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Life cycle GHG emissions of renewable and non-renewable electricity generation technologies

Part of the RE-Invest project

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Summary

This study is part of the Re-Invest project and aims to assess the greenhouse gas emissions of a considered number of both renewable and non-renewable electricity generation technologies over a life cycle perspective. The considered technologies are the following:

- Renewable electricity generation
  - Wind power
  - Photovoltaic power
  - Concentrated Solar Power
  - Hydropower
  - Wave power
  - Tidal power
  - Geothermal power
- Non-renewable electricity generation
  - Coal power
  - Natural gas power

The main findings of the analysis are summarized as follows:

Wave and photovoltaic power present the highest contribution to GHG emissions for the considered renewable electricity generation technologies, with an average value of 55.9 and 50.9 g CO_2-equivalent per kWh, respectively. Wind power, on the other hand, presents the lowest contribution to GHG emissions with an average contribution of 14.4 and 18.4 g CO_2-equivalent per kWh for onshore and offshore locations, respectively. Hydropower presents the second lowest contribution to GHG emissions with reservoir plants presenting an average contribution of 21.4 g CO_2-equivalent per kWh and run-of-river plants an average contribution of 19.1 g CO_2-equivalent per kWh. Nonetheless, in comparison with the non-renewable technologies, renewable technologies present much lower GHG emissions.

The results show that for renewable technologies, infrastructure is the most contributing life cycle phase to the total GHG emissions, with a contribution up to 99%, while from non-renewable technologies the operation phase is the most contributing one, with a contribution ranging from 80 % to 90 %.

The results also show that the GHG emissions might present significant variations within the same technology. As discussed throughout the report, such variations may be linked to differences according to “real variations”, such as local conditions (e.g. wind and solar conditions), national/regional energy mixes used for the manufacturing of materials, etc. However, the differences might be increased by varying methodological assumptions, such as data sources and degree of specific data used for the assessment, the assumed technologies’ lifetime, end-of-life assumptions, as well as the energy mixes considered for the production and assembly phases in the analysis.

When implementing renewable electricity technologies into the future smart energy systems, critical parameters for choosing technology according to GHG emissions, should be based on both local conditions (where the plant is assumed to be built) as well as impacts from production/building phase (infrastructure impact). This means that it is important to be aware about the origin of the raw

materials (what is the relevant electricity mix used?), the transport of the raw materials to the assembling plant (what is the travelled distance?) and what is the type of transport used, including vehicle's size class, category, capacity, type of fuel and its average consumption?), the location of the assembling plant (what are the energy requirements and their sources? How are the waste fractions handled and further treated?), what are the end-of-life options, etc. Furthermore, local parameters such as wind and sun conditions for the plants should be considered, as these are critical in order to utilize the installed electricity technology (and thus the already invested impacts) as much as possible.

Finally, it should be emphasised that this report assesses the considered technologies only from a greenhouse gas perspective which means that other environmental impact categories are not included.

List of abbreviations

a-Si	Amorphous thin-film silicon
CdTe	Cadmium Telluride
CIGS	Gallium selenide
CO_2	Carbon dioxide
CSP	Concentrated solar power
EGS	Enhanced geothermal systems
eq.	Equivalent
g	gram
GHG	Greenhouse gas
IGCC	Integrated gasification combined cycle
IPCC	International panel on climate change
IQR	Inter quartile range
kW	Kilowatt
kWh	Kilowatt hour
LCA	Life cycle assessment
MW	Megawatt

1 Introduction

The focus on renewable energy supply as well as on electricity and gas cross-border interconnections is increasing worldwide. However, there is a tendency to focus on renewable energy integration within one single sector - often electricity only, rather than looking at the transition as a complete redesign of the whole system. In this sense, there is an urgency to move beyond this single-sector or single-technology focus in research, industry and public authorities.

The RE-Invest project addresses how to overcome the described silo-thinking that characterizes traditional energy sectors and how to develop novel methodologies for renewable energy investment strategies based on a two-dimensional interconnectivity approach with the aim to:

- further develop the Smart Energy System concept and identify synergies in low-cost storages across sectors on one side and international electricity and gas transmission on the other side,
- support of expanding markets in Denmark and Europe for Danish industries and enable the industrial partners in RE-Invest to be early adaptors of trends in integrated energy markets, thus having cutting edge R&D for key technologies in future sustainable energy systems.

In overall, the RE-Invest project aims to contribute towards a low-carbon sustainable energy future in the Danish energy sector.

The role of Ostfold Research in the Re-Invest project is to assess over a life cycle perspective the environmental impact of a selected number of electricity generation technologies, hence enabling to analyse the overall impact from energy systems based on the two-dimensional interconnectivity approach. A further description of the methodology used as well as the assessed technologies is given in Chapter 2.

2 Methodology

This report aims to assess the life cycle greenhouse gas (GHG) emissions of the following electricity generation technologies:

- Renewable electricity generation
  - Wind power
  - Photovoltaic power
  - Concentrated Solar Power (CSP)
  - Hydropower
  - Wave power
  - Tidal power
  - Geothermal power
- Non-renewable electricity generation
  - Coal power
  - Natural gas power

The assessment was based on a literature review of life cycle GHG emissions studies for the aforementioned electricity generation technologies. Specifically, the current literature review attempts to address the following research questions:

1. Which electricity generation technology presents the highest contribution to the total GHG emissions? And the lowest?
2. Where in the life cycle occurs the highest contribution?
3. What are the key findings from this research?
4. What are the limitations of this research?

The research studies were collected from a variety of sources: ScienceDirect, Wiley Online Library, Taylor and Francis, Elsevier, IEEE, Scopus and Google Scholar; and the search terms used to identify the studies were the following: wind, photovoltaic, concentrated solar power, CSP, hydropower, wave, tidal, geothermal, coal, natural gas, energy, power, renewable, fossil, life cycle assessment (LCA), climate change, GHG emissions. The search was not bounded by a specific year range. Further, the list of references of the research studies identified were used to find additional papers, a technique known as snowballing.

To obtain comparable results, the following selection criteria was used:

- Only studies that express quantitatively the GHG emissions as a function of electricity generation are considered, and if not explicitly reported, one must be able to calculate the total GHG emissions per g CO_2-equivalent per kWh;
- The system boundaries must be clearly defined and may comprise at least the construction and operation life cycle phases (cradle to gate);
- Studies that originally included recycling credits have been adjusted in order to only cover cradle-to-grave impacts, excluding recycling credits. Hence, the presented studies include either the system boundary cradle to gate or cradle to grave (excluding recycling credits).

Electrical losses inherent to the voltage transformations as well as infrastructure related to electricity transmission and distribution are excluded from the analysis. Further, GHG emissions of eventually necessary backup electricity systems are excluded. The reference unit used corresponds to 1 kWh power generated.

It should be noted that the impact assessment methodologies used for calculating the life cycle GHG emissions were different: CML 2001, Eco-indicator 99, EDIP, IPCC (International Panel on Climate Change) method and Impact 2002+. A comparison between the different impact assessment methodologies is presented in Appendix 1.

3 Life cycle GHG emissions

This Chapter presents the life cycle GHG emissions for the selected electricity generation technologies. Section 3.1 presents the results for the considered renewable technologies, while the results associated with the non-renewable technologies are presented in Section 3.2. The variability of the results is described by using the median and arithmetic mean (hereafter referred to as “mean”), the maximum and minimum values, and the interquartile range (IQR, defined as the 75th percentile value minus the 25th percentile value). The sample size is also presented. The parameters used to present the variability of the results are depicted as shown in Figure 1.

