro generation would result in great differences with the NREL published figures. This presumption is based on the large number of published LCA studies included in the NREL project corresponding to these mature technologies, their relatively narrow range of distribution and the fact that majority of the existing fleets have been in service for many years. However, the IEA attempts to consider new science, methods, or context with major impacts on the life cycle intensities of various electricity generation technologies on a continuous basis to ensure the relevance of this database.

Under the *GHG Protocol*, the average-data approach, involves estimating emissions by using secondary (i.e., industry average) emission factors for upstream emissions per unit of consumption. These emissions are reported as part of the *Category 3: Fuel and energy-related activities not included in Scope 1 or Scope 2*. The factors included in this database can be used for estimation of the Scope 3 emissions related to the consumption of the purchased electricity which are reported under this category. However, as detailed in section 7 of this document, the limitations and uncertainties associated with these factors are important and should be noted.

The steps of life cycle for electricity generation technologies are shown in the following figure. The overall life cycle boundary includes the extraction of fuels or raw material for plant construction, the manufacturing of generation technologies, the processing of the fuel/product, transport and distribution to the power generation point, installation/construction of the generation facilities as well as the on-going emissions associated with operations and maintenance of these plants and the disposal/decommissioning of both fuels and facilities. The emissions associated with the construction of the grid infrastructure as well as operations and maintenance corresponding to the transmission and distribution companies are excluded from this scope.

The upstream life cycle emissions, which is the scope of the desired factors include all the components besides the direct emissions associated with the combustion of the fuels for the purpose of the generation.



Based on the *GHG Protocol*, the upstream life cycle emissions of purchased electricity are defined as *"Extraction, production, and transportation of fuels consumed in the generation of electricity, steam, heating, and cooling that is consumed by the reporting company"*. The definition of the upstream emission factors of purchased electricity currently provided by GHG Protocol explicitly refers to the fuel-cycle only, hence implying that the emissions associated with the material extraction/manufacturing, construction of the plant, on-going maintenance/operations activities which are not fuel related and the dismantling and decommissioning of the generation technologies and facilities are excluded. As an example, the emissions associated with the manufacturing of cement and steel that are used in the construction of an electricity generation facility are excluded. The IEA has communicated the need for clarification with the World Resources Institute (WRI) as the co-creator of the GHG Protocol and the entity in charge of any revisions to the guidance.

In order to prepare the output which will be useful for GHG footprint reporting purposes regardless of the potential update to the language included in the guidance, two types of upstream factors were developed:

1. **Total upstream factors:** Include the total upstream emissions associated with the electricity generation as described above. This is equal to the overall life cycle footprint of the electricity generation technology excluding direct emissions from combustion of the fuels at the generation point.

2. **Fuel-cycle factors:** Include the life cycle emissions corresponding to the fuel cycle including fossil fuels, uranium and biofuels. The non-fuel cycle life cycle emissions and the direct emissions from combustion of the fuels at the generation point are excluded.

As detailed in the *Methodology* section the total upstream and fuel-cycle factors corresponding to the national electricity grids are computed using the above fuel/technology specific factors and their respective shares in the electricity generation mix.

On top of the above, the database includes the emission intensities induced due to the transmission and distribution (T&D) losses of electricity in the grid developed from a life cycle perspective. These factors are different from the correction factors for T&D losses published within the *IEA Emission Factors* database as they are developed by multiplying the life cycle emission intensity of the electricity grids by the percentage of electricity which is lost as it flows from the generation facility to the point of consumption. As such, the factors include the incremental intensity corresponding to the overproduction of electricity to compensate losses, from a life cycle perspective.

4. DEFINITIONS

Flow dimension

Flow	Short name	Definition
Total upstream emission factors (CO_{2eq}/kWh)	$EF_{Total\ upstream}$	Correspond to the total upstream emissions intensity associated with the national electricity generation. The factors are computed using the overall life cycle footprint of the electricity generation technologies/fuels excluding direct emissions from combustion of the fuels at the generation point weighted by their respective shares in the generation mix. For the most recent year available, this value is estimated based on provisional data. Please refer to the *Methodology* section for details.
Fuel-cycle emission factors (CO_{2eq}/kWh)	$EF_{Fuel-cycle}$	Correspond to the fuel-cycle emissions intensity associated with the national electricity generation. The factors are computed using the life cycle emissions intensity corresponding to fossil fuels, uranium and biofuels fuel-cycles weighted by the respective shares of all fuels/technologies in the generation mix. The non-fuel cycle life cycle emissions and the direct emissions from combustion of the fuels at the generation point are excluded. Note that the fuel-cycle emission factors are a sub-component of total upstream emission factors. For the most recent year available, this value is estimated based on provisional data. Please refer to the *Methodology* section for details.
Life cycle adjustment factors for transmission and distribution losses (CO_{2eq}/kWh)	$T\&D_{\ life\ cycle}$	Include the emission intensities associated with the transmission and distribution losses of electricity in the grid developed from a life cycle perspective. The factors are developed by multiplying the life cycle emission intensity of the electricity grid by the percentage of the T&D losses occurred. Note that these adjustment factors are not included in the above emission factors and can be added to the above to derive a closer intensity figure at the final consumption point. Please refer to the *Methodology* section for details.

5. METHODOLOGY

Electricity grid emission factors

The following two sections details the methodology corresponding to development of the total upstream and fuel-cycle emission factors corresponding to national grids as well as the life cycle adjustment factors for T&D losses. These factors are disseminated within this database.

Total upstream and fuel-cycle grid emission factors

The overall methodology for developing country-specific fuel-cycle and upstream emission factors corresponding to electricity grids, includes the following listed steps:

1. Developing country-specific fuel-cycle and upstream emission factors for all the fuels and technologies used for electricity generation globally.

   Note: As it will be detailed in the following sections, depending on the fuel/technology and the source of the compiled data, the factors correspond to either the generation output (mass of CO_{2eq}/kWh electricity generation) or the unit of energy inputs to the generation plant (mass of CO_{2eq}/kWh fuel input to the generation plant).

2. Computing the fuel-cycle emission factors corresponding to electricity grid by multiplying the fuel specific factors developed in Step 1 with the corresponding activity data for each fuel and dividing by the total electricity generation as expressed by the equation below:

$$EF_{Fuel-cycle\ grid\ emission\ factor} = \frac{\sum_i (EF_{i,t} \times activity_{i,t})}{Total\ electricity\ output_t}$$

$EF_{i,t}$: fuel-cycle emission factor per kWh output or unit of energy input to the plant for each fuel i in year t expressed in gCO_{2eq}/kWh

activity i,t: electricity output or fuel input to the plant for fuel i in year t

Total electricity output: total electricity generation from all fuels and technologies (kWh) in year t

Note that the fuel-cycle emission factors are a sub-component of total upstream emission factors which are detailed below.

3. Computing the total upstream emission factors corresponding to electricity grid by multiplying the fuel/technology-specific factors derived in Step 1 with the corresponding activity data for each fuel/technology and dividing by the total electricity generation as expressed by the equation below:

$$EF_{Total\ upstream\ grid\ emission\ factor} = \frac{\sum_i (EF_{i,t} \times activity_{i,t})}{Total\ electricity\ output_t}$$

EF i,t: upstream emission factor per kWh output or unit of energy input to the plant for each fuel/technology i in year t expressed in gCO_{2eq}/kWh

activity i,t: electricity output or fuel input to the plant for fuel or technology i in year t

Total electricity output t: total electricity generation from all fuels and technologies (kWh) in year t

The factors published for the provisional year (year 2023 in this edition) are based on a simplified methodology. The available data for the latest year only include the breakdown of electricity generated by fuel, but not the fuel input to the plants. Hence, it is not possible to use the emission factors per unit of energy input to the plants which were applied in the above equations for a subset of the fuels. Considering this limitation, the assumption is that there has been no change in the efficiency of these plants and in the energy content of the input products compared to the previous year. Following these assumptions, both the fuel-cycle and total upstream factors are derived as expressed by the following equation:

$$EF_Y = \frac{\sum_i (EF_{i,y-1} \times electricity\ ouput_{\ i\ ,y})}{Total\ electricity\ output_{\ y}}$$

EF y: total grid Upstream or grid fuel-cycle emission factor per kWh output in provisional year Y expressed in gCO_{2eq}/kWh

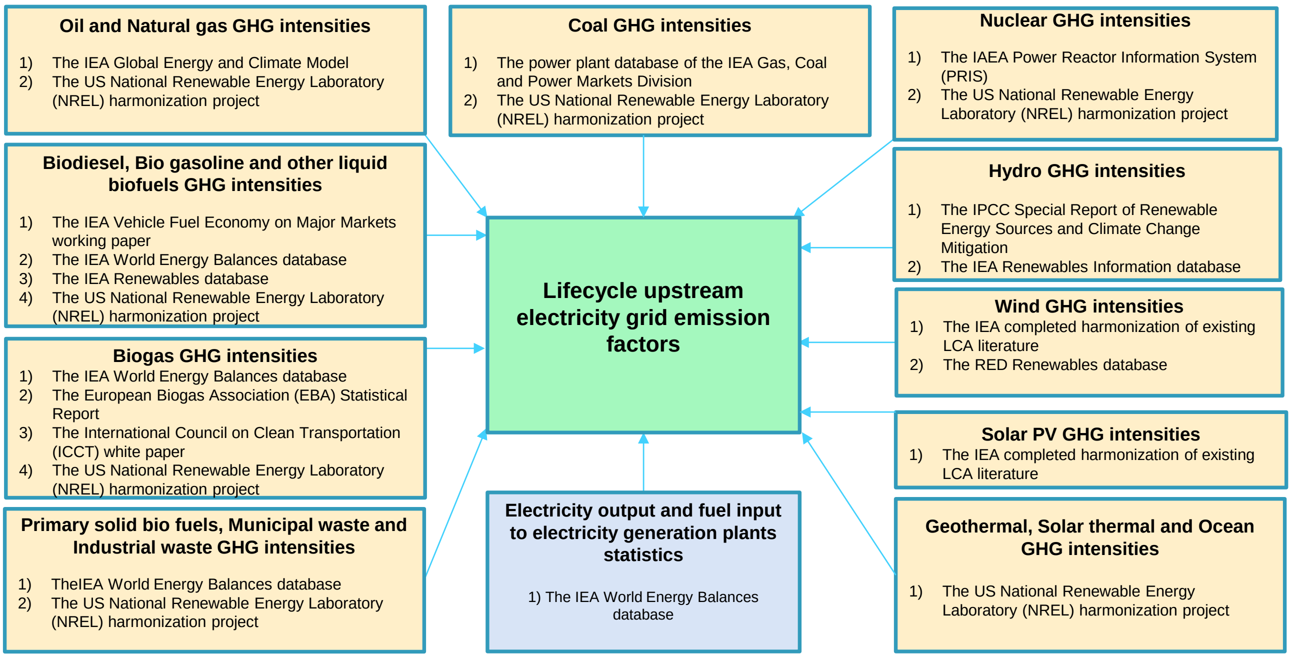
EF i,y-1: total upstream or fuel-cycle emission factor for each fuel/technology i per kWh output in year Y-1 expressed in gCO_{2eq}/kWh

electricity output i,y: electricity output (kWh) from each fuel or technology i in provisional year Y

Total electricity output t: total electricity generation from all fuels and technologies (kWh) in provisional year Y

The relative weights of the intensities corresponding to each fuel/technology in determining the overall life cycle grid emission factor is dissimilar. The statistical significance of each fuel/technology on determining the overall grid intensity, depends on the respective share in the electricity generation mix as well as the magnitude of each fuel/technology-specific emission factors. On a global level, coal and to a lesser extent natural gas correspond to high upstream intensities and at the same time are major contributors to the global electricity mix, hence their relative weight in determining the overall global life cycle grid intensity is significant. On the other hand, the relative importance of technologies such as wave/tidal and fuels like biogas are minor.

The simplified schematic below provides an overview of the various components required for developing these emission factors and the corresponding source(s) used for each constituent. The source for the energy data used for the above is the IEA World Energy Balances database. The fuel/technology-specific emission intensities have been derived based on data from multiple sources as shown in the figure and detailed in the following sections. Each of the following fuel/technology specific sections is comprised of two sub-sections including fuel-cycle and total upstream emission factors.



Life cycle adjustment factor for T&D losses

As electricity is transmitted through a grid from the generation plant to the final consumption point, losses can occur along the way for different reasons. The occurred T&D losses typically represent between 5 and 15% of the energy transmitted, mainly depending on the distance and quality of the lines. This means that for each unit of electricity consumed, a higher amount had to be generated.

In order to account for the emission intensity induced due to the T&D losses from a life cycle perspective, the overall life cycle emission intensity of the electricity grid is multiplied by the percentage of the T&D losses occurred as detailed by the following equation. The factors include all greenhouse gases including CO_2, CH_4 and N_2O.

$$T\&D_{life\ cycle} = (EF_{Total\ upstream} + EF_{Direct})\ x\ Loss\ factor$$

T&D $_{Life\ cycle}$*: emission intensities associated with the transmission and distribution losses of electricity in the grid developed from a life cycle perspective expressed in* gCO_{2eq}/kWh.

EF $_{Total\ upstream}$*: total upstream emissions intensity associated with the national electricity grid expressed in* gCO_{2eq}/kWh

EF $_{Direct}$*: direct emissions intensity associated with the national electricity grid expressed in* gCO_{2eq}/kWh*. This is the total emissions at the point of generation from fossil fuels consumed for electricity generation, divided by output of electricity generated from all fossil and non-fossil sources.*

Loss factor = $\frac{T\&D\ losses}{Grid\ electricity\ throughput}$

Where:

- $T\&D\ Losses$ *: total transmission and distribution losses in the grid.*
- $Grid\ electricity\ throughput$ *: total amount of electricity flowing through the national electricity grid, computed as gross electricity generation – own use of electricity in generation plants + imports.*

Note that these adjustment factors are not included in the above detailed total upstream and fuel-cycle emission factors and can be added to the above to derive a closer intensity figure at the final consumption point.

The data quality for electricity transmission and distribution losses may be very variable across countries.

Fuel/Technology-specific emission factors

The following sections detail the methodology corresponding to development of fuel/technology-specific emission factors which have been used as building blocks for deriving the above discussed electricity grid emission factors. Each of the following fuel/technology-specific sections is comprised of two sub-sections including fuel-cycle and total upstream emission factors. Note that these factors have only been used as inputs to the model and are not disseminated within this database.

Natural gas

1. Fuel-cycle factors

The IEA models the upstream emissions corresponding to the natural gas fuel cycle for the Global Energy and Climate Model (GEC) regions. The fuel-cycle emission factors for natural gas are built from five main building blocks as summarized below:

- Methane (CH_4) emissions corresponding to the upstream production
- CO_2 emissions from fuel combustion corresponding to the upstream production
- Vented CO_2 across the supply chain
- Transport emissions differentiated by mode (pipeline vs liquified natural gas (LNG))
- Downstream methane emissions

The CO_2 and CH4 intensities per unit of production are estimated for various types of gas fields, including conventional onshore, shallow, deep, ultra-deep offshore and arctic production as well as unconventional production from tight, coal bed methane (CBM) and shale reservoirs.