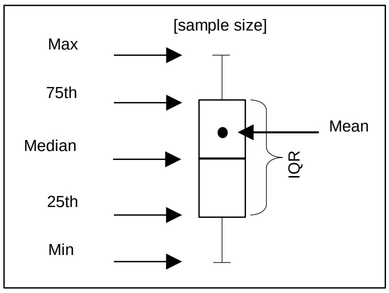


Figure 1 Parameters used to describe the variability of the results

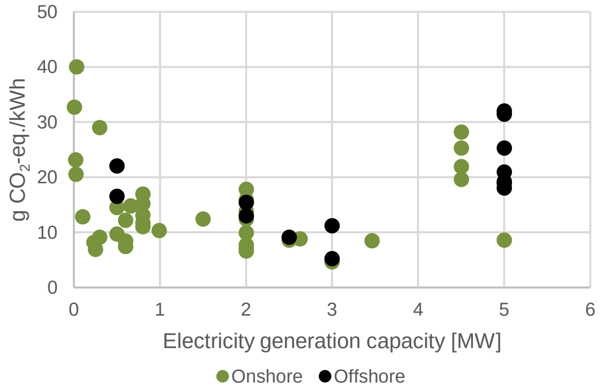
3.1 Renewable electricity generation

3.1.1 Wind

This section presents the GHG emissions from wind power generation. The literature review comprises studies that are assessed in a life cycle perspective for a specific wind turbine or wind power plant. Studies compiling average data on wind power from previous research are also considered. In total, the analysis comprises 54 studies (1–22), published between 2000 and 2017.

The assessed studies present significant differences in their goal and geographical, temporal and technological scopes. Differences in the definition of system boundaries were also noticed. Some studies follow a cradle-to-grave perspective, but a significant share only performed a cradle-to-gate analysis, excluding the decommissioning phase. Most of the studies consider a 20-year life time.

Figure 2 shows a summary of the GHG emissions based on turbine size and capacity factor in order to give an overview of the results from all assessed LCA studies. The results are presented in g CO_2-equivalent per kWh. The capacity factor expresses the actual annual electricity generation divided by the maximum possible annual electricity generation (operating full time at full power). It is expressed as a fraction or a percentage and is a term describing wind conditions (the more days with good wind conditions, the more electricity is produced).



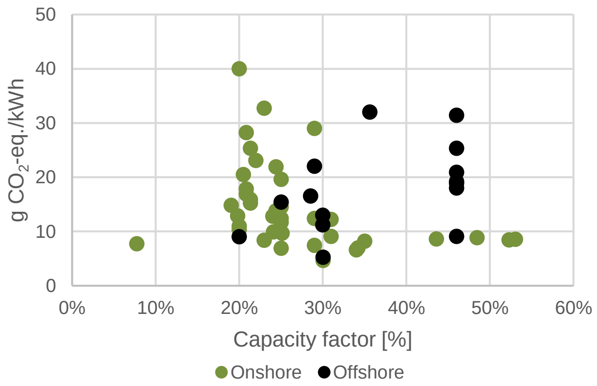


Figure 2 Summary of life cycle GHG emissions from wind power based on location and categorised in accordance with turbine electricity generation capacity (left) and capacity factor (right)

Figure 22 shows that there is a tendency for a decrease in GHG emissions where there are, respectively, increased turbine size and capacity factors. This is in accordance with results from other studies (2, 3, 23, 83). Despite this general tendency, the figure shows that the variations in the data are still relatively large. Such variations can be explained by differing presuppositions concerning the wind farm. These can include lifetime; end-of-life treatment of wind turbine components; the energy source invested to build and install the wind turbines; reinvestment rates and maintenance as well as whether current or future conditions have been analysed.

For the offshore concepts, specific platform/foundation steel masses are important for the overall GHG emissions relating to offshore wind power. Other parameters of importance are lifetime of the turbines, wind conditions, distance to shore, and installation and decommissioning activities (3).

The investigated studies show that the infrastructure phase is the heaviest contributor to the total GHG emissions, representing 85-99%. The infrastructure phase comprises material production and processing, transport, assembly and installation, and decommissioning. Steel and concrete production are the most contributing activities within this phase.

3.1.2 Photovoltaic

This section sets out the GHG emissions from the generation of photovoltaic power based on 45 studies (1,15–17,20,24–37), published between 2002 and 2017. The investigated studies comprise assessments in a life cycle perspective of a specific photovoltaic panel or a photovoltaic power plant. Studies presenting average data on photovoltaic power from previous research are also considered.

Photovoltaic power also represents an intermittent electricity generation technology. The results are presented for 1 kWh photovoltaic power generated.

The investigated studies present significant differences regarding system boundaries, with most studies performing a cradle-to-gate analysis. Significant differences regarding the device lifetime are also noticed, with values ranging from 15 to 30 years lifetime.

Figure 3 presents the GHG emissions for the considered samples of photovoltaic power, in g CO_2-equivalent per kWh, based on panel electricity generation capacity. The results were grouped in 4 different groups, namely: 0 kW - 3 kW, 3 kW - 1 MW, 1 MW - 4 MW and > 4 MW.

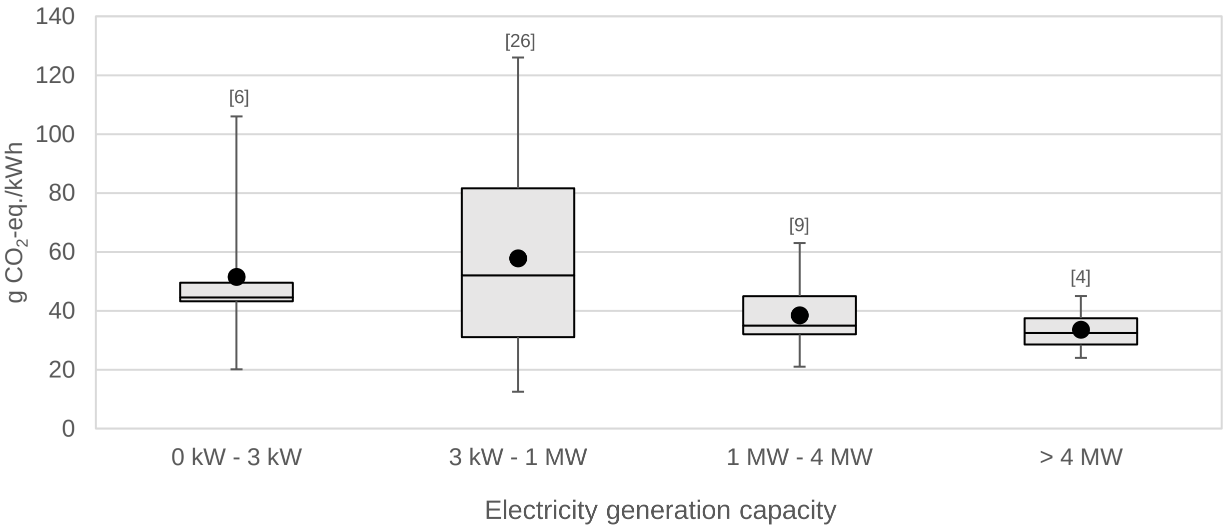


Figure 3 Summary of life cycle GHG emissions from photovoltaic power based on panel electricity generation capacity

Figure 3 shows that the GHG emissions range from 12.5 (30) to 126.0 (16) g CO_2-equivalent per kWh. This variability is comprised in the third largest electricity generation capacity group, 3 kW to 1 MW, and may be linked to differences in energy requirements during the production and assembly phases as well to the energy mixes used to produce the photovoltaic panels (34). Further, significant differences in energy conversion efficiencies, ranging from 3-15%, and devices lifetime, varying from 15-30 years, may also play and important role (38). In addition, the results show that the mean value decreases with increasing electricity generation capacity.

The assessed studies show that the infrastructure phase is the most contributing life cycle phase to the total GHG emissions, with contributions ranging from 93% to 99%. This phase comprises material production and processing, transport, assembly and installation, and decommissioning. From these, material production is the most contributing activity, where steel and aluminium production play an important role.

Photovoltaic cells are made of different kinds of semi-conductive materials, with approximately 85-90% being composed of monocrystalline or polycrystalline silicon (Si) cells and the remaining of thin-film cells (36). The silicon cells are the so-called first generation of photovoltaic cells, having thus reached a good maturity in its development and application. On the other hand, thin-film cells are considered as the second generation of photovoltaic cells. Most of the reviewed studies assessed the GHG emissions of silicon cells, both monocrystalline and polycrystalline. In comparison, the thin-film cells are studied to a much lesser extent. Figure 4 presents the GHG emissions of photovoltaic power categorised into monocrystalline, polycrystalline and thin-film photovoltaic cells.

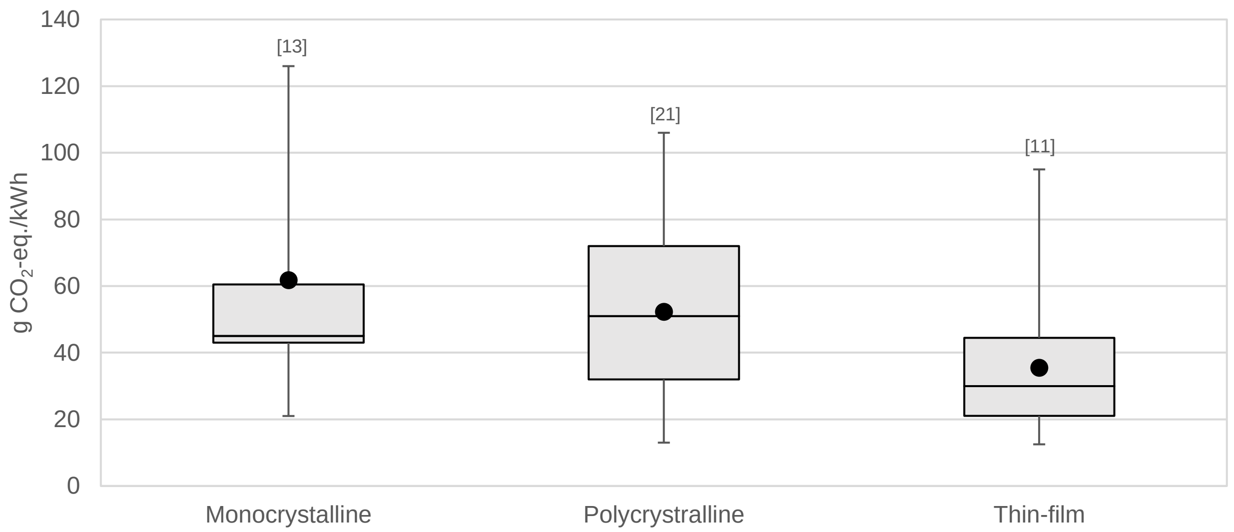


Figure 4 Summary of life cycle GHG emissions from photovoltaic power based on technology

The results presented in Figure 4 show that monocrystalline panels present in average higher GHG emissions than the other two technologies, which is in line with previous findings (20,24,34,39,40). The GHG emissions mean value for monocrystalline, polycrystalline and thin-film have been estimated in the order of 61.8, 52.2 and 35.5 g CO_2-equivalent per kWh, respectively. Energy requirements in cells and modules manufacture are the main reason behind such variability. In comparison, thin-film technology has much lower energy requirements.

Thin-film panels are commercially used in several technologies, including cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and amorphous thin-film silicon (a-Si). In this sense, the eleven studies that assessed the GHG emissions of thin-film panels are further categorised. Figure 5 shows the GHG emissions for CdTe, GIGS and a-Si thin-film technologies.

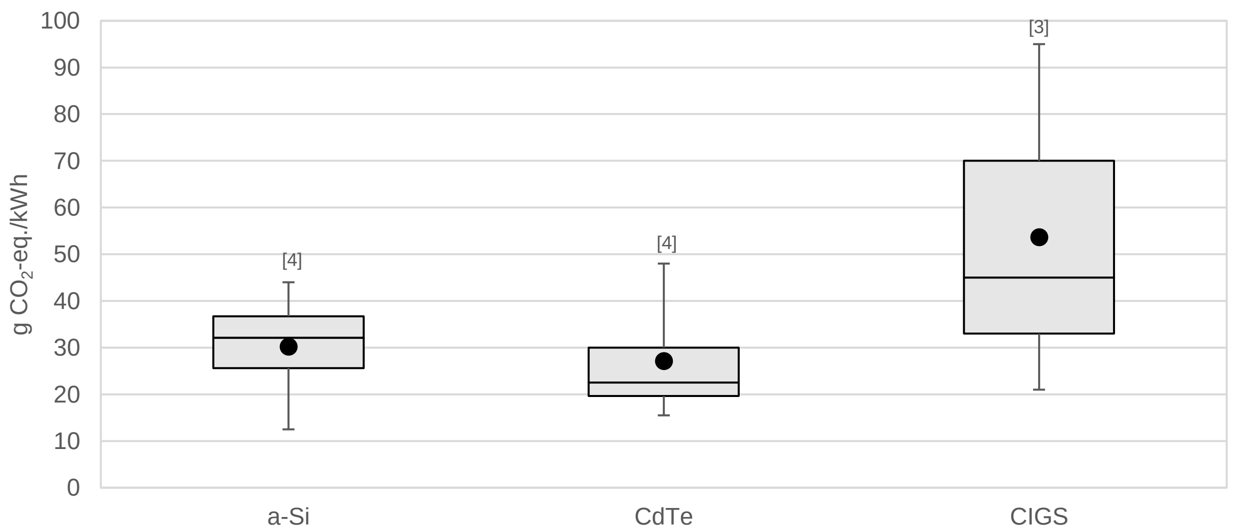


Figure 5 Summary of life cycle GHG emissions from thin-film technology

As shown in Figure 5, the GHG emissions range between 12.5 (30) to 95.0 (26) g CO_2-equivalent per kWh, with thin-film a-Si technology representing the lowest value and CIGS the highest. The results also show that thin-film CdTe technology presents the lowest GHG emissions mean value. This is in line with previous findings and is mainly linked to the fact that thin-film CdTe photovoltaic panels requires a lower amount of energy during its production in comparison to the other technologies (34,39).

The performance of photovoltaic power is directly linked to insolation. As a result, in low-sunny regions, the high resource requirement of photovoltaic panels can be badly balanced against low electrical output, thus leading to higher GHG emissions. Therefore, photovoltaic panels located in regions with relatively low insolation such as the United Kingdom are expected to have larger GHG emissions compared with high-sunny regions with high insolation, such as Spain and USA. Figure 6 depicts the GHG emissions of the investigated studies according to the location of the photovoltaic panels.

The locations were grouped into Northern Europe (16), Western and Central Europe (15,20,27,35), Southern Europe (15,24–26,31,32,34,36), North America (1,28,30,34,41), South America (33) and Asia (17,37).