Both upstream and downstream methane intensities as well as the estimates corresponding to vented CO_2 are based on the work completed for the IEA Global Methane Tracker. The bottom-up approach adopted to estimate the methane and carbon dioxide emissions from global gas operations includes applying country-specific and production type-specific emission intensities to the production and consumption data. For natural gas related fugitive emissions, the starting point are emission intensities for upstream and downstream gas in the United States, based on the 2023 greenhouse gas inventory of the United States along with a range of other data sources, including an IEA survey of companies and countries. The United States intensities are then scaled to obtain intensities for all other countries, based upon a range of auxiliary country-specific data and information. Scaling factors were finally applied to production (for upstream emissions) or consumption (for downstream emissions) within each country. For detailed information on methodologies and definitions, please consult the Global Methane Tracker documentation.

The production fuel combustion CO_2 intensities, are based on the work originally completed for the Emissions from Oil and Gas Operations in Net Zero Transitions report and will feed the upcoming 2024 edition of World Energy outlook (WEO).

For the purpose of estimating the transport emissions, a trade matrix including information on natural gas trade in between 20 regions has been developed based on data form the IEA Natural Gas Information with IEA expert adjustments as required to fill the missing gaps. The developed matrix has been complemented by underlying data from the academic publication (UKERC 2022) for intensities corresponding to pipeline and LNG transport. The trade matrices are then used for adjusting the regional intensities based on the trade data to derive factors representing the intensities corresponding to consumption of natural gas.

For the purpose of deriving the emission intensities corresponding to the natural gas fuel-cycle required for developing the electricity grid fuel-cycle emission factors, the following steps were followed:

- For each of the importing regions the total intensities of the corresponding exporting regions were multiplied by the respective energy figures to derive the GHG emissions.

- The calculated GHG emissions associated with each importing region were summed to compute the total upstream fuel-cycle GHG emissions associated with natural gas consumption.
- This above derived figure was divided by the total consumption of the selected importing region to compute the corresponding regional consumption-based intensity.
- Finally, the countries are mapped against the trade regions and a selected regional intensity is associated with each specific country.

The above derived factors are per unit of energy inputs to the generation plant (mass of CO_{2eq}/kWh fuel input to the generation plant).

2. Total upstream factors

The US National Renewable Energy Laboratory (NREL) has carried out a life cycle assessment harmonization project to review and harmonise the ranges of inconsistent and conflicting estimates of the life cycle GHG emissions for electricity production from various sources and clarify the central tendencies of existing estimates. This study resulted in the reduction of 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.

In order to derive the total upstream factors for electricity generation from natural gas, the above developed country-specific fuel-cycle factors were complemented by data from the NREL project. The supporting information from the NREL review of life cycle GHG emissions of electricity generated from natural gas provides the central tendencies for the upstream, downstream as well as on-going non-fuel emission intensities corresponding to gas turbine and combined cycle generation based on a systematic review of over 70 LCA studies. The upstream stage includes raw materials extraction, material/component manufacturing, transportation and on-site construction. The on-going non-fuel block include the non-fuel emissions associated with the operation and maintenance of the generation plant. The downstream stage encompasses decommissioning, disassembly, transportation to the waste site and disposal and/or recycling of the plant components and other site material.

The above developed fuel-cycle factors are complemented by the NREL central tendencies published for upstream and downstream emission intensities to derive the total upstream factor corresponding to natural gas electricity generation. The pool of LCA's included in the NREL review include studies mainly related to North America, Europe and China with more than 30% corresponding to the United States. The heterogeneity associated with the manufacturing processes can largely influence the emissions from the upstream block. The manufacturing emissions intensity is largely dependent on the electricity mix as well as the energy intensity of the processes. Hence, applying the central tendencies published by the NREL project as global proxies for this stage of the life cycle is associated with notable limitations. However, based on the published central tendencies by the NREL project, the upstream phase corresponds to less than 10% of the total upstream factors corresponding to natural gas generation.

Coal

1. Fuel-cycle factors

The NREL has carried out a systemic review and harmonization of life cycle GHG emission of coal-fired electricity generation. The study publishes harmonized central tendencies for life cycle emission intensities corresponding to both subcritical and supercritical coal generation. Although fuel-cycle intensities such as mining, processing and transport are slightly different among various types of coal used for power generation, the published intensities by the study are not differentiated per coal type. However, the published harmonized central tendencies are based on over 50 studies among which various types of primary coal typically used for power generation exist. Hence, the estimates provide a reasonable global proxy for the fuel-cycle intensities corresponding to coal-fired generation per technology type.

The power plant database of the IEA Gas, Coal and Power Markets Division, includes the country-specific share of installed capacities for subcritical, supercritical and ultra-supercritical coal-fired generation.

For the purpose of deriving the emission intensities corresponding to the coal fuel-cycle required for developing the electricity grid fuel-cycle emission factors, the following steps and assumptions were followed:

- The country-specific shares of installed capacity for supercritical vs subcritical technologies were developed based on the data from the power plant database of the IEA Gas, Coal and Power Markets Division. Note that as the NREL harmonization project does not differentiate in between supercritical and ultra-supercritical generation, the corresponding installed capacities of the two technologies were aggregated and labelled as supercritical.

- Table 1 from the NREL review includes the combustion-based emission factors for all the selected studies for the harmonization. On the other hand, the corresponding supporting information provides the harmonized fuel-cycle emission intensities for each technology as an aggregated figure with the fuel combustion intensity. Hence, the fuel combustion medians from the set of studies for each technology type were calculated and deducted from the aggregated figures to estimate the portion corresponding to the fuel-cycle for each technology type.

- The country-specific derived shares per technology were applied to the above developed fuel-cycle factors in order to populate the country-specific fuel-cycle emission factors. This is based on the assumption that the share of generation from each technology type is comparable to the corresponding shares of installed capacity.

Note: The above developed factors correspond to generation from primary coal products. However, in addition to primary coal, derived coal gases including blast furnace gas, coke oven gas and gas works gas are sometimes used for electricity generation in smaller quantities for a limited set of countries. Blast furnace gas is produced during the combustion of coke in blast furnaces in the iron and steel industry. Similarly, gas works gas and coke oven gas are both by-products of coke oven coke production. Hence, the marginal emission intensities corresponding to conversion of coking coal to these derived gases were excluded for the purpose of this analysis and the same fuel-cycle intensities derived for primary coal products were selected for generation from derived coal gases.

The derived fuel-cycle factors are per unit of electricity output (mass of CO_{2eq}/kWh electricity generation).

2. Total upstream factors

The supporting information from the NREL systematic review of life cycle GHG emissions of coal-fired generation provides the central tendencies for the upstream, downstream as well as on-going non-fuel emission intensities corresponding to each technology type. The upstream stage includes raw materials extraction, material/component manufacturing, transportation and on-site construction. The on-going non-fuel block include the non-fuel emissions associated with the operation and maintenance of the generation plant. The downstream stage encompasses decommissioning, disassembly, transportation to the waste site and disposal and/or recycling of the plant components and other site material.

The above developed fuel-cycle factors are complemented by these three building blocks to formulate the country-specific total upstream factors for coal-fired generation. The pool of LCA’s included in the NREL review are mainly focused on studies related to North America, Europe, Australia, China and Japan. The heterogeneity associated with the manufacturing processes can largely influence the emissions from the upstream block. The manufacturing emissions intensity is largely dependent on the electricity mix as well as the energy intensity of the processes. Hence, applying the central tendencies published by the NREL project as global proxies for this stage of the life cycle is associated with notable limitations. However, based on the published central tendencies by the NREL project, the upstream phase correspond to about 4% and 8% of the total upstream factors corresponding to subcritical and supercritical coal generation respectively. Considering this point, the corresponding uncertainties with these estimates is unlikely to have a significant impact on the developed factors.

Oil

1. Fuel-cycle factors

The IEA, models the fuel-cycle emissions corresponding to gasoline, kerosene and diesel for the Global Energy and Climate Model (GEC) regions. The modelled fuel-cycle emission factors for these oil products are built from five main building blocks as summarized below:

- Emission intensities corresponding to the upstream production (including flaring)
- Emission intensities corresponding to crude transport
- Emission intensities corresponding to Natural Gas Liquids (NGL) fractionation
- Refinery emission intensities
- Emission intensities corresponding to transport of final products

The emission intensities corresponding to the upstream production are based on the work completed for the IEA Global Methane Tracker. The bottom-up approach adopted to estimate the GHG emissions from global oil production operations includes applying country-specific and production type-specific emission intensities to the production and consumption data. For oil-related fugitive emissions, the starting point are emission intensities for upstream and downstream oil in the United States, based on the 2023 greenhouse gas inventory of the United States along with a range of other data sources, including an IEA survey of companies and countries. The United States intensities are then scaled to obtain intensities for all other countries, based upon a range of auxiliary country-specific data and information. Scaling factors were finally applied to production (for upstream emissions) or consumption (for downstream emissions) within each country. For detailed information on methodologies and definitions, please consult the Global Methane Tracker documentation.

The refinery and fractionation energy requirements (including direct and indirect energy consumption) were estimated for various types of crude inputs and refinery configurations. The main input for estimating the refinery intensities are the data from the IEA World Energy Balances database. Additionally, product-specific refinery intensities from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model were used in order to allocate the overall refinery intensities to various products.

For the purpose of estimating the crude transport emissions, a trade matrix including information of crude trade in between the GEC regions was developed mainly based on the IEA Oil Market Report (OMR) data with IEA expert adjustments to fill the data gaps. Similarly, in order to estimate intensities of product transport, product-specific trade matrixes were developed for the three above-mentioned oil products. As the developed factors represent the life cycle intensities corresponding to consumption of the fuels, the product trade matrixes were used for adjusting the regional intensities based on the trade data. The assumptions for transport intensities per length of pipelines and seaborn transport are based on data from the IEA World Energy Outlook (WEO) modelling.

The countries are mapped against the GEC regions and a selected regional intensity is associated with each specific country in order to develop the country-specific fuel-cycle emission factors associated with generation from the above three oil products.

Besides the three oil products discussed above, IEA complete modelling for fuel-cycle emission factors corresponding to other primary and secondary oil products used for electricity generation is not available. As a result, the factors for the remaining products were developed based on the following listed assumptions:

- For LPG, Naphtha, and fuel oil, the modelling for the block corresponding to refining intensities is available. For the upstream production and crude transport blocks the variation among various products is minimal. Thus, the average figures associated with the above discussed three products were selected. For the intensities corresponding to product transport, the differences among the various products are more visible. However, considering the small contribution of this block to the overall fuel-cycle factor, the average figure associated with the three products which are fully modelled were applied to complement the factors for this set of products.

- For petroleum coke and non-specified oil products, the fuel-cycle intensities were developed based on similar assumptions as listed above with the difference that in the absence of modelled refinery intensities for these two products, the modelled refinery intensities allocated to other non-modelled oil products were selected to complement the factors.

- Crude oil and NGL are primary oil energy products and their life cycle does not include the refining and product transport building blocks. For the upstream production and crude transport blocks the average figures associated with the three products which are fully modelled were also selected for this set of products. The averages corresponding to the available modelled crude transport intensities were doubled based on the assumption that the transport distance to the electricity generation facility (which is the case of primary products) is larger than the modelled distance from production facilities to refineries.

The derived factors are per unit of energy inputs to the generation plant (mass of CO_{2eq}/kWh fuel input to the generation plant).

Note: The LPG intensities detailed above are refinery-based and correspond to an oil-based production route. For this analysis, these intensities have been complemented with LPG intensities corresponding to a natural gas-based production route in order to estimate weighted average intensities considering both oil-based and gas-based production. The country-specific split of the two types of production routes are estimated based on the granular data included in the IEA World Energy Balances database. The estimation assumes that all the LPG production from inter-product transfers included in the energy balance are from natural gas liquids (NGL) and can be considered to be natural gas-based.

2. Total upstream factors

Unlike other generation fuels and technologies, the NREL project has not completed a systematic review corresponding to life cycle emissions from oil-based generation. However, according to the extensive published literature and similar to the natural gas generation, the contribution of the remaining building blocks comparing to the fuel-cycle is deemed to be marginal. As a result, proportion of total upstream to fuel-cycle factors derived from gas generation were applied to the above developed fuel-cycle intensities in order to estimate the total upstream factors corresponding to oil-based electricity generation. As the results from the natural gas harmonization project are used for developing these factors, the corresponding limitations detailed in the *Natural gas section* also apply here. However, as detailed in the *Natural gas section* the corresponding uncertainties with these estimates does not have a significant impact on the developed total upstream factors.

Biodiesel

1. Fuel-cycle factors

The IEA Vehicle Fuel Economy in Major Markets working paper provides regional modelling of well-to-tank (WTT) emission intensities for multiple production routes corresponding to biodiesels. The first production route utilises transesterification to produce Fatty Acid Methyl Ester (FAME) which is referred to as biodiesel. Vegetable oils from oilseed food crops (i.e. palm, soybean, rapeseed) or energy crops (i.e. jatropha) are reacted with methanol to produce biodiesel. Waste oils from used cooking oils or animal fats can also undergo transesterification, to produce FAME. The second route reacts oil feedstocks such as vegetable oils and waste oils with hydrogen. The resulting mixture include a hydrotreated vegetable oil (HVO) which is also known as renewable diesel. Several main data sources were used to calculate the WTT emissions intensities. Emissions associated with feedstock cultivation, including fuel inputs and fertiliser, pesticide and insecticide application, were taken from GREET (2020 version). Biofuel yields and WTT emission factors for fossil fuels were taken from IEA ETP supply modelling, and results were calculated based on ETP's Mobility Model. For additional information please consult Annex 2 of the published working paper.

Additionally, the IEA Renewables 2023 database, includes country-specific production data from different feedstocks for each of the above discussed two pathways. The feedstocks-specific shares corresponding to each of the two pathways were applied to the modelled WTT emission intensities discussed above to develop the country-specific biodiesel fuel-cycle emission factors for each of the two pathways. In parallel, the production shares of pathways were applied to the country-specific biodiesel inputs to electricity generation plants from the IEA World Energy Balances database to estimate the fraction of generation from FAME vs HVO.

Finally, country-specific fuel-cycle emission factors were developed, by merging the derived country-specific generation share from each pathway with the developed pathway-specific emission intensities.

The derived factors are per unit of energy inputs to the generation plant (mass of CO_{2eq}/kWh fuel input to the generation plant).

Note: The direct and indirect land-use change emissions estimates were taken from the GREET CCLUB LUC add-on (Carbon Calculator for Land Use and Land Management Change from Biofuels Production) and the GLOBIOM report commissioned by the European Commission. The GREET model focuses on data for the USA, while the GLOBIOM report is based on data for the European Union. Hence, the geographical representativeness of the land-use impacts considered in this analysis is limited.