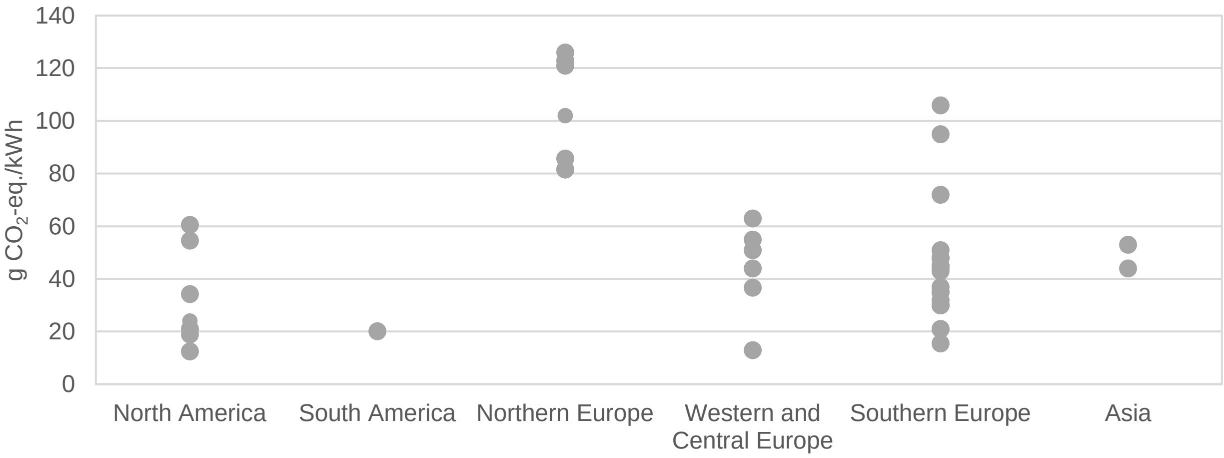


Figure 6 Summary of life cycle GHG emissions from photovoltaic power based on location

Figure 6 shows that the photovoltaic systems located in the Northern Europe present in average higher GHG emissions than the remaining locations. Further, the results show that GHG emissions from photovoltaic systems located in the Southern Europe vary significantly from 15.5 to 106.0 g CO_2-equivalent per kWh. The highest value comprised within the Southern Europe category (106.0 g CO_2-equivalent per kWh) refers to a study that assesses a photovoltaic plant located in Italy (31). The study is the only one that considers the impact associated with the land use, which may explain the result. The two following highest results (95,0 and 72,0 g CO_2-equivalent per kWh) refer to a study where the Southern European insolation conditions are considered but applies the European electricity production mix in the production life cycle phase (26). Other studies also apply the Southern Europe insolation conditions and different electricity production mixes in the production phase, such as US mix (25) and Western-Europe mix, UCTE (24). Hence, the electricity mixes used in the production phase of the different technologies in the Southern Europe may explain such variation in results.

3.1.3 Concentrated Solar Power

This section presents the GHG emissions from the generation of concentrated solar power. CSP technology generates electric power by means of reflecting mirrors, which reflect the sun's radiation on special receivers. The receivers used to capture concentrated solar radiation are the following: power tower, parabolic through collectors, parabolic dish systems and linear fresnel reflectors, with the two first ones being the most common (36).

The results presented in this section are based on 29 LCA studies (42–49), published between 1990 and 2010. As CSP also represents an intermittent electricity generation technology, the GHG emissions of the backup power are excluded from the analysis. Electrical losses and infrastructure related to electricity transmission and distribution are also excluded. The results are presented for 1 kWh CSP generated.

Most of the considered studies performed a cradle-to-grave analysis and used the following impact assessment methodologies: Eco-indicator 99 and IPPC. Further, the assumed device lifetime from the investigated studies ranged between 25 to 40 years.

Figure 7 presents the GHG emissions for the considered samples of CSP, in g CO_2-equivalent per kWh, based on electricity generation capacity.

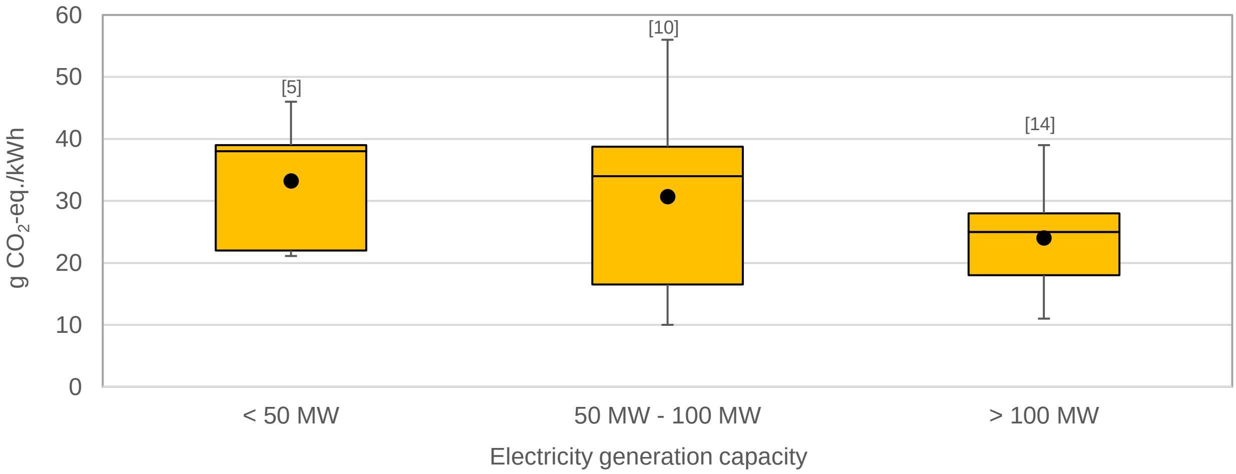


Figure 7 Summary of life cycle GHG emissions from CSP based on electricity generation capacity

The results presented in Figure 7 show a large variation for CSP systems for an electricity generation capacity ranging between 50 and 100 MW, with GHG emissions presenting a minimum value of 10.0 g CO_2-equivalent per kWh and a maximum value of 56.0 g CO_2-equivalent per kWh. The results also show that the mean value decreases with the increase of electricity generation capacity: CPS systems with an electricity generation capacity lower than 50 MW present a mean value of 33.2 g CO_2-equivalent per kWh, while systems with an electricity generation capacity higher than 100 MW have associated a mean value of 24.0 g CO_2-equivalent per kWh.

Figure 8 shows the GHG emissions for the investigated samples of CSP, in g CO_2-equivalent per kWh, based on the most common receiver types: parabolic trough and power tower.

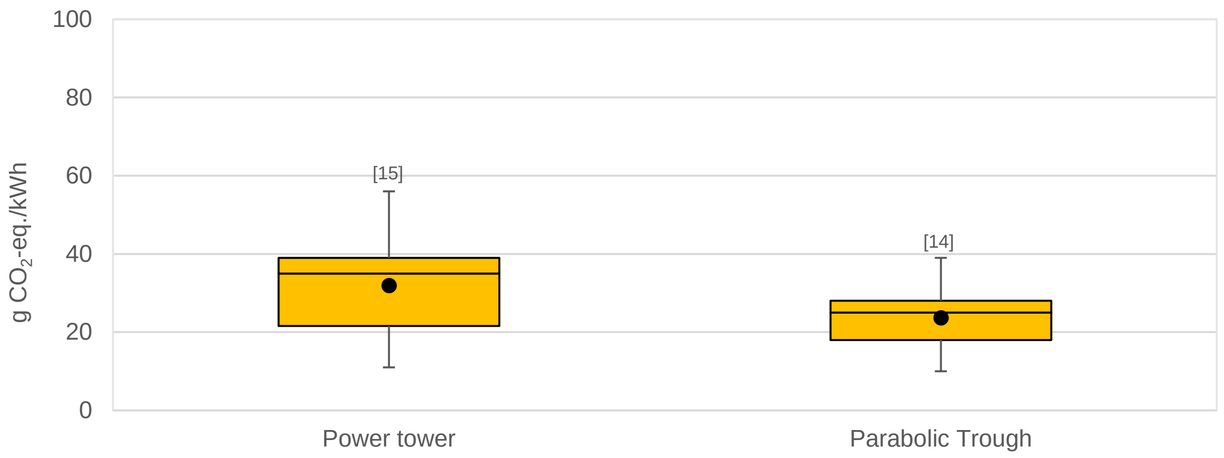


Figure 8 Summary of life cycle GHG emissions from CSP based on receiver type

According to the results presented in Figure 8, power tower receivers present in average a higher contribution to GHG emissions than parabolic trough receivers, with the first presenting a mean value of 31.9 while the latter presents a mean value of 23.6 g CO_2-equivalent per kWh. For power tower, the GHG emissions are ranging between 11.0 (47) and 56.0 (44) g CO_2-equivalent per kWh, while for parabolic trough the results are varying between 10.0 (46) and 39.0 (42) g CO_2-equivalent per kWh. This is in line with previous findings (46,47,50).

3.1.4 Hydropower

This section presents the GHG emissions from hydropower generation. It investigates studies that assess in a life cycle perspective the pumped storage, run-of-river and reservoir hydropower technologies, resulting in a total of 97 studies (15–17,51–64) published between 2004 and 2018. In line with the previously assessed renewable energies, electrical losses and infrastructure related to electricity transmission and distribution were excluded from the analysis. The reference unit used corresponds to 1 kWh of hydropower.

Most of the investigated studies performed a cradle-to-gate analysis, i.e., including the extraction of raw materials through, manufacturing, assembly and operation, hence excluding the decommissioning phase. In what concerns the lifetime assumed by the investigated studies, significant differences were noticed regarding the reservoir and run-of-river technologies, with values ranging from 30-150 years lifetime. Regarding the impact assessment methodologies, the IPCC method was the most used.

Figure 9 presents the GHG emissions for the sample of studies of hydropower categorised into pumped storage, reservoir and run-of-river plants. GHG emissions associated with reservoir plants were further divided into GHG emissions including or excluding emissions from flooded land, as the emissions from the decomposition of flooded biomass may influence significantly the total GHG emissions (65).

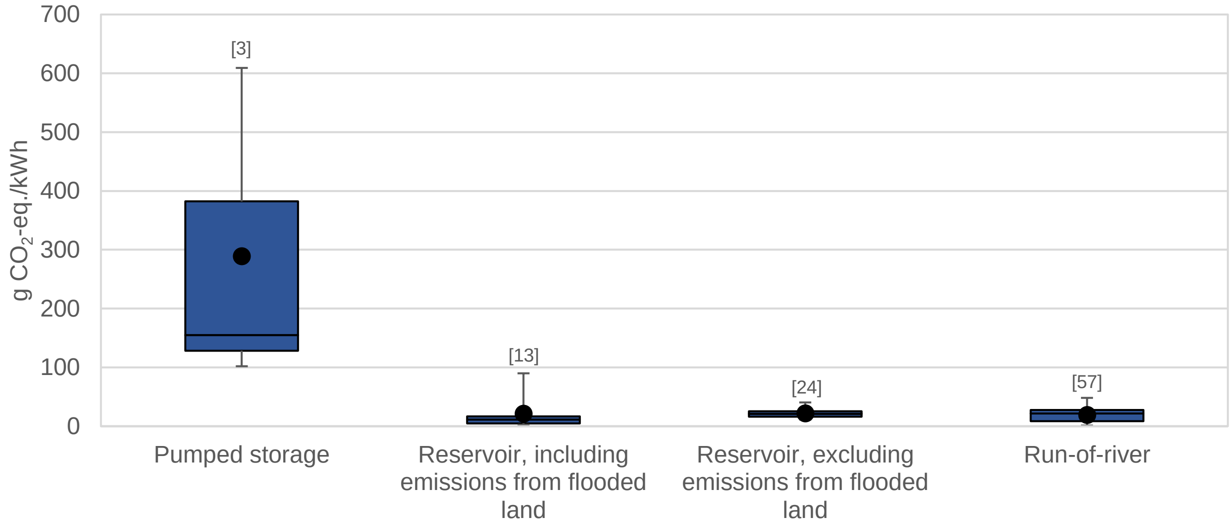


Figure 9 Summary of life cycle GHG emissions from hydropower based on technology

Figure 9 shows large variations in GHG emissions from these hydropower technologies. The results disclose, not unsurprisingly, that pumped storage presents a much higher contribution to GHG emissions in comparison with reservoir and run-of-river plants. However, as the pumped storage results are based on only two references (16,62), which comprise three case studies (Switzerland, Europe and Sweden), it should be noticed that it presents a high level of associated uncertainty. The GHG emissions from pumped storage mostly (> 90%) come from the electricity used for pumping the water. For the three cases shown above the electricity mix is European (ENTSO), Swiss and Swedish for the cases representing highest, middle and lowest results, respectively. However, it can be discussed whether pumped storage represents a generation technology or a storage (battery). For these reasons, the results associated with this technology will not be further discussed. To make the results more illustrative, Figure 10 depicts the GHG emission from reservoir and run-of-river technologies.

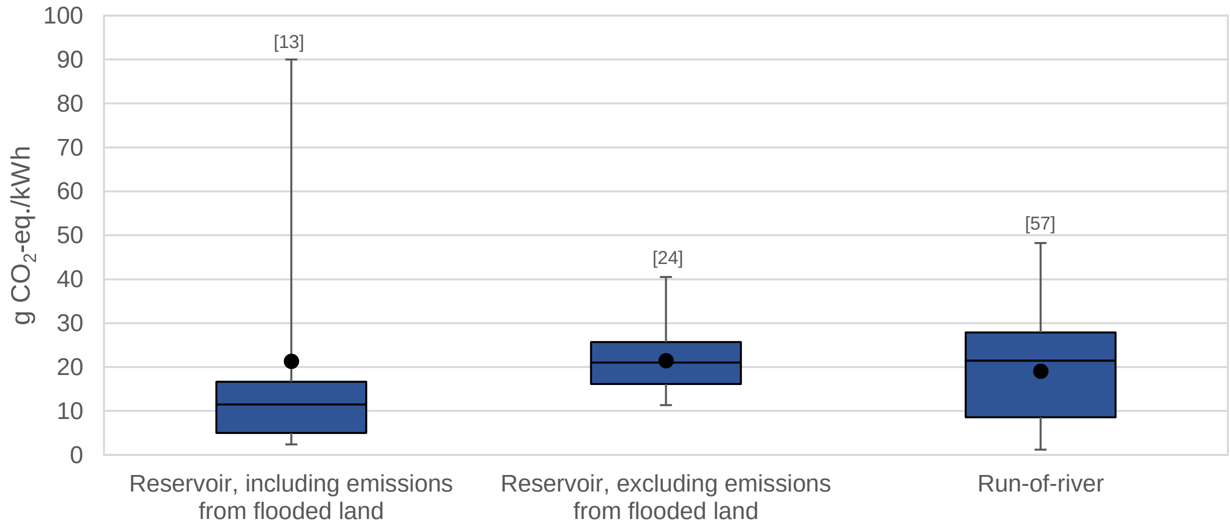


Figure 10 Summary of life cycle GHG emissions from hydropower based on reservoir and run-of-river technologies