2. Total upstream factors

As stated in the literature review of biopower LCA published by the NREL Harmonization project and similar to generation from other thermal sources, the contribution of the building blocks other than the fuel-cycle intensity in the total upstream factor is marginal. The average proportion of multiple literature sourced by the NREL review were applied to the above developed country-specific fuel-cycle intensities in order to estimate the total upstream factor corresponding to biodiesel-based electricity generation.

Biogasoline

1. Fuel-cycle factors

The reported figures in the IEA World Energy Balances database for biogasoline, correspond to the aggregated figures for bioethanol, biomethanol, bioETBE and bioMTBE. Although access to the disaggregated figures is not available, it is known that globally a large proportion of the reported figures as biogasoline correspond to bioethanol. This is especially true in the case of major producers including the United States and Brazil. Additionally, due to similar feedstocks and processes the fuel-cycle intensities of the above listed products are deemed to be comparable. As a result, for the purpose of this analysis it was assumed that the biogasoline figures reported for electricity generation can be considered to be bioethanol.

The IEA Vehicle Fuel Economy in Major Markets working paper provides regional modelling of well-to-tank (WTT) emission intensities for production of bioethanol based on different feedstocks. This includes production of conventional bioethanol from sugar or starchy food crops as well as advanced or cellulosic bioethanol production from woody feedstocks such as crop residues. Emissions associated with feedstock cultivation, including fuel inputs and fertiliser, pesticide and insecticide application, were taken from GREET (2020 version). Biofuel yields and WTT emission factors for fossil fuels were taken from IEA ETP supply modelling, and results were calculated based on ETP's Mobility Model. For additional information please consult Annex 2 of the published working paper.

Additionally, the IEA Renewables 2023 database, includes country-specific production data from the above-discussed feedstocks. Product mapping was performed to map the disaggregated feedstock data from the IEA Renewables 2023 to one of the three feedstock families (sugar-based, starch-based, cellulosic). The derived feedstocks-specific shares were applied to the modelled WTT emission intensities discussed above to develop the country-specific bioethanol fuel-cycle emission factors.

The derived factors are per unit of energy inputs to the generation plant (mass of CO_{2eq}/kWh fuel input to the generation plant).

Note: The direct and indirect land-use change emissions estimates were taken from the GREET CCLUB LUC add-on (Carbon Calculator for Land Use and Land Management Change from Biofuels Production) and the GLOBIOM report commissioned by the European Commission. The GREET model is US centric, while the GLOBIOM report *is based on EU data. Hence, the geographical representativeness of the land-use impacts considered in this analysis is limited.*

2. Total upstream factors

As stated in the literature review of biopower LCA published by the NREL Harmonization project and similar to generation from other thermal sources, the contribution of the building blocks other than the fuel-cycle intensity in the total upstream factor is marginal. The average proportion of multiple literature sourced by the NREL review were applied to the above developed country-specific fuel-cycle intensities in order to estimate the total upstream factor corresponding to biogasoline-based electricity generation.

Other liquid biofuels

1. Fuel-cycle factors

The reported figures in the IEA World Energy Balances database for other liquid biofuels are mainly vegetable oils used directly for energy purposes.

The IEA Vehicle Fuel Economy in Major Markets working paper provides regional modelling of well-to-tank (WTT) emission intensities for multiple production routes corresponding to biodiesels. One of the reported production routes is based on vegetable oils from oilseed food crops (i.e. palm, soybean, rapeseed). The average intensities corresponding to biodiesel based on different types of vegetable oils was selected and multiplied by a factor of 0.8. The 0.8 factor was selected as approximately 20% of the life cycle intensity corresponding to biodiesel consumption is related to the fuel conversion step which is not applicable to vegetable oils as they do not undergo this step.

The derived factors are per unit of energy inputs to the generation plant (mass of CO_{2eq}/kWh fuel input to the generation plant).

2. Total upstream factors

As stated in the literature review of biopower LCA published by the NREL Harmonization project and similar to generation from other thermal sources, the contribution of the building blocks other than the fuel-cycle intensity in the total upstream factor is marginal. The average proportion of multiple literature sourced by the NREL review were applied to the above developed country-specific fuel-cycle intensities in order to estimate the total upstream factor corresponding to electricity generation from other liquid biofuels.

Biogas

1. Fuel-cycle factors

The reported figures in the IEA World Energy Balances database for biogas, correspond to an aggregate of gases arising from the anaerobic fermentation of biomass (which are composed of principally methane) as well as mixture of gas resulting from gasification of solid biomass. However, as per the 2022 Statistical Report published by the European Biogas Association (EBA), the European biogas production is almost entirely based on anaerobic fermentation as production from the gasification pathway is still in demonstration phase. As a result, for the purpose of this analysis it was assumed that the biogas figures reported for electricity generation correspond to biomethane.

The International Council on Clean Transportation (ICCT), has published a white paper including life cycle emission intensities corresponding to biomethane and hydrogen. The paper includes biomethane fuel-cycle intensities from various feedstocks including maize, manure and others. The shares of biomethane production in Europe published by EBA, were applied to these published feedstock-specific intensities to develop a weighted average global proxy for biogas fuel-cycle emission factors.

The derived factors are per unit of energy inputs to the generation plant (mass of CO_{2eq}/kWh fuel input to the generation plant).

Note: The land-use change emissions estimates incorporated in the above estimates are based on Renewable Energy Directive II (RED II) publication and largely based on EU data. Hence, the geographical representativeness of the included land-use impacts is limited.

2. Total upstream factors

As stated in the literature review of biopower LCA published by the NREL Harmonization project and similar to generation from other thermal sources, the contribution of the building blocks other than the fuel-cycle intensity in the total upstream factor is marginal. The average proportion of multiple literature sourced by the NREL review were applied to the above developed country-specific fuel-cycle intensities in order to estimate the total upstream factor corresponding to electricity generation from biogas.

Primary solid biofuels

1. Fuel-cycle factors

The reported figures in the IEA World Energy Balances database for primary solid biofuels cover a multitude of woody materials generated by industrial process or provided directly by forestry and agriculture including firewood, wood chips, bark, sawdust, shavings, chips, sulphite, black liquor and animal materials/wastes.

The literature review and sensitivity analysis of biopower life cycle assessments, published by the NREL harmonization project, publishes harmonized central tendencies of total life cycle carbon intensities for various types of primary solid biofuels including dedicated woody crops, agriculture residues, forest residues and animal waste. Hence, the average of the reported harmonized central tendencies of these products was selected as a global proxy for the total upstream factor corresponding to electricity generation from primary solid biofuels.

As stated by the NREL project and similar to electricity generation from other thermal sources, contribution of building blocks other than the fuel-cycle intensity is marginal when formulating the total upstream factor. The average proportion of multiple literature sourced by the NREL review were applied to the developed global proxy for total upstream intensities in order to estimate the fuel-cycle upstream factor corresponding to electricity generation from primary solid biofuels.

The derived fuel-cycle factors are per unit of electricity output (mass of CO_{2eq}/kWh electricity generation).

2. Total upstream factors

As detailed above, the average of harmonized central tendencies for multiple types of primary solid biofuels published by the NREL harmonization project was selected as a global proxy for the total upstream factor corresponding to electricity generation from primary solid biofuels.

Municipal waste (renewable)

1. Fuel-cycle factors

The reported figures in the IEA World Energy Balances database as municipal waste (renewable) comprises the renewable fraction of wastes produced by households, hospitals and the tertiary sector.

The literature review and sensitivity analysis of biopower life cycle assessments published by the NREL harmonization project, publishes harmonized central tendencies of total life cycle carbon intensities for biogenic urban residues. This published central tendency was selected as a global proxy for the total upstream factor corresponding to electricity generation from the renewable fraction of municipal waste.

As stated by the NREL project and similar to electricity generation from other thermal sources, contribution of building blocks other than the fuel-cycle intensity is marginal when formulating the total upstream factor. The average proportion of multiple literature sourced by the NREL review were applied to the developed global proxy for total upstream intensities in order to estimate the fuel-cycle factor corresponding to electricity generation from the renewable fraction of municipal waste.

The derived fuel-cycle factors are per unit of electricity output (mass of CO_{2eq}/kWh electricity generation).

2. Total upstream factors

As detailed above, the average of harmonized central tendencies for biogenic urban residues published by the NREL harmonization project was selected as a global proxy for the total upstream factor corresponding to electricity generation from the renewable fraction of municipal waste.

Nuclear

1. Fuel-cycle factors

The NREL has carried out a systemic review and harmonization of life cycle GHG emission of nuclear electricity generation. The study publishes harmonized central tendencies for life cycle emission intensities corresponding to light water reactors (LWR), pressurized water reactors (PWR) and boiling water reactors (BWR). Additionally, the corresponding supporting information publishes central tendencies for gas-cooled reactors (GCR) and heavy water reactors (HWR). On top of this, the supporting information provides central tendencies for the fraction of upstream, fuel-cycle and downstream blocks of the life cycle intensity for the five listed reactor types. The reactor-specific fraction of the fuel-cycle building blocks were applied to the published central tendencies for total life cycle intensities in order to develop a global proxy for fuel-cycle emission factors per each reactor type.

The IAEA Power Reactor Information System (PRIS) database, provides the country-specific data corresponding to generation per reactor. The generation shares from each reactor type were derived using this data and applied to the above populated global fuel-cycle intensities per each reactor type to develop weighted average country-specific nuclear fuel-cycle factors.

The derived fuel-cycle factors are per unit of electricity output (mass of CO_{2eq}/kWh electricity generation).

Note: Due to the limited number of available related literature, the NREL project does not publish harmonized life cycle emission intensities for fast breeder reactors (FBR) or high-temperature gas-cooled reactors (HTGR). There are currently only two countries globally with minor generation shares from these two reactor types. This includes the Russian Federation (less than 5% of the country's nuclear generation share is from FBR in 2022) and the People's Republic of China (less than 0.5% of the country's nuclear generation share is from HTGR in 2021). Given the minor contribution of the generation from the two technologies in the respective country's nuclear generation mix and in the absence of reliable life cycle data, their corresponding shares were excluded from the developed weighted average nuclear fuel-cycle intensities.

2. Total upstream factors

Similar to above, the total country-specific nuclear upstream factors were developed by applying the IAEA PRIS generation shares for each reactor type to the reactor-specific central tendencies of life cycle emission intensities published by the NREL project. The pool of LCA's included in the NREL review include mainly studies corresponding to the United States, Europe, Australia and Japan. The variabilities related to the geographical location, namely the heterogeneity associated with the manufacturing processes can largely influence the emissions from the upstream stage. The manufacturing emissions intensity is mainly dependent on the electricity mix as well as the energy intensity of the processes. Hence, applying the central tendencies published by the NREL project as global proxies for this building block of the life cycle is associated with notable limitations.

Based on the published central tendencies (medians) by the NREL project, the upstream stage corresponds to 8 to 15 percent of the total upstream factors corresponding to generation using GCR, BWR, LWR and PWR reactors. On the other hand, this fraction is above 70% for HWR-based generation. Hence, the corresponding uncertainties with these estimates is likely to have a noteworthy impact on the developed total upstream factors for the handful of countries which have generation using HWR reactors.

Hydro

1. Fuel-cycle factors

Hydro generation does not include a fuel-cycle; hence the corresponding fuel-cycle factors are equal to zero.

2. Total upstream factors

The IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, has carried out a systemic review and harmonization of life cycle GHG emissions of hydro generation. This study which is also used as a reference by the NREL harmonization project, publishes harmonized central tendencies for life cycle emission intensities corresponding to both reservoir and run-off river hydro generation. Based on the pool of studies included in this harmonization, the life cycle of hydropower plants consists of three main stages as summarized below:

- Manufacturing and Construction: In this phase, GHGs are emitted from production and transportation of materials (e.g., concrete, steel) and the use of civil work equipment for the construction of the facility (e.g., diesel engines).

- Operation and maintenance: This stage includes GHG emissions associated with the operation and maintenance activities, such as heating/colling systems, auxiliary generating units and staff transportation.

- Decommissioning/dismantling: Dams can be decommissioned for economic, environmental or safety reasons. However, emissions associated with this stage have only been included in a handful of studies from the selected pool.

On top of the above, some of studies from the selected pool, also include the emissions associated with the land use change (LUC) induced by reservoir creation and/or its decommissioning and the associated modification of the terrestrial carbon cycle. While the magnitude of potential LUC-related emissions from reservoir hydropower is high, the uncertainties in the quantification of these emissions are also significant. The outliers from the estimated emission factors in the selected pool of studies correspond to the ones which account for the LUC emissions.

The IPCC review is based on around 20 and 10 estimates for reservoir and run-off river generation respectively. The pool of the included LCA's represent a relatively wide geographical coverage including countries from all continents. However, a large proportion of the studies are based on generation plants in North America and Europe. The heterogeneity associated with the manufacturing processes can largely influence the life cycle emissions from hydro generation. The manufacturing emissions intensity is mainly dependent on the electricity mix as well as the energy intensity of the processes. Hence, applying the central tendencies published by this review as global proxies for the two types of hydro generation can be associated with notable uncertainties.

The IEA Renewables Information database, includes the share of reservoir vs run-off river hydro generation for a total of 48 countries including all OECD members. In the absence of a reliable database including the breakdown of generation on a global level, a breakdown of 90 (reservoir) to 10 (run-off river) percent was selected as an approximate for the countries not covered by the database. This assumption is based on the well-known large fraction of reservoir-based hydro generation, particularly among major hydro producers including People's Republic of China, Brazil and the Russian Federation.

The above discussed country-specific shares per hydro generation type were applied to the global central tendencies per technology type published by the IPCC Special Report, to develop weighted-average country-specific upstream intensities corresponding to hydro generation.

The derived upstream factors are per unit of electricity output (mass of CO_{2eq}/kWh electricity generation).

Wind

1. Fuel-cycle factors

Wind generation does not include a fuel-cycle; hence the corresponding fuel-cycle factors are equal to zero.

2. Total upstream factors

The IEA completed a systematic review of the most recent published literature on life cycle assessment of GHG emission intensities corresponding to onshore wind generation. The project began with literature research including journal articles, reports, theses, conference papers, technical reports and industry publications. Approximately 120 published LCA studies corresponding to onshore wind generation were systematically reviewed and references which met strict criteria for quality and relevance were selected considering the scope and objective of the project. This approach included eliminating references which used out-dated life cycle data or assumptions not applicable to more recent technologies. Additionally, the relevance of the evaluated study to modern systems were considered.

The selected pool of approximately 50 estimates passing the screening process, included considerable variability in results due to both methodological and technical/performance parameter variabilities of the studies. In order to reduce the variability in the figures and at the same time clarify the central tendency of the published results, an analytical procedure called “harmonization” was performed to adjust the selected figures to ones based on a more consistent set of methodologies and assumptions. This approach follows a similar methodology established by NREL in order to reduce the uncertainty around life cycle estimates corresponding to various power generation fuels and technologies.