The investigated run-of-river plants present results varying between 1.2 (64) and 48.2 (55) g CO_2-equivalent per kWh, with a mean value of 19.1 g CO_2-equivalent per kWh. Reservoir plants including emissions from flooded land present results ranging from 2.4 (60) to 90.0 (15) g CO_2-equivalent per kWh, while reservoir plants excluding emissions from flooded land present results varying between 11.3 (55) and 40.5 (54) g CO_2-equivalent per kWh. However, the GHG emissions mean value for reservoir plants including emissions from flooded land (21.0 g CO_2-equivalent per kWh) is lower than the mean value for reservoir plants when such emissions are excluded (21.5 g CO_2-equivalent per kWh). Nonetheless, one should take into consideration that the GHG emissions associated with the decomposition of flooded biomass is site-specific and may therefore be highly uncertain (17). Besides, the methodology used to calculate these emissions is complicated (66). Further, the characteristics of region where the plant is located may play an important role. According to previous findings, a reservoir plant built in an alpine region may have higher GHG emissions than a reservoir plant built in a “flat” region (61,65,67).

Figure 11 present a summary of the GHG emissions based on electricity generation capacity for reservoir and run-of-river hydropower plants.

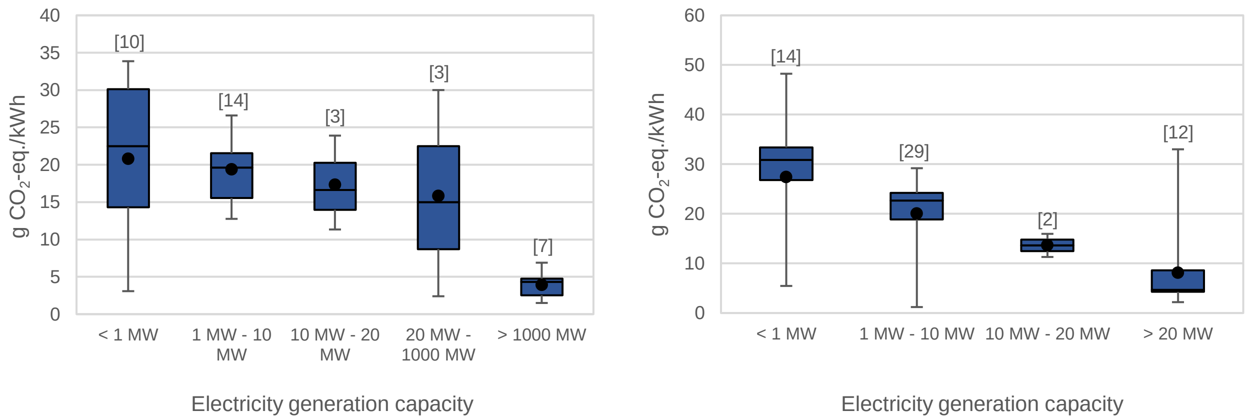


Figure 11 Summary of life cycle GHG emissions from reservoir plants [on the left] and from run-of-river plants [on the right], based on electricity generation capacity

Figure 11 shows that, in average, an increase in electricity generation capacity for both types of hydropower technologies result in a decrease of GHG emissions. This is in line with previous findings (55), and is due to the fact that for big capacity hydropower plants the resource requirements for the generation of 1 kWh of electricity is reduced in comparison with small hydropower plants.

Results from the investigated LCA studies show that the relative contribution of the infrastructure phase varies from 48% to 99% to the run-of-river plants. Further, the total GHG emissions vary from 10% to 99%. The concrete production and the transportation of rocks for the construction of dams and tunnels are the major contributing factors to the reservoir plants. In contrast, the building construction and the equipment production are the major contributing factors to the run-of-river plants.

3.1.5 Wave Power

This section presents the GHG emissions from wave power generation. The analysis is based on 11 LCA studies (68–70), published between 2009 and 2016. The reference unit used corresponds to 1 kWh of wave power.

The assessed studies comprised a cradle-to-grave analysis. However, infrastructure related to the electricity distribution is excluded from the analysis. Noteworthy is that the assessed LCAs on wave energy were mostly focused on energy use and GHG emissions indicators, excluding other environmental impact categories. In addition, it should be noted that most of the studies assessed the GHG emissions by using the IPCC emission factors. Further, a device lifetime of 20 years was mostly assumed.

Figure 12 shows a summary of the GHG emissions from all the investigated LCAs of wave power categorised into electricity generation capacity. These are grouped into three categories, namely lower than 500 kW, 500 kW - 1 MW and higher than 1 MW.

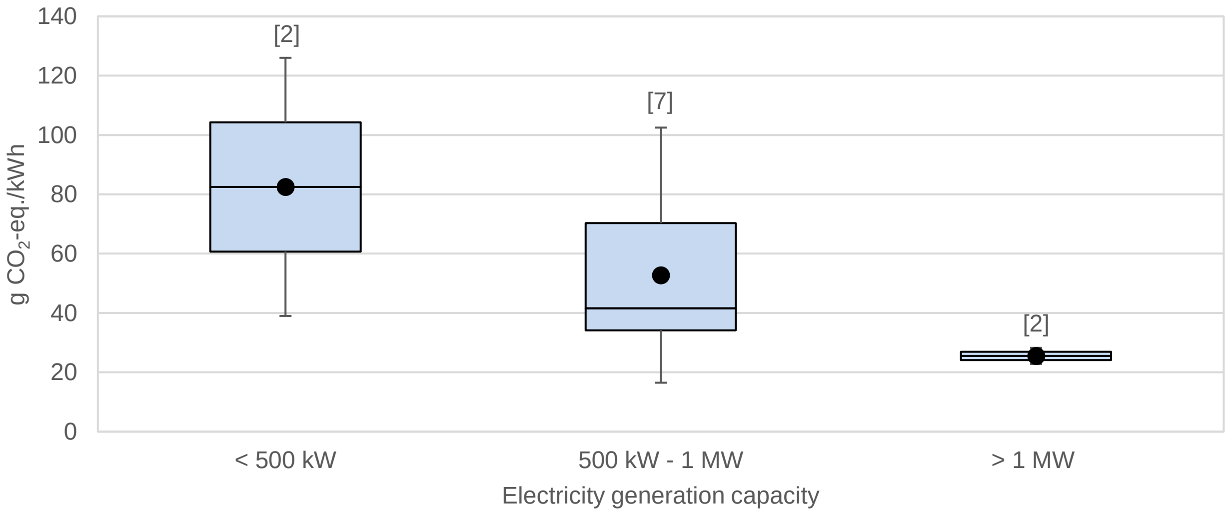


Figure 12 Summary of life cycle GHG emissions from wave power based on electricity generation capacity

Figure 12 shows a large variation in GHG emissions, with results varying from 16.5 (70) to 126.0 (69) g CO_2-equivalent per kWh. The results also show that the mean values decrease with increasing electricity generation capacity, from 82.5 to 25.5 g CO_2-equivalent per kWh.

The main environmental impacts from an LCA perspective are due to material use at the manufacturing phase, whereas installation, maintenance, operation and end-of-life contribute to a much lesser extent. The manufacturing phase present a contribution between 85% and 95% to the total GHG emissions, which is due to the intensity of the metal working processes.

Figure 13 shows the average life cycle GHG emissions from the assessed wave power technologies.

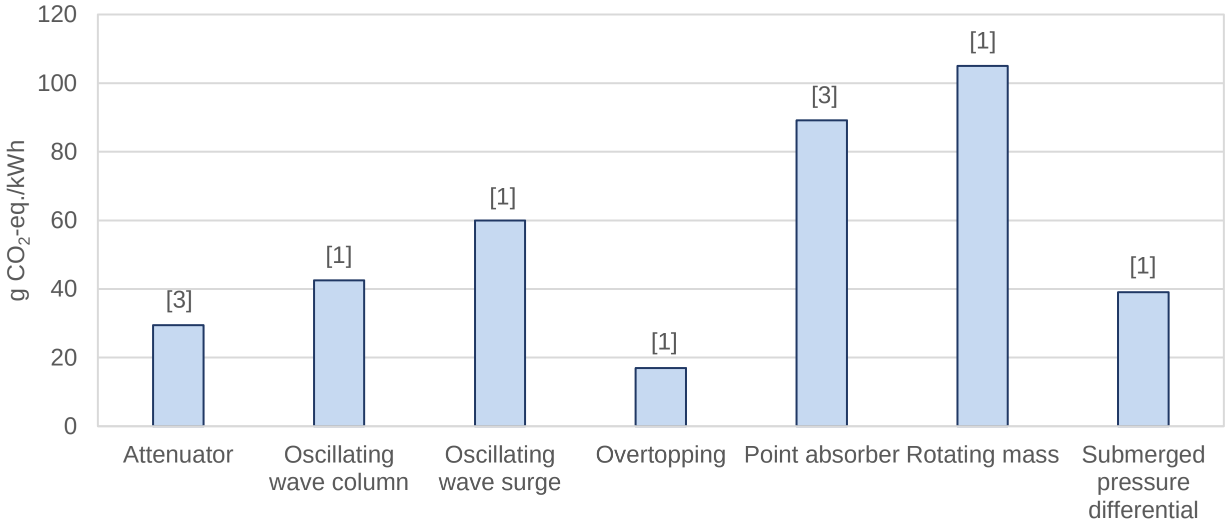


Figure 13 Average life cycle GHG emissions from wave power based on technology

According to the results presented in Figure 13, rotating mass and point absorber technologies for wave power present in average higher contribution to GHG emissions with 105.0 and 89.2 g CO_2-equivalent per kWh, respectively. This is linked to the positive correlation between component mass and the environmental impacts as well as to the share of materials used to produce the wave energy device.

3.1.6 Tidal Power

This section presents the GHG emissions from tidal power generation. The analysis is based on 13 LCA studies (70–73), published between 2008 and 2016. Infrastructure related to the electricity distribution is excluded from the analysis. Further, the GHG emissions of eventually necessary backup electricity systems are not included. The reference unit used corresponds to 1 kWh of tidal power.

From the thirteen assessed studies, only one did not include the decommissioning of the tidal power device (73). In line with LCAs of other renewable energies, the assessed studies were mostly focused on energy use and GHG emissions indicators. Most studies assumed a lifetime between 20 and 25 years.

Figure 14 shows the GHG emissions for the studied samples of tidal power based on electricity generation capacity.

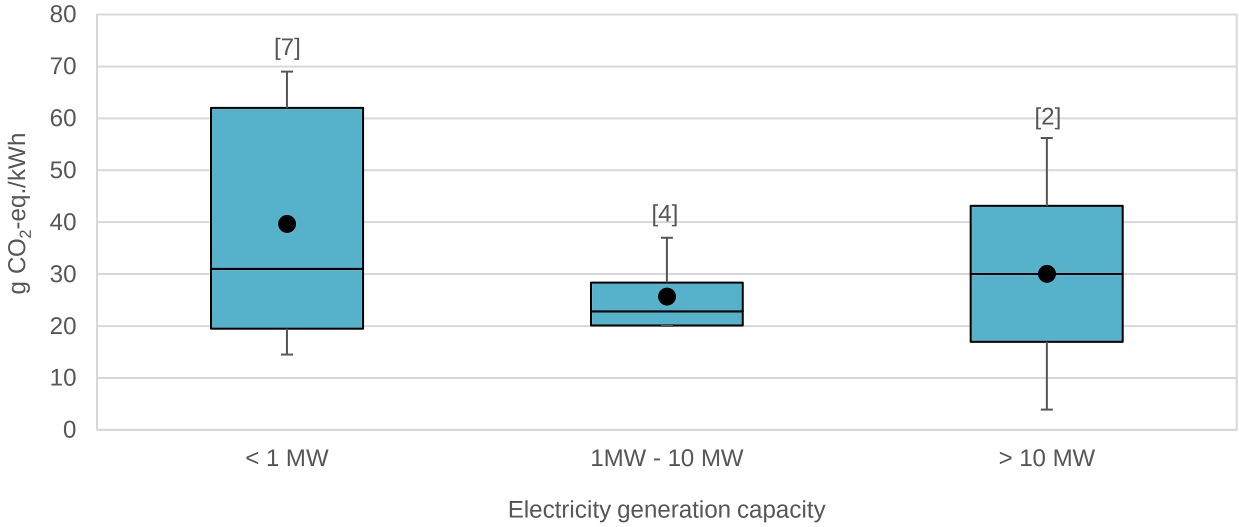


Figure 14 Summary of life cycle GHG emissions from tidal power based on electricity generation capacity

Figure 14 shows that the results range from 3.9 (71) to 69.0 (70) g CO_2-equivalent per kWh with the lower value representing a tidal device of 20 MW electricity generation capacity and the highest value representing a device with an average capacity of 0.75 MW.

The results from the investigated tidal power also show that the infrastructure phase presents a relative contribution between 97% and 99%. The production of materials, such as steel, is the most contributing activity.

3.1.7 Geothermal Power

This section presents the GHG emissions from geothermal power generation. The analysis is based on 13 LCA studies (17,74–81), published between 2005 and 2018. Infrastructure related to the electricity distribution is excluded from the analysis. The reference unit used corresponds to 1 kWh of geothermal power.

Most of the investigated studies comprise a cradle-to-gate analysis, thus excluding the decommissioning phase. The assessed studies considered the following impact assessment methodologies: IPCC, Impact 2002+, CML and ILCD (see Appendix 1). Further, most studies assumed a device lifetime between 20 and 25 years.

Figure 15 present a summary of the GHG emissions based on electricity generation capacity for the studied samples of geothermal power.