The equation below represents the key parameters which include the life cycle intensity corresponding to wind generation:

$$\frac{CO2}{kWh} = \frac{(CO2 + CH4\ x\ GWP100 + N2O\ x\ GWP100)}{Capacity\ factor\ (\%)\ x\ name\ plate\ capacity\ (MW)\ x\ lifetime\ (year) x\ \frac{hours}{year}}$$

The numerator represents the life cycle GHG emissions and is influenced by two sets of parameters:

- Technical parameters: This set include parameters such as the energy intensity of material extraction and manufacturing and the carbon intensity of the electricity used.
- Methodological parameters: This set include scope of the included GHG gases and the type of the GWP figures used.

The denominator represents the life cycle electricity generation and is influenced by one set of parameters:

- Performance parameters: This set include capacity factor, system lifetime and name plate capacity.

A resource intensive harmonization requires, adjusting all technical, performance and methodological parameters. However, large majority of the selected pool of studies do not include detailed data corresponding to technical parameters influencing the life cycle GHG emissions (e.g., carbon intensity of the electricity used for manufacturing the components). Additionally, the role of the harmonization should not be to consolidate all the variability as harmonizing all the technical parameters of the published results, would result in compromising the objective which is to identify a global proxy for life cycle GHG intensity of onshore wind generation. Hence, similar to the approach followed by the NREL harmonization project, a less intensive procedure with focus on harmonizing the methodological and key performance characteristics was selected.

The process involved two main stages as detailed below:

Step 1 – Methodological harmonization

This step consists of adjusting the selected published life cycle figures to a consistent set of methodological parameters and boundaries to ensure comparability of results.

The first selected parameter was the Global Warming Potential (GWP). The published life cycle studies use various GWP figures for converting the non-CO_2 GHG emissions to units of CO_{2eq}. For harmonizing the published figures based on a consistent set of GWP, the 100-year GWP from the 6th Assessment of the IPCC report (AR6) was selected. The logic behind this selection was to ensure alignment with the latest requirements from European Sustainability Reporting (ESRS) and other major disclosure standards. For details on the corresponding arithmetic used for this step of harmonization please refer to Annex I.

The second selected parameter was the scope of the included GHG gases in the studies. As some of the published literature included CO_2 emissions only, while other comprised of non-CO_2 emissions including CH_4 and N_2O. For details on the corresponding arithmetic used for this step please refer to Annex I.

Step 2 – Key performance characteristics harmonization

This step includes adjusting the selected published life cycle figures to a consistent set of performance characteristics to ensure comparability of results.

As depicted by the above equation, the capacity factor of wind generation, largely influences the amount of power generated over the life cycle of the system and therefore the corresponding life cycle emission intensities. In order to develop a representative global capacity factor for the purpose of harmonization, the five-year average of the latest global onshore wind generation and installed capacity figures from the IEA Renewables 2023 database were used. For details on the corresponding arithmetic adopted for this step please refer to Annex II.

The second performance characteristic influencing the life cycle emission intensity is the lifetime of the generation plant. The central tendency of the lifetime corresponding to onshore wind generation from the selected pool of literature was selected as a global proxy for performing this step of the harmonization. For details on the corresponding arithmetic used for this purpose please refer to Annex II.

Note: In practice and especially with the recent advancements in turbine manufacturing, the economy of scale and industrial learning has reduced the material usage and hence the embodied emissions per MW of installed capacity for larger size turbines. This means that the name plate capacity which is the remaining parameter influencing the life cycle GHG intensity from wind generation could have been selected as an additional parameter for the purpose of harmonization. However, within the selected pool of literature there is almost a linear correlation in between the size of the turbine and the corresponding life cycle GHG emissions, meaning that larger turbines have larger footprints. As a result, and similar to the approach followed by the NREL project, harmonizing based on this parameter was not deemed necessary.

Following the cumulative harmonization based on the above discussed four parameters, the resulting central tendency was selected as a global proxy for total upstream factor corresponding to onshore wind generation. For details on the corresponding arithmetic and results please refer to Annex II and Annex III respectively.

The heterogeneity associated with the manufacturing processes can largely influence the life cycle emissions from wind generation. The manufacturing emissions intensity is mainly dependent on the electricity mix as well as the energy intensity of the processes. Majority of estimates included in the selected pool for this analysis, are country-specific mainly related to studies corresponding to generation in Europe, North America and China. However, over 40% of the selected estimates are based on analyses representing global figures. Considering these points and despite the associated uncertainties, selecting the central tendency from this review is expected to provide a reasonable global proxy.

The derived figure largely matches the harmonized figure published by the NREL project (within 5%), suggesting that the more recent published literature do not largely differ from the resources used in the NREL systematic review. Hence, performing the same assessment for offshore wind was deemed unnecessary and the harmonized figure published by the NREL project was selected as a global proxy for offshore wind generation.

The IEA Renewables 2023 database includes country-specific wind generation data disaggregated by onshore and offshore generation. The shares of each generation type for each country were applied to the above developed global proxies for onshore and offshore generation to populate country-specific total upstream factors corresponding to wind generation.

The derived upstream factors are per unit of electricity output (mass of CO_{2eq}/kWh electricity generation).

Solar PV

1. Fuel-cycle factors

Solar PV generation does not include a fuel-cycle; hence the corresponding fuel-cycle factors are equal to zero.

2. Total upstream factors

The IEA completed a systematic review of the most recent published literature on life cycle assessment of GHG emission intensities corresponding to solar PV electricity generation. The project began with literature research including journal articles, reports, theses, conference papers, technical reports and industry publications. Approximately 90 published LCA studies corresponding to solar PV generation were systematically reviewed and references which met strict criteria for quality and relevance were selected considering the scope and objective of the project. This approach included eliminating references which used out-dated life cycle data or included assumptions not applicable to more recent technologies. Additionally, the relevance of the evaluated study to modern systems were considered. In the absence of sufficient life cycle studies on other material used for manufacturing of solar PV systems, the selection focused on crystalline silicon (c-Si) PV generation as the dominant technology in the market.

The selected pool of approximately 40 estimates passing the screening process, included considerable variability in results due to both methodological and technical/performance parameter variabilities of the studies. In order to reduce the variability in the figures and at the same time clarify the central tendency of the published results, an analytical procedure called “harmonization” was performed to adjust the selected figures to ones based on a more consistent set of methodologies and assumptions. This approach follows a similar methodology established by NREL in order to reduce the uncertainty around life cycle estimates corresponding to various power generation fuels and technologies.

The equation below represents the key parameters which include the life cycle intensity corresponding to Solar PV generation:

$$\frac{CO2eq}{kWh} = \frac{(CO2 + CH4\ x\ GWP100 + N2O\ x\ GWP100)}{Irradiation\ \left(\frac{kWh}{m2.year}\right) x\ Module\ efficiency\ (\%)\ x\ \ Performance\ ratio\ (\%) x\ lifetime\ (year) x\ total\ module\ area\ (m2)}$$

The numerator represents the life cycle GHG emissions and is influenced by two sets of parameters:

- Technical parameters: This set include the parameters such as the energy intensity of material extraction and manufacturing and the carbon intensity of the electricity used
- Methodological parameters: This set include the scope of the included GHG gases and the GWP figures used.

The denominator represents the life cycle electricity generation and is influenced by one set of parameters:

- Performance parameters: This set include Irradiation, Module efficiency, performance ratio, lifetime and total module area.

A resource intensive harmonization requires, adjusting all technical, performance and methodological parameters. However, large majority of the selected pool of studies do not include detailed data corresponding to technical parameters influencing the life cycle GHG emissions (e.g., carbon intensity of the electricity used for manufacturing the components). Additionally, the role of the harmonization should not be to consolidate all the variability as harmonizing all the technical parameters of the published results, would result in compromising the objective which is to identify a global proxy for life cycle GHG intensity of (c-Si) solar PV electricity generation. Hence, similar to the approach followed by the NREL harmonization project, a less intensive approach with focus on harmonizing the methodological and key performance characteristics was selected.

The process involved two main stages as detailed below:

Step 1 – Methodological harmonization

This step consists of adjusting the selected published life cycle figures to a consistent set of methodological parameters and boundaries to ensure comparability of results.

The first selected parameter was the GWP. The published life cycle studies use various GWP figures for converting the non-CO_2 GHG emissions to units of CO_{2eq}. For harmonizing the published figures based on a consistent set of GWP, the 100-year GWP from the 6th Assessment of the IPCC report (AR6) was selected. The logic behind this selection was to ensure alignment with the latest requirements from European Sustainability Reporting (ESRS) and other major disclosure standards. For details on the corresponding arithmetic used for this step of harmonization please refer to Annex I.

The second selected parameter was the scope of the included GHG gases in the studies. As some of the published literature included CO_2 emissions only, while other comprised of non-CO_2 emissions including CH_4 and N_2O. For details on the corresponding arithmetic used for this step please refer to Annex I.

Step 2 – Key performance characteristics harmonization

This step includes adjusting the selected published life cycle figures to a consistent set of performance characteristics to ensure comparability of results.

Irradiation is the average energy flux from the sun and largely influences the amount of power generated over the life cycle of the system and therefore the corresponding life cycle emission intensities. Irradiation depends on geographical location. As a result, the best proxy for selecting a consistent criterion for the harmonization process was to select the most common figure used in the studies included in the harmonization pool. For details on the corresponding arithmetic used for this step of the harmonization process please refer to Annex II.

The module efficiency corresponds to the percentage of the solar energy converted to direct current (DC) by the PV module. Performance ratio, is the ratio of the alternating current (AC) produced by the PV system, after accounting for system losses, to the nameplate electricity output calculated based on the module efficiency and irradiation. The figure is generally different for roof top and ground mounted systems. Both parameters influence the amount of power generated over the life cycle of the system and therefore the corresponding life cycle emission intensities. In order to select consistent criterion, the median figures from the selected pool of published figures were taken as global proxies for harmonization based on these two key performance parameters. For details on the corresponding arithmetic used for this step of the harmonization process please refer to Annex II.

The last characteristic influencing the life cycle emission intensity is the lifetime of the PV generation plant. The central tendency of the lifetime corresponding to solar PV generation from the selected pool of literature was selected as a global proxy for performing this step of the harmonization. For details on the corresponding arithmetic used for this purpose please refer to Annex II.

Note: As the life cycle emission intensity corresponds to reporting the life cycle GHG emissions per unit of electricity generated, harmonization of system/module area was not deemed required.

Following the cumulative harmonization based on the above discussed six parameters, the resulting central tendency was selected as a global proxy for total upstream factor corresponding to solar PV electricity generation. For details on the corresponding arithmetic and results please refer to Annex II and Annex III respectively.

The heterogeneity associated with the manufacturing processes can influence the life cycle emissions from solar PV generation. The manufacturing emissions intensity is mainly dependent on the electricity mix as well as the energy intensity of the processes. However, the pool of the estimates included in the IEA's review represent a relatively wide geographical coverage including Europe, North America, China, South-East Asia, India and Brazil. Additionally, it should be noted that a large majority of the Solar PV manufacturing capacity is based in China. Considering the above points and despite the associated uncertainties, selecting the central tendency from this review is expected to provide a reasonable global proxy. The derived upstream factors are per unit of electricity output (mass of CO_{2eq}/kWh electricity generation).

Geothermal

1. Fuel-cycle factors

Geothermal generation does not include a fuel-cycle; hence the corresponding fuel-cycle factors are equal to zero.

2. Total upstream factors

The NREL has carried out a systemic review of life cycle GHG emission from Geothermal electricity generation. Unlike the NREL review of the other generation technologies, this work only performs a systematic review of the literature and publishes central tendencies for life cycle emission intensities without any harmonization. The review is focused on the three main geothermal generation technologies including enhanced geothermal systems (EGS) binary, hydrothermal (HT) flash and HT binary systems.

Based on the NREL review, the life cycle GHG emissions are dominated by different stages of the life cycle depending on the technology. The HT flash plants operate using an open loop flash cycle where the CO_2 entertained in the geothermal fluid is released to the atmosphere. As a result, for this technology, the majority of the life cycle emission are associated with the operations phase. On the other hand, for EGS and HT binary systems which operate based on closed-loop process designs, emissions are predominately from the construction phase.

The selected pool of estimates included in the review consist of 18, 9 and 8 estimates corresponding to EGS, HT flash and HT binary systems respectively. The estimates are country-specific and include the United States, Germany, Switzerland, NZ, Iceland and Japan. The heterogeneity associated with the manufacturing processes can largely influence the life cycle emissions from geothermal generation. The manufacturing emissions intensity is mainly dependent on the electricity mix as well as the energy intensity of the processes. In the case of HT flash plants where the emissions are mainly from the operation phase, the central tendency from this review is expected to provide a reasonable global proxy. For EGS and HT binary systems where a large fraction of the life cycle emissions are associated with the construction of the plants, the corresponding uncertainties are more significant. In the absence of a global reliable database providing the country-specific geothermal generation figures disaggregated per technology type, the median of the NREL published central tendencies for the three technologies was selected as a global proxy for the total upstream intensities corresponding to geothermal generation.

The derived upstream factors are per unit of electricity output (mass of CO_{2eq}/kWh electricity generation).

Solar thermal

1. Fuel-cycle factors

Solar thermal electricity generation does not include a fuel-cycle; hence the corresponding fuel-cycle factors are equal to zero.

2. Total upstream factors

The NREL has carried out a systemic review and harmonization of life cycle GHG emission of trough and tower concentrating solar power electricity generation. The study publishes harmonized central tendencies for life cycle emission intensities corresponding to parabolic trough, power tower and parabolic dish solar thermal electricity generation systems.

The selected pool of estimates included in the review consist of 19, 17 and 6 estimates corresponding to parabolic trough, power tower and parabolic dish systems respectively. The estimates are based on studies corresponding to three countries including the United States, Spain and Australia. The heterogeneity associated with the manufacturing processes can largely influence the life cycle emissions from solar thermal generation. The manufacturing emissions intensity is mainly dependent on the electricity mix as well as the energy intensity of the processes. Hence, applying the central tendencies published by this review as global proxies can be associated with uncertainties.

In the absence of a global reliable database providing the country-specific solar thermal generation figures disaggregated per technology type, the median of the NREL published harmonized central tendencies for the three technologies was selected as a global proxy for the total upstream intensities corresponding to solar thermal generation.

The derived life cycle factors are per unit of electricity output (mass of CO_{2eq}/kWh electricity generation).

Tide, wave and ocean

1. Fuel-cycle factors

Electricity generation from tide, wave and ocean technologies does not include a fuel-cycle; hence the corresponding fuel-cycle factors are equal to zero.

2. Total upstream factors

The IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, has carried out a systemic review of life cycle GHG emissions of ocean-based electricity generation technologies. The study only performs a systematic review of the literature and publishes central tendencies for life cycle emission intensities without any harmonization and is also used as a reference by the NREL harmonization project.

The selected pool of estimates included in the review include 10 estimates corresponding to wave and tidal energy converter systems. The estimates are based on studies corresponding to the United Kingdom, Denmark, Italy and New Zealand. The heterogeneity associated with the manufacturing processes can largely influence the life cycle emissions from ocean-based generation technologies. The manufacturing emissions intensity is mainly dependent on the electricity mix as well as the energy intensity of the processes. Hence, applying the central tendencies published by this review as global proxies can be associated with certain uncertainties.

The central tendency published by the study which is based on the review of various types of ocean generation technologies, including tidal range, tidal current and wave generation systems, was selected as a global proxy for the total upstream intensities corresponding to ocean-based electricity generation.

The derived upstream factors are per unit of electricity output (mass of CO_{2eq}/kWh electricity generation).

Municipal waste (non-renewable)

1. Fuel-cycle factors

The reported figures in the IEA World Energy Balances database as municipal waste (non-renewable) comprises the non-renewable fraction of wastes produced by households, hospitals and the tertiary sector.

The main life cycle stages corresponding to generation from the non-renewable fraction of municipal waste comprise of collection, transport, separation, drying and storage which are largely comparable with the processes corresponding to the generation from the renewable fraction of the municipal waste.

In the absence of a reliable literature on the life cycle GHG emission intensity corresponding to electricity generation from the non-renewable fraction of municipal waste, the same fuel-cycle factor selected for the renewable fraction was selected as a reasonable proxy. For additional details on the selected factor refer to the *Municipal waste (renewable)* section of this document.

The derived fuel-cycle factors are per unit of electricity output (mass of CO_{2eq}/kWh electricity generation).

2. Total upstream factors

Similar to the fuel-cycle factors, the total upstream factor selected for the renewable fraction of municipal waste was also adopted for the non-renewable fraction. For additional details on the selected factor refer to the *Municipal waste (renewable)* section of this document.

The derived upstream factors are per unit of electricity output (mass of CO_{2eq}/kWh electricity generation).

Industrial waste

1. Fuel-cycle factors

The reported industrial waste figures in the IEA World Energy Balances database comprise of non-renewable origin of solid and liquid industrial wastes, usually combusted in specialized plants to produce electricity.

The main life cycle stages corresponding to generation from industrial waste comprise of collection, transport, separation, drying and storage which are generally comparable with the processes corresponding to the generation from the municipal waste.

In the absence of a reliable literature on the life cycle GHG emission intensity corresponding to electricity generation from industrial waste, the same fuel-cycle factor selected for municipal waste was selected as a reasonable proxy. For additional details on the selected factor refer to the *Municipal waste (renewable)* section of this document.

The derived fuel-cycle factors are per unit of electricity output (mass of CO_{2eq}/kWh electricity generation).

2. Total upstream factors

Similar to the fuel-cycle factors, the total upstream factor selected for the renewable fraction of municipal waste was also adopted for industrial waste. For additional details on the selected factor refer to the *Municipal waste (renewable)* section of this document.

The derived upstream factors are per unit of electricity output (mass of CO_{2eq}/kWh electricity generation).

Remaining products (heat and other)

On top of all the fuels and technologies detailed in the above sections, within the IEA World Energy Balances database, there are handful of countries which have minor quantities of electricity generation from chemical heat and other sources such as fuel cells.

Given the miniscule fraction of the generation from the above two sources and in the absence of a reliable source publishing their life cycle GHG emission intensity, the corresponding fuel cycle and total life cycle factors were excluded from this analysis.

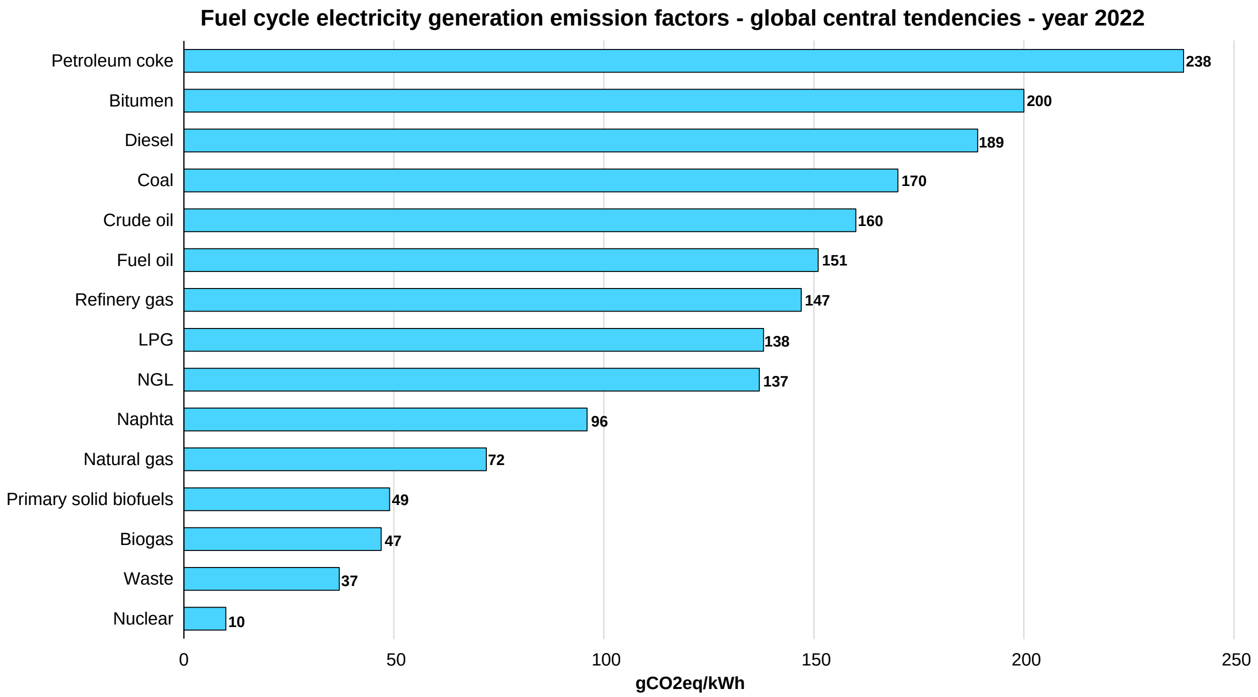
6. RESULTS

The graph below depicts global medians for the fuel-cycle emission factors based on the country-specific fuel-cycle intensities for year 2022 as detailed in the *methodology* section. These factors correspond to generation from fossil fuels including coal, natural gas, various primary and secondary oil products and waste alongside biofuels and nuclear. Electricity generation from other renewable sources besides biomass does not include a fuel-cycle and the corresponding fuel-cycle intensities are equal to zero.

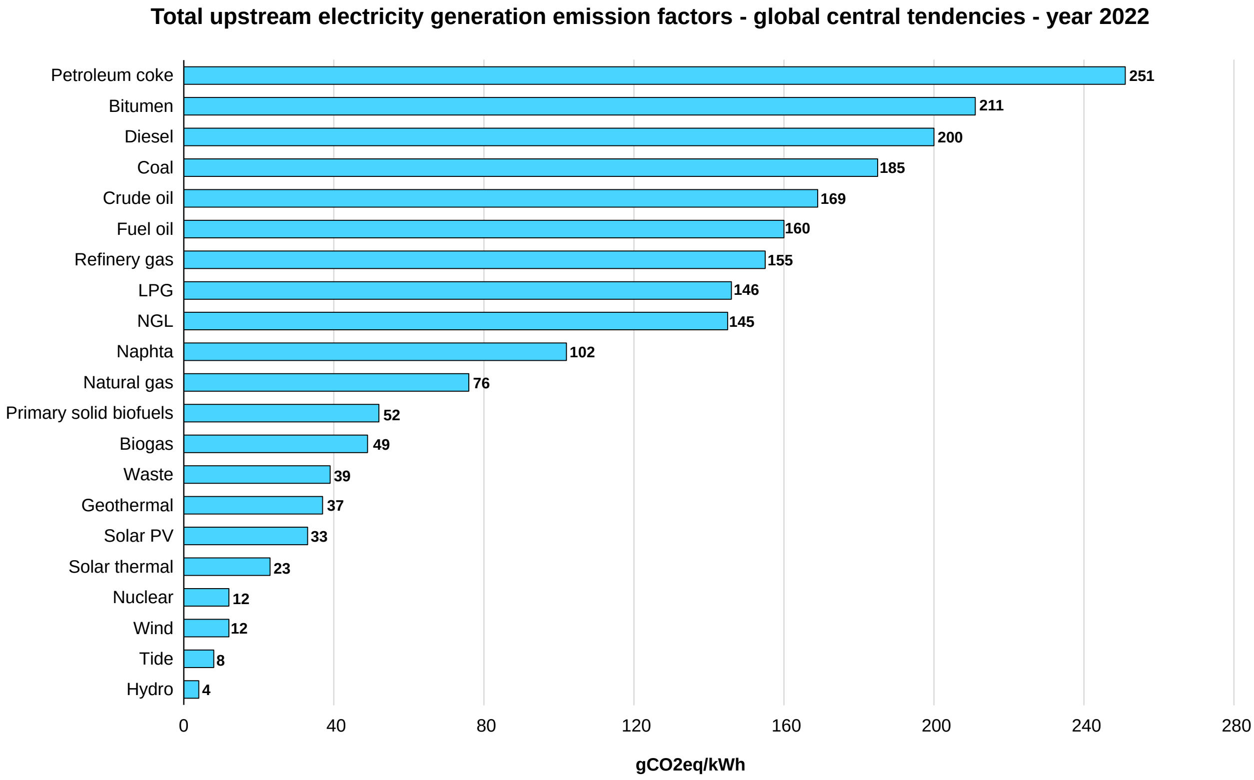
Generation from some of the oil products correspond to the highest global fuel-cycle intensities. This is influenced by the low generation efficiency from these sources globally which results in higher emissions footprints per kWh of electricity output. As an example, global electricity generation efficiency from petroleum coke in 2022 is 28% while the generation efficiencies from coal and natural gas are 37% and 48% respectively.

Note: Liquid biofuels are currently rarely used for power generation. As a result, the global central tendencies corresponding to their electricity generation emission factors are largely influenced by generation efficiencies corresponding to handful of countries and have been excluded from the below graphs.

Note: Over 70% of the global electricity production from LPG in 2022 is associated with Japan. Hence the global LPG-related central tendency shown below is heavily weighted by Japanese data. The data quality issues corresponding to national data submission to the IEA in the absence of access to plant specific information may impact the results shown.

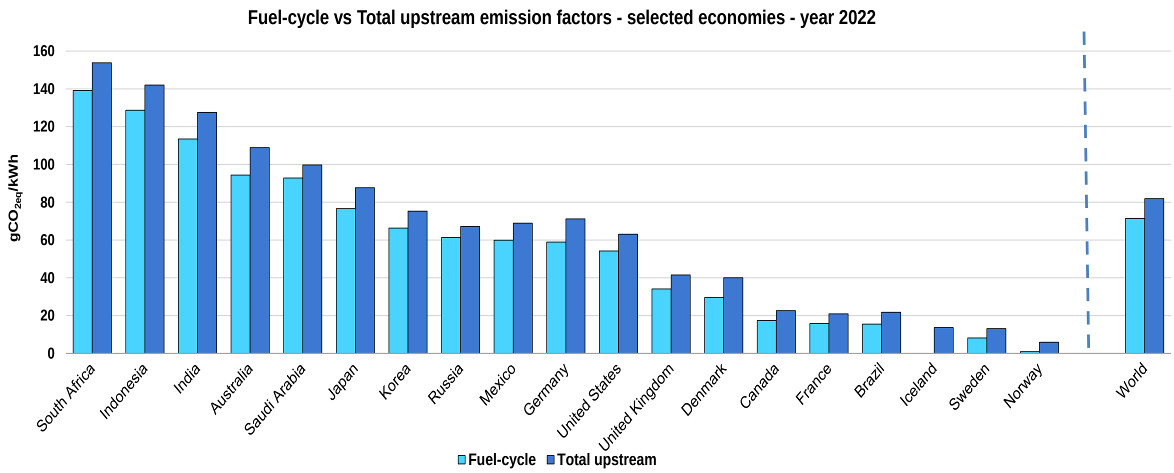


The following figure shows the year 2022 global medians for the total upstream life cycle emission factors based on the developed country-specific upstream intensities as detailed in the *methodology* section. Unlike the fuel-cycle factors, the total upstream factors also include electricity generation from other renewable sources besides biomass. As shown in the figure, for the fuel-based electricity generation the order of the intensities closely matches the fuel-cycle intensities as a large fraction of the total upstream intensities are associated with the corresponding fuel-cycles.



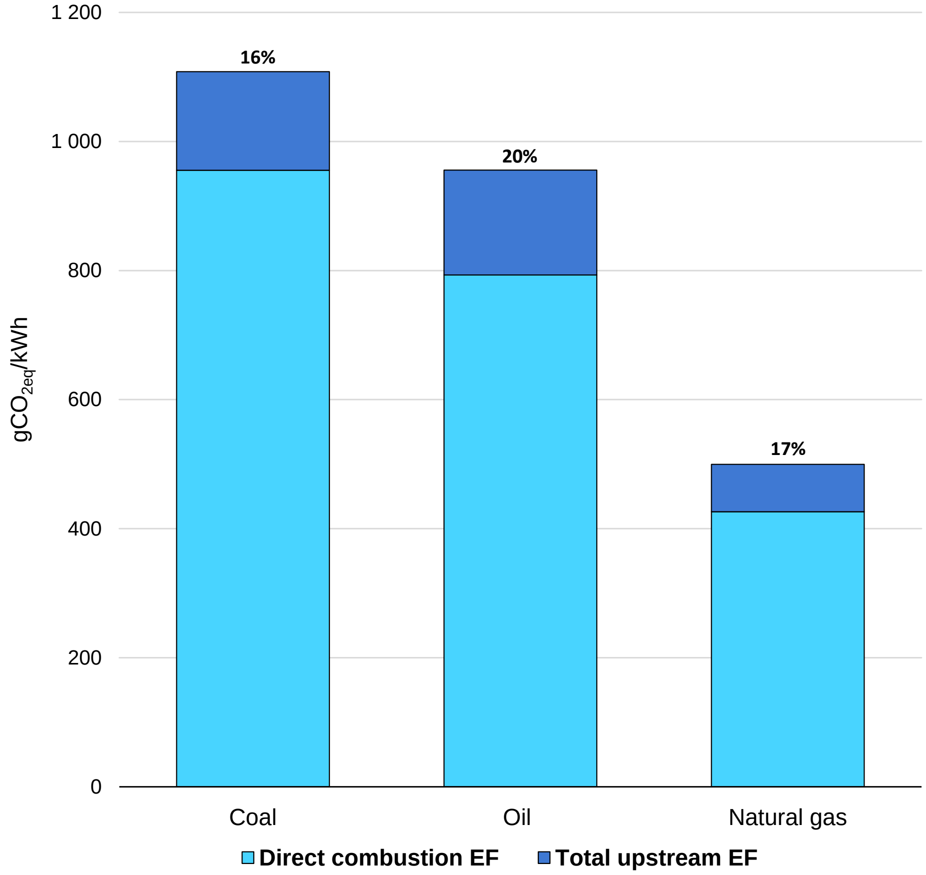
The graph below presents the comparison between fuel-cycle vs upstream emission factors corresponding to electricity generation for a selected set of economies. Among the countries with a diverse mix of generation from various fuels and technologies the upstream factors are typically around 10 to 20 percent higher than the fuel-cycle factors. Globally, the year 2022 fuel-cycle and upstream factors are 72 and 82 gCO_{2eq}/kWh respectively.

However, in specific cases, where the large fraction of generation is based on non-bio renewable sources, the relative difference among the two populated factors is much larger. As an example, for Norway, where over 98% of the generation in 2022 is based on non-bio renewables, the upstream factor is approximately six times larger than the fuel-cycle factor. Similarly, in Iceland, where almost the entire generation is based on non-bio renewables, the upstream factor is around 700 times larger than the fuel-cycle intensity.



The graph below presents the global contribution of direct emission factor at the point of generation in comparison with the developed upstream emission factors for year 2022 per fuel type. As depicted upstream emissions have a considerable contribution to the electricity generation GHG footprint from all types of fossil fuels. This highlights the importance of considering the GHG intensity over the life cycle of electricity generation in order to better understand the level of emission mitigation potential from fuel-switching.

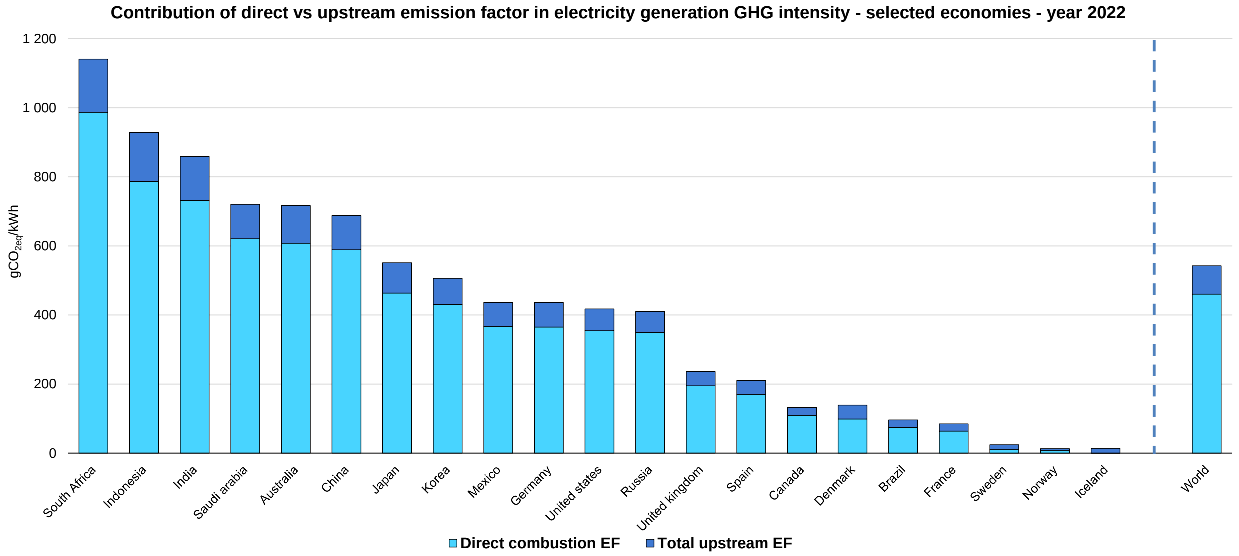
Contribution of direct vs upstream emission factor in electricity generation GHG intensity per fuel - World* - year 2022



**In the above graph, world correspond to the weighted average of the 149 countries included in the scope of this database.*

The figure below outlines the emission factor at the point of generation alongside the developed total upstream emission factors for a selected set of economies. The figure also shows the percentage of the upstream factor in comparison to the corresponding direct emission factor.

Globally, for 2022, the emission factor at the generation point is 462 gCO_{2eq}/kWh, while the upstream factor is 82 gCO_{2eq}/kWh, corresponding to 18% of the direct emission factor. As shown below for countries such as Iceland and Sweden which include a large share of generation from low carbon energy sources, the upstream factors are larger than the direct emission factor at the point of generation. These results highlight the importance of considering the GHG emissions over the life cycle of electricity generation to better understand the level of emission mitigation potential from electrification. This life cycle view is also decisive in assessing the benefits corresponding to penetration of low carbon generation and fuel-switching to the decarbonization goals.



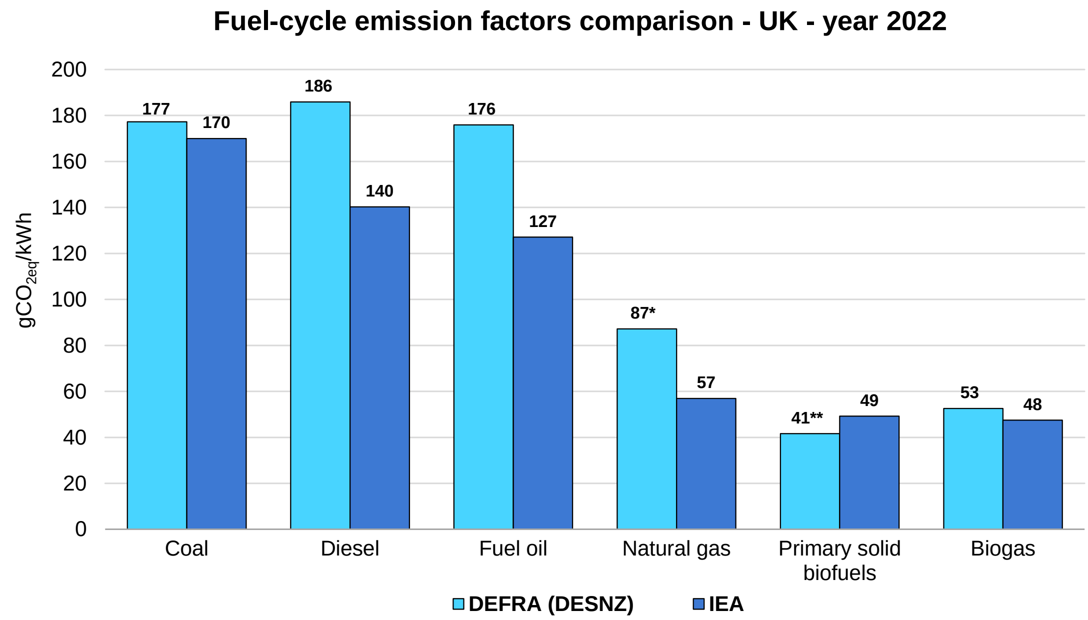
A well-known database including country-specific fuel-cycle emission factors corresponding to electricity generation was historically published by the United Kingdom government's Department for Environment Food and Rural Affaires (Defra). Defra used to publish the fuel-cycle factors for a set of approximately 60 countries up to year 2021. This database was selected in order to provide a benchmark for the database. The Defra's published factors included the fuel-cycle intensities corresponding to fossil and bio generation. Hence, fuel-cycle emissions corresponding to nuclear generation were excluded in their developed factors. Additionally, Defra did not publish the total upstream factors which also include the intensities corresponding to non-bio renewables generation.

Note: The UK government is still publishing the upstream emission factors corresponding to the UK's electricity grid by now the Department for Energy Security & Net Zero (DESNZ). However, the factors corresponding to oversees electricity grids have been discontinued.

As detailed in the Defra's corresponding Methodological paper, the fuel-specific fuel-cycle emission intensities used are mainly taken from a literature published by Exergia in 2015 and a report published by JEC (JRC-Eucar-Concawe) in 2020. Defra has applied some assumptions to estimate the figures for the missing fuels not included in either of the two studies. The figures included in the two studies are mainly based on EU based production, processing and transport intensities. Using these fuel-specific figures and the Digest of UK Energy Statistics (DUKES) published UK generation data, Defra develops the UK specific fuel-cycle emission intensities corresponding to electricity generation. Following that the ratio of the calculated fuel-cycle factor to the direct emission factor at the point of generation for UK was multiplied by the direct emission factors from other countries, in order to estimate the country-specific fuel-cycle emission intensities.

The figure below compares the UK's fuel-specific fuel-cycle intensities used by Defra with the IEA-developed factors. The factors for coal and biofuels seem comparable while Defra's intensities corresponding to natural gas and oil products are larger.

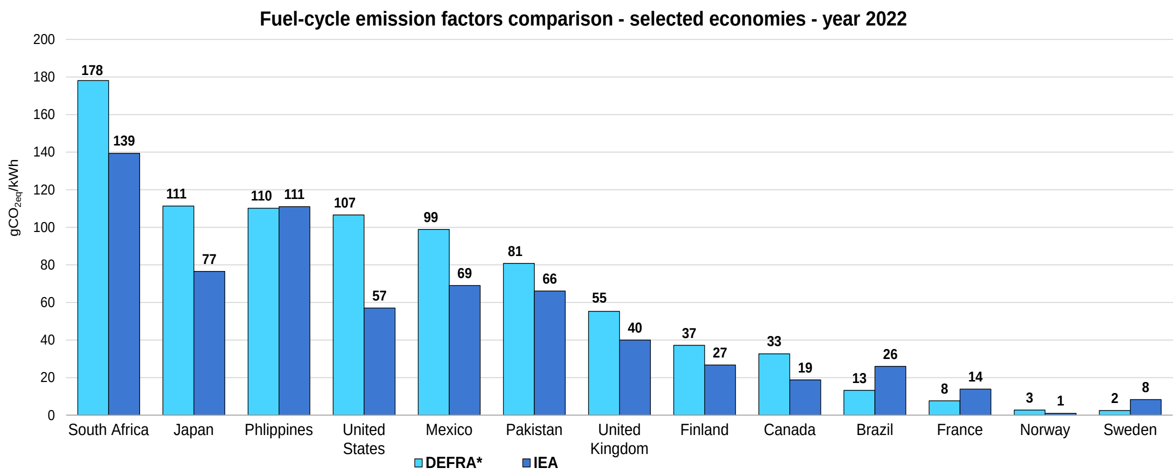
Note: In order to derive Defra's fuel-specific emission factors per unit of electricity generation (gCO_{2eq}/kWh), the fuel-specific generation efficiencies for UK computed based on the IEA World Energy Balances (2024 edition) were applied to the DESNZ published 2022 fuel-specific emission factors.



**The UK government publishes the fuel-cycle intensities for pipeline natural gas and LNG in a disaggregated manner. In order to derive the above natural gas emission factor, the respective shares of LNG and pipeline supply for year 2022 taken from the corresponding Methodological note were applied to the respective fuel-cycle intensities.*

***Primary solid biofuels represent the average of published intensities corresponding to wood logs, wood chips, wood pallets and grass/straw.*

The graph below depicts the IEA-developed and Defra-published fuel-cycle intensities for a selected set of countries for year 2021. As shown in the figure the Defra-published figures are systematically larger than the IEA-developed factors. These discrepancies are largely associated with the difference in between UK's natural gas fuel-cycle intensities in between the two databases shown in the figure above. Natural gas contributed to over 40% of UK's generation mix in year 2021, hence the intensity corresponding to this fuel largely influences the grid fuel-cycle intensity. As Defra estimates the intensities corresponding to other countries based on the ratio of their calculated fuel-cycle factor to the direct emission factor for UK, the discrepancies are visible among all countries with notable shares of gas generation. On the other hand, the IEA-developed factors are larger for countries such as Brazil, Sweden and France which correspond to relatively lower shares of gas generation and higher shares of nuclear and bio generation. It shall be noted that Defra's fuel-cycle factors do not include the fuel-cycle intensities corresponding to nuclear generation.



**Defra's fuel-cycle factors do not include the fuel-cycle intensities corresponding to nuclear generation.*

7. LIMITATIONS

Electricity plays a central role in modern societies and continuous increase of electrification across sectors is crucial for achieving emission reduction targets. Understanding the climate impacts over the life cycle of electricity generation is key in order to inform effective policy making. This database attempts to assess and compile reliable data on this topic with the objective of providing a global harmonized database of life cycle emission intensities corresponding to electricity generation.

Although the database aims to publish country-specific life cycle emission intensities, some of the building blocks used to develop the emission factors are based on regional or global estimates as detailed in the *Methodology* section and summarized below:

- For generation from natural gas, various oil products, liquid biofuels and biogas, the fuel-specific intensities correspond to regional estimates based on the IEA modelling work.
- For generation from coal and nuclear, global technology-specific intensities based on the NREL harmonization project have been selected and merged with country-specific data corresponding to technology-specific generation figures in order to derive country-specific proxies for the factors.
- The intensities corresponding to generation from wind and solar PV are global estimates based on IEA performed harmonization of the latest LCA studies.
- The intensities corresponding to generation from all other renewable sources and waste are based on harmonized global estimates published by the NREL project.

The heterogeneity associated with the manufacturing processes can largely influence the upstream block of life cycle emissions. The manufacturing emissions intensity is mainly dependent on the electricity mix as well as the energy intensity of the processes. In the case of generation from renewables, a large fraction of life cycle emissions is linked to the manufacturing stage. Hence, applying the harmonized central tendencies as global proxies can be associated with certain uncertainties. On the other hand, the energy data (electricity generation) which are a major component for developing the grid factors are from IEA's country-specific statistics. This enables the attempt to develop country-specific proxies for life cycle intensities corresponding to electricity grids.

The estimates corresponding to liquid biofuels and biogas include land-use change emissions estimates which largely represent US-based and/or EU-based data. Hence, the geographical representativeness of the included land-use impacts in this database is limited. However, given the miniscule contribution of these fuels in electricity generation the influence on the published grid upstream intensities is negligible.

Other limitations are associated with the nature of life cycle harmonization which impacts the multiple fuel/technology specific intensities developed based on this approach. Harmonization analysis is limited by the pool of studies selected for the analysis. While harmonization attempts to update (e.g., by modernizing assumed performance characteristics) and reconcile the scope and assumptions of previously deficient works (e.g. GWPs and gases), it cannot make up for a lack of study of certain design variations or other technical characteristics. On top of this, there are remaining dimensions of inconsistency and harmonization along these dimensions could potentially further reduce the variability in the published estimates. However, harmonizing across all technical parameters might hamper the goal of having a representative central tendency.

It is additionally important to understand that the studies passing the screens used in the harmonization performed by IEA and the NREL harmonization project, do not necessarily represent a statistically independent sample. Clustering of published results owing to the use of similar methods could exist along at least one of the following two dimensions: multiple estimates from similar author groups publishing serially, and multiple references citing the same sources of input data. Clustering, if significant enough, could influence the estimates of central tendency. Another limitation associated with harmonization analysis is in areas where new science, methods, or context with major impacts on the corresponding life cycle intensities have emerged, while the published LCAs are based on older technologies.

Considering the above detailed limitations, the level of uncertainty associated with the published data is notable. However, this is an attempt in order to provide a global database based on a harmonized methodology for these factors. IEA welcomes feedback from experts as it will be of great value to us for enhancing the quality of this database.

8. GEOGRAPHICAL COVERAGE AND COUNTRY NOTES

Countries and regions

This document is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area. In this publication, 'country' refers to country or territory, as case may be.

Note: In the absence of reliable modelling for life cycle emissions corresponding to oil shales and the corresponding large fraction of electricity generation from this fuel in Estonia, data corresponding to this country is currently missing from the database.

Country/Region	Short name	Definition
World	WORLD	Corresponds to the weighted average of the 149 countries included in this database.
Albania	ALBANIA	
Algeria	ALGERIA	
Angola	ANGOLA	
Argentina	ARGENTINA	
Armenia	ARMENIA	
Australia	AUSTRALI	Excludes the overseas territories. Data are reported on a fiscal year basis. By convention data for the fiscal year that starts on 1 July Y-1 and ends on 30 June Y are labelled as year Y.
Austria	AUSTRIA	
Azerbaijan	AZERBAIJAN	
Bahrain	BAHRAIN	
Bangladesh	BANGLADESH	Data are reported on a fiscal year basis. By convention data for the fiscal year that starts on 1 July Y-1 and ends on 30 June Y are labelled as year Y.
Belarus	BELARUS	
Belgium	BELGIUM	
Benin	BENIN	
Bolivia	BOLIVIA	
Bosnia and Herzegovina	BOSNIAHERZ	
Botswana	BOTSWANA	
Brazil	BRAZIL	
Brunei Darussalam	BRUNEI	

Country/Region	Short name	Definition
Bulgaria	BULGARIA	
Cambodia	CAMBODIA	
Cameroon	CAMEROON	
Canada	CANADA	
Chile	CHILE	
People's Republic of China	CHINA	
Colombia	COLOMBIA	
Congo	CONGO	
Costa Rica	COSTARICA	
Côte d'Ivoire	COTEIVOIRE	
Croatia	CROATIA	
Cuba	CUBA	
Curaçao	CURACAO	
Cyprus	CYPRUS	**Note by the Republic of Türkiye (Türkiye):** The information in the report with reference to "Cyprus" relates to the southern part of the Island. There is no single authority representing both Turkish and Greek Cypriot people on the Island. Türkiye recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Türkiye shall preserve its position concerning the "Cyprus" issue. **Note by all the European Union Member States of the OECD and the European Union:** The Republic of Cyprus is recognised by all members of the United Nations with the exception of Türkiye. The information in this report relates to the area under the effective control of the Government of the Republic of Cyprus. At its seventeenth session, the Conference of the Parties decided to amend Annex I to the Convention to include Cyprus (Decision 10/CP.17). The amendment entered into force on 9 January 2013.
Czech Republic	CZECH	
Democratic People's Republic of Korea	KOREADPR	
Democratic Republic of Congo	CONGOREP	
Denmark	DENMARK	Excludes Greenland and the Danish Faroes.
Dominican Republic	DOMINICANR	
Ecuador	ECUADOR	

Country/Region	Short name	Definition
Egypt	EGYPT	Data for Egypt are reported on a fiscal year basis. By convention, data for the fiscal year that starts on 1 July Y and ends on 30 June Y+1 are labelled as year Y.
El Salvador	ELSALVADOR	
Equatorial Guinea	EQGUINEA	
Eritrea	ERITREA	
Kingdom of Eswatini	ESWATINI	
Ethiopia	ETHIOPIA	Data are reported on a fiscal year basis. By convention, data for the fiscal year that starts on 1 July Y and ends on 30 June Y+1 are labelled as year Y.
Finland	FINLAND	
France	FRANCE	Includes Monaco and excludes the overseas collectivities: New Caledonia; French Polynesia; Saint Barthélemy; Saint Martin; Saint Pierre and Miquelon; and Wallis and Futuna. Energy data for the following overseas departments: Guadeloupe; French Guiana; Martinique; Mayotte; and Réunion are included.
Gabon	GABON	
Georgia	GEORGIA	
Germany	GERMANY	
Ghana	GHANA	
Gibraltar	GIBRALTAR	
Greece	GREECE	
Guatemala	GUATEMALA	
Guyana	GUYANA	
Haiti	HAITI	
Honduras	HONDURAS	
Hong Kong, China	HONGKONG	
Hungary	HUNGARY	
Iceland	ICELAND	
India	INDIA	Data are reported on a fiscal year basis. By convention, data for the fiscal year that starts on 1 April Y and ends on 31 March Y+1 are labelled as year Y. This convention is different from the one used by Government of India, whereby fiscal year starts on 1 April Y and ends on 31 March Y+1 are labelled as year Y+1.
Indonesia	INDONESIA	

Country/Region	Short name	Definition
Islamic Republic of Iran	IRAN	Data are reported according to the Iranian calendar year. By convention data for the year that starts on 20 March Y and ends on 19 March Y+1 are labelled as year Y
Iraq	IRAQ	
Ireland	IRELAND	
Israel	ISRAEL	The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.
Italy	ITALY	Includes San Marino and the Holy See.
Jamaica	JAMAICA	
Japan	JAPAN	Includes Okinawa. Data are reported on a fiscal year basis. By convention data for the fiscal year that starts on 1 April Y and ends on 31 March Y+1 are labelled as year Y.
Jordan	JORDAN	
Kazakhstan	KAZAKHSTAN	
Kenya	KENYA	
Korea	KOREA	
Kosovo	KOSOVO	This designation is without prejudice to positions on status, and is in line with United Nations Security Council Resolution 1244/99 and the Advisory Opinion of the International Court of Justice on Kosovo's declaration of independence.
Kuwait	KUWAIT	
Kyrgyzstan	KYRGYZSTAN	
Latvia	LATVIA	
Lao People's Democratic Republic	LAO	
Lebanon	LEBANON	
Libya	LIBYA	
Lithuania	LITHUANIA	
Luxembourg	LUXEMBOU	
Madagascar	MADAGASCAR	
Malaysia	MALAYSIA	
Malta	MALTA	

Country/Region	Short name	Definition
Mauritius	MAURITIUS	
Mexico	MEXICO	
Republic of Moldova	MOLDOVA	
Mongolia	MONGOLIA	
Montenegro	MONTENEGRO	
Morocco	MOROCCO	
Mozambique	MOZAMBIQUE	
Myanmar	MYANMAR	Data are reported on a fiscal year basis. By convention data for the fiscal year that starts on 1 April Y and ends on 31 March Y+1 are labelled as year Y
Namibia	NAMIBIA	Electricity data are reported on a fiscal year basis. By convention data for the fiscal year that starts on 1 July Y and ends on 31 June Y+1 are labelled as year Y.
Nepal	NEPAL	Data are reported on a fiscal year basis. By convention data for the fiscal year that starts on 1 July Y and ends on 30 June Y+1 are labelled as year Y.
Netherlands	NETHLAND	Excludes Suriname, Aruba and the other former the Netherlands Antilles (Bonaire, Curaçao, Saba, Saint Eustatius and Sint Maarten).
New Zealand	NZ	
Nicaragua	NICARAGUA	
Niger	NIGER	
Nigeria	NIGERIA	
Republic of North Macedonia	NORTHMACED	
Norway	NORWAY	
Oman	OMAN	
Pakistan	PAKISTAN	Data are reported on a fiscal year basis. By convention data for the fiscal year that starts on 1 July Y and ends on 30 June Y+1 are labelled as year Y.
Panama	PANAMA	
Paraguay	PARAGUAY	
Peru	PERU	
Philippines	PHILIPPINE	
Poland	POLAND	
Portugal	PORTUGAL	Includes the Azores and Madeira.

Country/Region	Short name	Definition
Qatar	QATAR	
Romania	ROMANIA	
Russian Federation	RUSSIA	
Rwanda	RWANDA	
Saudi Arabia	SAUDIARABI	
Senegal	SENEGAL	.
Serbia	SERBIA	
Singapore	SINGAPORE	
Slovak Republic	SLOVAKIA	
Slovenia	SLOVENIA	
South Africa	SOUTHAFRIC	Nuclear data are reported on a fiscal year basis. By convention data for the fiscal year that starts on 1 April Y and ends on 31 March Y+1 are labelled as year Y.
South Sudan	SSUDAN	
Spain	SPAIN	Includes the Canary Islands.
Sri Lanka	SRILANKA	
Sudan	SUDAN	
Suriname	SURINAME	
Sweden	SWEDEN	
Switzerland	SWITLAND	Includes Liechtenstein for the oil data. Data for other fuels do not include Liechtenstein.
Syrian Arab Republic	SYRIA	
Chinese Taipei	TAIPEI	
Tajikistan	TAJIKISTAN	
United Republic of Tanzania	TANZANIA	
Thailand	THAILAND	
Togo	TOGO	
Trinidad and Tobago	TRINIDAD	
Tunisia	TUNISIA	
Republic of Türkiye	TURKEY	

Country/Region	Short name	Definition
Turkmenistan	TURKMENIST	
Uganda	UGANDA	
Ukraine	UKRAINE	
United Arab Emirates	UAE	
United Kingdom	UK	
United States	USA	Includes the 50 states and the District of Columbia but generally excludes all territories, and all trade between the U.S. and its territories. Oil statistics include Guam, Puerto Rico and the United States Virgin Islands; trade statistics for coal include international trade to and from Puerto Rico and the United States Virgin Islands. Starting with 2017 data, inputs to and outputs from electricity and heat generation include Puerto Rico.
Uruguay	URUGUAY	
Uzbekistan	UZBEKISTAN	
Venezuela	VENEZUELA	
Viet Nam	VIETNAM	
Yemen	YEMEN	
Zambia	ZAMBIA	
Zimbabwe	ZIMBABWE	

Fiscal year

This table lists the countries for which data are reported on a fiscal year basis. More information on beginning and end of fiscal years by country is reported in the column ‘Definition’. This document is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

Country/Region	Short name	Definition
Australia	AUSTRALI	Data are reported on a fiscal year basis. By convention, data for the fiscal year that starts on 1 July Y-1 and ends on 30 June Y are labelled as year Y.
Bangladesh	BANGLADESH	Data are reported on a fiscal year basis. By convention data for the fiscal year that starts on 1 July Y-1 and ends on 30 June Y are labelled as year Y.
Egypt	EGYPT	Data are reported on a fiscal year basis. By convention, data for the fiscal year that starts on 1 July Y and ends on 30 June Y+1 are labelled as year Y.
Ethiopia	ETHIOPIA	Data are reported on a fiscal year basis. By convention, data for the fiscal year that starts on 1 July Y and ends on 30 June Y+1 are labelled as year Y.
India	INDIA	Data are reported on a fiscal year basis. By convention, data for the fiscal year that starts on 1 April Y and ends on 31 March Y+1 are labelled as year Y. This convention is different from the one used by Government of India, whereby fiscal year starts on 1 April Y and ends on 31 March Y+1 are labelled as year Y+1.
Islamic Republic of Iran	IRAN	Data are reported according to the Iranian calendar year. By convention data for the year that starts on 20 March Y and ends on 19 March Y+1 are labelled as year Y.
Japan	JAPAN	Starting 1990, data are reported on a fiscal year basis. By convention, data for the fiscal year that starts on 1 April Y and ends on 31 March Y+1 are labelled as year Y.
Myanmar	MYANMAR	Data are reported on a fiscal year basis. By convention data for the fiscal year that starts on 1 April Y and ends on 31 March Y+1 are labelled as year Y.
Namibia	NAMIBIA	Electricity data are reported on a fiscal year basis. By convention data for the fiscal year that starts on 1 July Y and ends on 31 June Y+1 are labelled as year Y.
Nepal	NEPAL	Data are reported on a fiscal year basis. By convention data for the fiscal year that starts on 1 July Y and ends on 30 June Y+1 are labelled as year Y.
Pakistan	PAKISTAN	Data are reported on a fiscal year basis. By convention fiscal year Y/Y+1 is labelled as year Y.
South Africa	SOUTHAFRIC	Nuclear data are reported on a fiscal year basis. By convention data for the fiscal year that starts on 1 April Y and ends on 31 March Y+1 are labelled as year Y.

9. ABBREVIATIONS

CO_2	carbon dioxide
CH4	methane
GJ	gigajoule
GWh	gigawatt hour
kg	kilogramme
kt	thousand tonnes
kWh	kilowatt hour
MJ	megajoule
$MtCO_2$	million tonnes of carbon dioxide
m^2	square meter
tC	tonne of carbon
GWP	global warming potential
UNFCCC	United Nations Framework Convention on Climate Change
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
UNFCCC	United Nations Framework Convention on Climate Change
GHG	greenhouse gas
LCA	life cycle assessment
GEC	Global Energy and Climate Model
LNG	liquified natural gas
CBM	coal bed methane
WEO	World Energy outlook
NREL	National Renewable Energy Laboratory
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
OMR	Oil Market Report
ETP	Energy Technology Perspectives
NGL	Natural Gas Liquids
WTT	well-to-tank
FAME	Fatty Acid Methyl Ester
HVO	hydrotreated vegetable oil
EBA	European Biogas Association
ICCT	The International Council on Clean Transportation
LWR	light water reactors
PWR	pressurized water reactors
BWR	boiling water reactors
GCR	gas-cooled reactors
HWR	heavy water reactors
FBR	fast breeder reactors
HTGR	high-temperature gas-cooled reactors
PRIS	Power Reactor Information System
IAEA	International Atomic Energy Agency
AR4	4th Assessment of the IPCC report
c-Si	crystalline silicon
MRV	Measurement, Reporting and Verification
DC	direct current
AC	alternating current
EGS	enhanced geothermal systems
HT	hydrothermal
Defra	Department for Environment Food and Rural Affaires
JEC	JRC-Eucar-Concawe

ANNEX I – METHODOLOGICAL HARMONIZATION OF WIND AND SOLAR PV

This section details the arithmetic behind the methodological harmonization performed by the IEA applied to the selected pool of studies from the systematic review of electricity generation from onshore wind and solar PV generation. Refer to the *Wind* and *Solar PV* sections in this document for the corresponding details.

1. Harmonization per GWP used:

The published life cycle studies included in IEA's systematic review of onshore wind and solar PV generation literatures, use various GWP figures for converting the non-CO_2 GHG emissions to units of CO_{2eq}. For harmonizing the published figures based on a consistent set of GWP, the 100-year GWP from the 6th Assessment of the IPCC report (AR4) was selected and the following arithmetic was followed. The logic behind this selection was to ensure alignment with the latest requirements from European Sustainability Reporting (ESRS) and other major disclosure standards.

GWP	CO_2	CH_4	N_2O
GWP 100, AR1	1	21	290
GWP 100, AR2	1	21	310
GWP 100, AR3	1	23	296
GWP 100, AR4	1	25	298
GWP 100, AR5	1	28	265
GWP 100, AR6 (Reference)	1	27	273

Harmonization Coefficient:

$$C_{GWP,i} = 1 + \frac{E_{CH_4}}{E_{CO_2-eq,i}} \times \left(GWP_{CH_{4,ref}} - GWP_{CH_{4,i}}\right) + \frac{E_{N_2O}}{E_{CO_2-eq,i}} \times \left(GWP_{N_2O,ref} - GWP_{N_2O,i}\right)$$

$C_{GWP,i}$ Harmonization coefficient for study i

E: Total emissions [kg]

$GWP_{gas_{ref}}$: The global warming potential of the gas in the reference case

GWP_{gas_i}: The global warming potential of the gas in the studied case

Harmonized Emission Factor:

$$EF_H = C_{\ GWP,i} \times EF_{pub}$$

EF_H: Harmonized emission factor per GWP used

EF_{pub}: Published emission factor for each selected study

2. Harmonization for the scope of included gases:

The second selected methodological parameter for the purpose IEA's harmonization of wind and solar PV generation is the scope of the included GHG gases in the studies. As some of the published literature included CO_2 emissions only, while other comprised of non-CO_2 emissions, the following arithmetic was followed to harmonize the boundary of included gases among the selected pool of studies:

Gas ratio:

$$R\ (gas/CO_2)_i = \frac{E_{gas_i} \times GWP_{gas_i}}{E_{CO_{2,i}}}$$

E: Total emissions [kg] in a reference selected study

GWP_{gas_i}: The global warming potential of non-CO_2 gas in study i

Harmonization Coefficient:

$$C_{\ gases,i} = 1 + \sum_{gas} R\ (gas/CO_2)_i \quad , \ \text{gas} = (CH_4, \ N_2O)$$

$C_{gases,i}$ Harmonization coefficient for study i

Harmonized Emission Factor:

$$EF_{H,\ gases} = C_{\ gases,i} \times EF_{pub}$$

EF_H: Harmonized emission factor for the scope of included gases

EF_{pub}: Published emission factor for each selected study

ANNEX II – CUMULATIVE HARMONIZATION OF WIND AND SOLAR PV

This section details the arithmetic behind the IEA performed key performance characteristics harmonization and the cumulative harmonization applied to the selected pool of studies from the systematic review of onshore wind and solar PV electricity generation. Refer to the *Wind* and *Solar PV* sections in this document for the corresponding details.

The life cycle GHG intensity corresponding to both technologies can be represented as per the following equation:

$$\mathrm{EF}(\ \mathrm{gCO_{2eq}/kWh}) = \frac{Lifetime\ GHG\ emissions\ (gCO_{2eq})}{Lifetime\ electricity\ output\ (kWh)}$$

For onshore wind generation, the denominator from the above equation which corresponds to the lifetime electricity output is defined as per the following equation:

$$Lifetime\ electricity\ output\ (kWh) = Capacity\ factor\ (\%)\ \times\ name\ plate\ capacity\ (MW)\ \times\ lifetime\ (year) \times \frac{hours}{year}$$

As detailed in the *Wind* section in this document, the capacity factor and lifetime have been selected as the appropriate performance characteristics for the purpose of the harmonization.

Similarly, and for solar PV generation, the denominator which corresponds to the lifetime electricity output is defined as per the following equation:

$$Lifetime\ electricity\ output\ (kWh) = Irradiation\ \left(\frac{kWh}{m2.year}\right) x\ Module\ efficiency\ (\%)\ x\ \ Performance\ ratio\ (\%) x\ lifetime\ (year) x\ total\ module\ area\ (m2)$$

As detailed in the *Solar PV* section in this document, all parameters besides the module area have been selected as the appropriate performance characteristics for the purpose of the harmonization.

The equation below was applied in order to harmonize the published emission factors with respect to each of the above listed performance characteristics as per the reference parameters listed in the following table:

Harmonized Emission Factor:

$$EF_{H,\ parameter} = EF_{published} \times \frac{published\ \text{performce}\ parameter}{reference\ \text{performce}\ parameter}$$

$EF_{H,parameter}$: Harmonized emission factor for each of the above listed performance parameters

EF_{pub}: Published emission factor for each selected study

Technology	Performance parameter	Reference figure	Source
Onshore wind	Capacity factor	34 %	IEA Renewables 2023
	Lifetime	20 years	Median of the study pool
	Module efficiency	14 %	Median of the study pool
	Performance ratio	75 %	Median of the study pool

Technology	**Performance parameter**	**Reference figure**	**Source**
Solar PV	Solar irradiation	1700 (kWh/m^2.year)	Median of the study pool
	Lifetime	30 years	Median of the study pool

Following the methodological and key performance criterion harmonization as detailed in Annex I and this section, the following equation was used for the cumulative harmonization in order to develop the final harmonized life cycle emission intensities:

$$EF_{H,cum} = EF_{pub} \times \prod \frac{EF_{H,parameter}}{EF_{pub}}$$

$EF_{H,cum}$: Final harmonized emission factor

$EF_{H,parameter}$: Emission factors harmonized by each of the methodological and key performance parameters

EF_{pub}: Published emission factor for each selected study

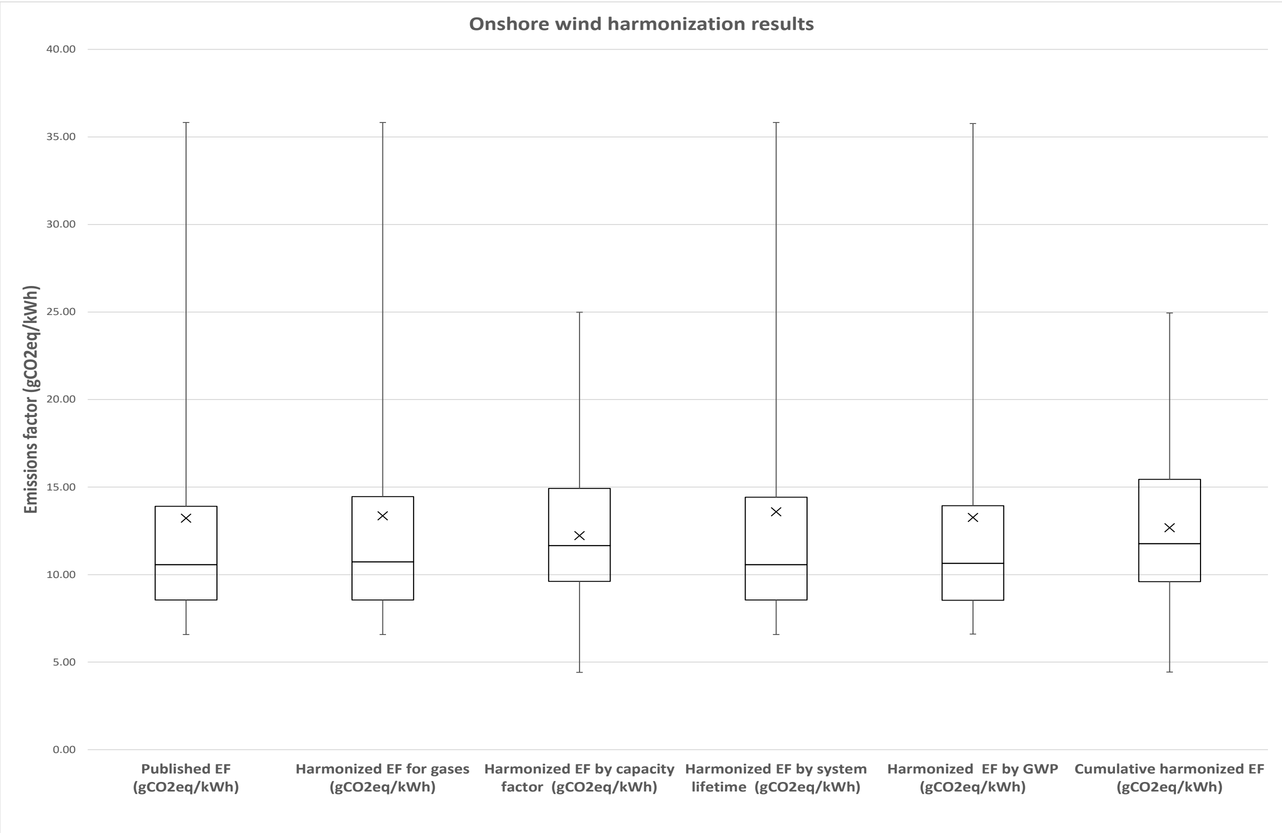
ANNEX III –HARMONIZATION RESULTS - WIND AND SOLAR PV

This section includes the detailed results from the IEA performed systematic review and harmonization corresponding to onshore wind and solar PV electricity generation.

1. Onshore wind harmonization results

Statistical measure	EF_{pub}	$EF_{H,GWP}$	$EF_{H,gases}$	$EF_{H,CF}$	$EF_{H,lifetime}$	$EF_{H,cum}$
Min	6.58	6.60	6.58	4.42	6.58	4.43
25th %	8.55	8.54	8.55	9.61	8.55	9.60
Median	10.57	10.65	10.73	11.66	10.57	**11.76***
75th %	13.90	13.94	14.46	14.92	14.43	15.44
Max	35.83	35.77	35.83	24.99	35.83	24.95
IQR	5.35	5.40	5.91	5.31	5.88	5.85
Range	29.25	29.17	29.25	20.57	29.25	20.51

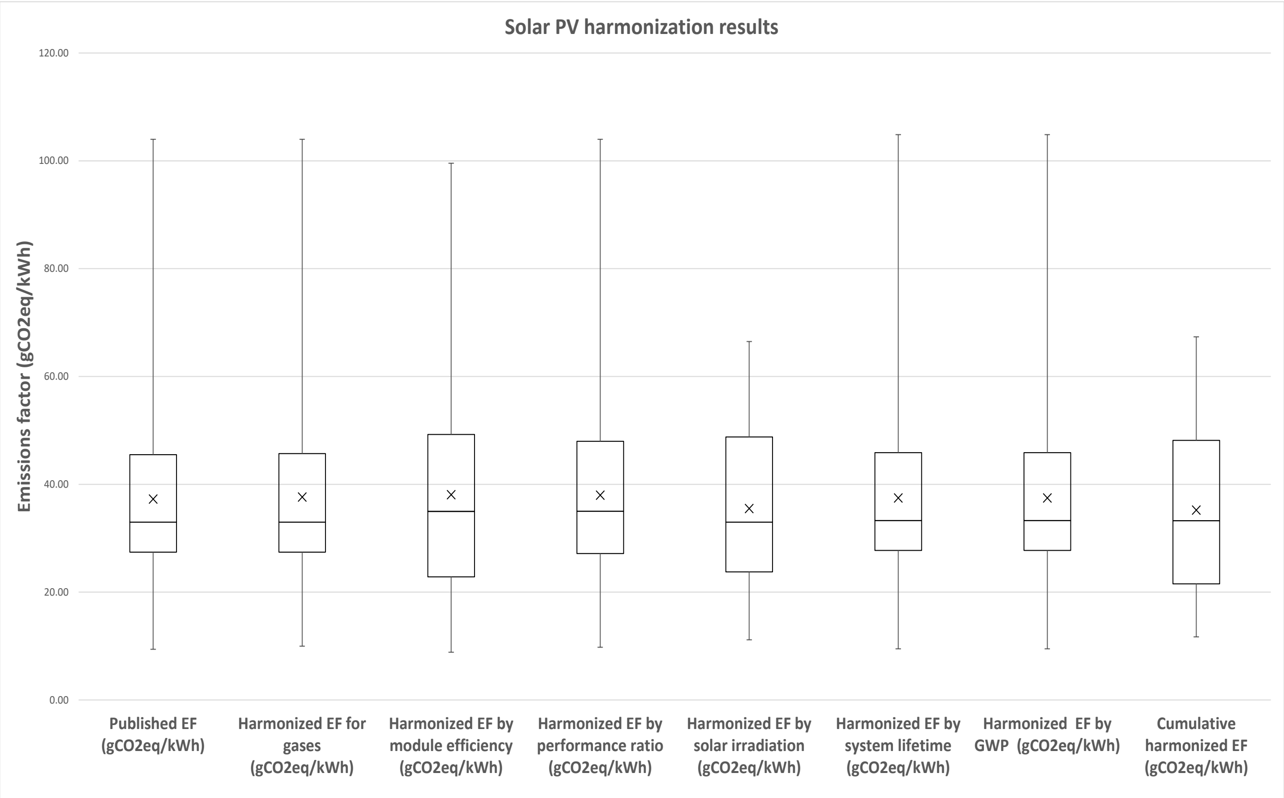
***** The median corresponding to the cumulative harmonization based on all the parameters was selected as a global proxy for life cycle emission intensity corresponding to onshore wind generation. Please refer to *Wind* section for details.



2. Solar PV harmonization results

Statistical measure	EF_{pub}	$EF_{H,GWP}$	$EF_{H,gases}$	$EF_{H,SI}$	$EF_{H,ME}$	$EF_{H,PR}$	$EF_{H,lifetime}$	$EF_{H,cum}$
Min	9.40	9.48	9.98	11.15	8.86	9.78	9.48	11.70
25th %	27.41	27.75	27.41	23.75	22.85	27.16	27.75	21.54
Median	33.00	33.28	33.00	33.00	34.99	35.00	33.28	**33.23***
75th %	45.50	45.88	45.70	48.78	49.24	47.99	45.88	48.16
Max	104.00	104.87	104.00	66.50	99.54	104.00	104.87	67.36
IQR	18.09	18.13	18.29	25.02	26.39	20.83	18.13	26.62
Range	94.60	95.39	94.02	55.34	90.68	94.22	95.39	55.65

***** The median corresponding to the cumulative harmonization based on all the parameters was selected as a global proxy for life cycle emission intensity corresponding to onshore wind generation. Please refer to *Wind* section for details.



References

1) IEA (2024) - World Energy Balances

2) IEA (2024) - Global Energy and Climate Model

3) IEA (2024) - Renewables Information database

4) IEA (2023) - Renewables database

5) IEA (2021) - Vehicle Fuel Economy in Major Markets Working Paper

6) NREL Life Cycle Assessment Harmonization - Accessed September 2023

7) IPCC (2011) - Special Report on Renewable Energy Sources and Climate Change Mitigation

8) European Biogas Association (2022) - Statistical Report

9) International Council on Clean Transportation (2021) - White Paper

10) UNFCCC - Decision 18/CMA.1

11) UNFCCC - Decision 24/CP.19

12) European Commission (2023) - European Sustainability Reporting (ESRS)

13) IEA (2024) - Global Methane Tracker

14) IEA (2023) - Emissions from Oil and Gas Operations in Net Zero Transitions

15) IEA (2024) - Natural Gas Information

16) UKERC 2022

17) Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model (GREET) model

18) GREET CCLUB LUC add-on (Carbon Calculator for Land Use and Land Management Change from Biofuels Production)

19) Transport and Environment (2020) - GLOBIOM Report

20) Renewable Energy Directive II (RED II)

21) Department for Energy Security & Net Zero (2024) - Methodology Paper for Conversion factors

22) Exergia (2015) - Study on actual GHG data for diesel, petrol, kerosene and natural gas

23) JEC (JRC-Eucar-Concawe) (2020)

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Typeset in France by IEA –September 2024

Cover design: IEA