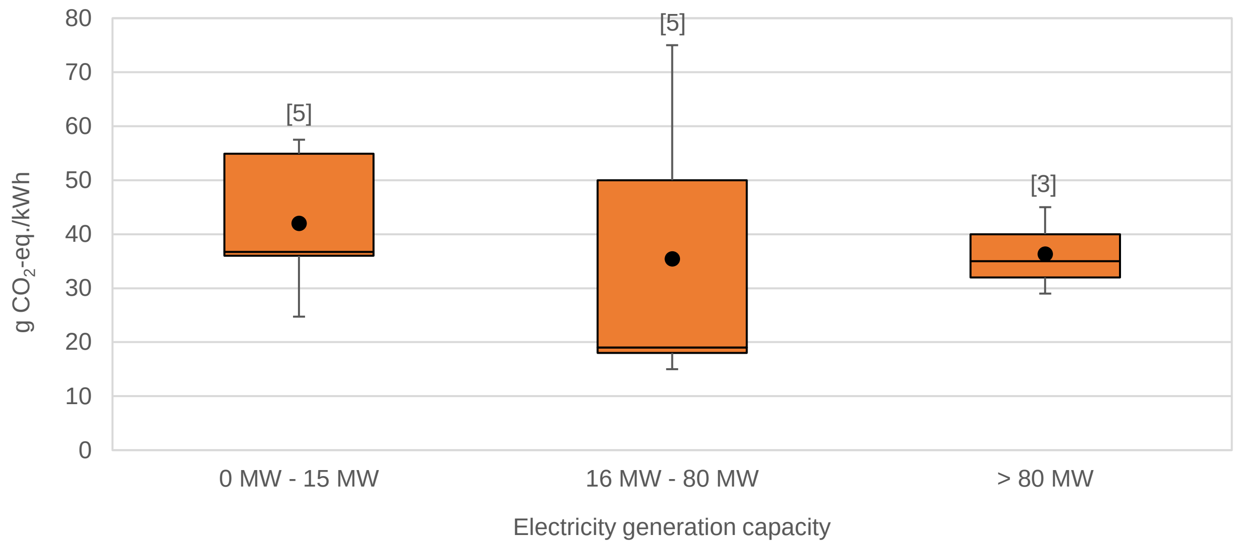


Figure 15 Summary of life cycle GHG emissions from geothermal power based on electricity generation capacity

As seen from the figure above, the plants with an electricity generation capacity between 16 and 80 MW present the minimum and maximum values towards GWP, 15.0 and 75.0 g CO_2-equivalent per kWh, respectively. Further, results show that the mean value presents a slightly decrease with increased electricity generation capacity.

The generation of electricity by means of geothermal power is done by using different technologies, including binary, flash-binary combined cycle, double-flash plant or single flash plant. However, over the last years, enhanced geothermal systems (EGS) have gained much attention as a promising application for geothermal energy. In this sense, Figure 16 presents the GHG emissions based on EGS and flash steam technologies.

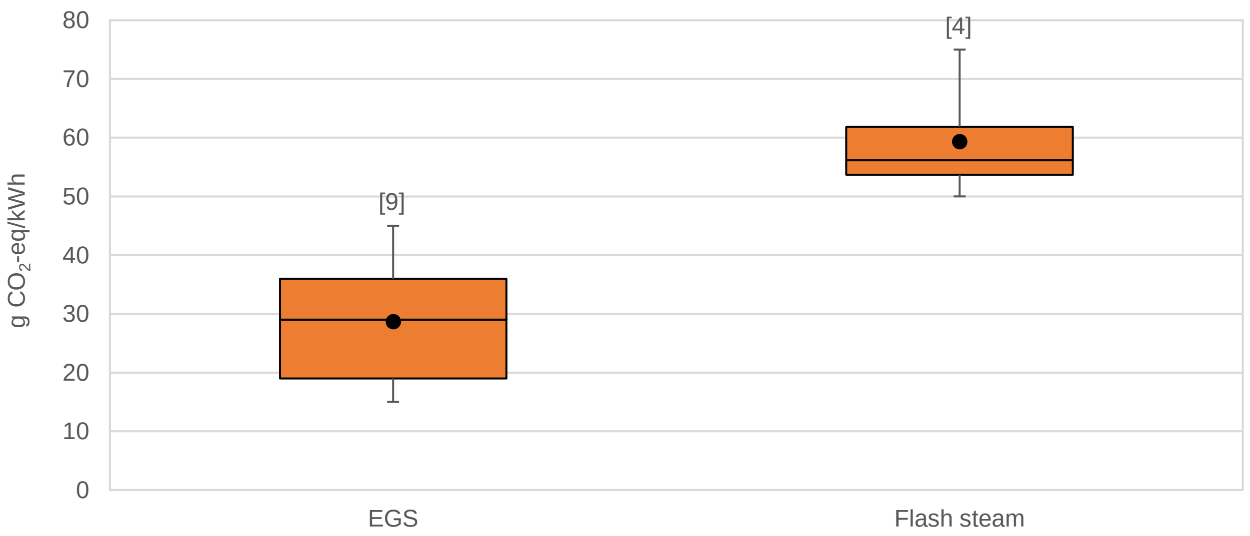


Figure 16 Summary of life cycle GHG emissions from geothermal power based on technology.

Figure 16 shows that flash steam technology presents a higher contribution to GHG emissions than EGS technology, with the first presenting mean value of 59.4 g CO_2-equivalent per kWh and the latter a value of 28.7 g CO_2-equivalent per kWh. For flash steam, the GHG emissions are ranging between 50.0 (78) and 75.0 (81) g CO_2-equivalent per kWh, while for EGS technology results are varying between 15.0 (17) and 45.0 (75) g CO_2-equivalent per kWh.

3.2 Non-renewable electricity generation

This Section presents a literature review of two different non-renewable sources of electricity generation, namely coal and natural gas. The selection of these two sources has been based on the Danish electricity production mix for 2017 which includes import and export over the year, see Figure 17.

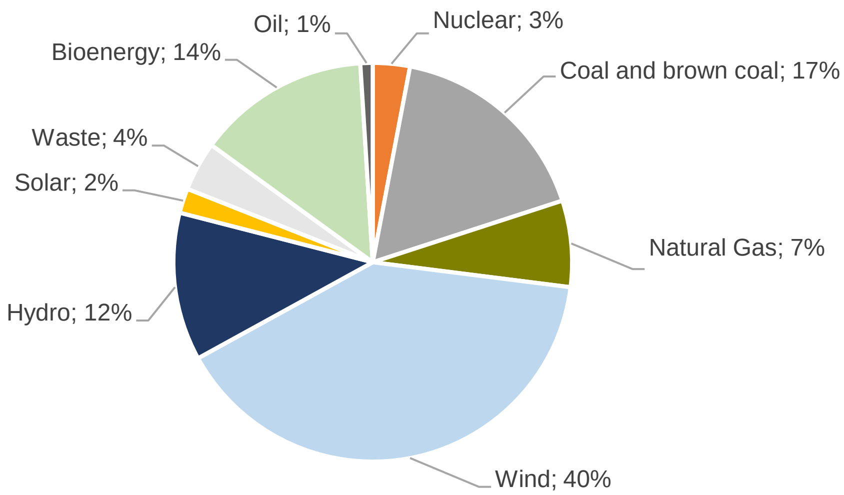


Figure 17 Average electricity production mix in Denmark in 2017. Adapted from Energinet (82)

According to Figure 17, coal and natural gas were the main sources of non-renewable grid-supplied electricity in Denmark in 2017. In this sense, the next Sections present the life cycle greenhouse gas emissions associated with the production of coal and natural gas.

3.2.1 Coal

Coal represents the largest non-renewable source of grid-supplied electricity in Denmark, as shown in Figure 17. In this sense, the GHG emissions from coal electricity generation over a life cycle perspective are presented in this Section. The results are based on 42 LCA studies (17,41,48,84–101), published between 2000 and 2010. The reference unit used corresponds to 1 kWh from coal.

The assessed studies typically follow a cradle-to-grave perspective, thus including upstream impacts from plant construction and material supply; operating phase impacts related to coal mining and processing, transport of coal to the power plant, coal combustion to generate electricity, and coal power plant operations and maintenance; and downstream impacts related to waste disposal, mine rehabilitation, and plant decommissioning. Further, most of the studies assessed the GHG emissions by using the IPCC emission factors. In addition, the assessed studies considered a device lifetime between 20 and 40 years, being the 30 years lifetime the mostly used.

Figure 18 shows the GHG emissions for the studied samples of coal power based on electricity generation capacity.

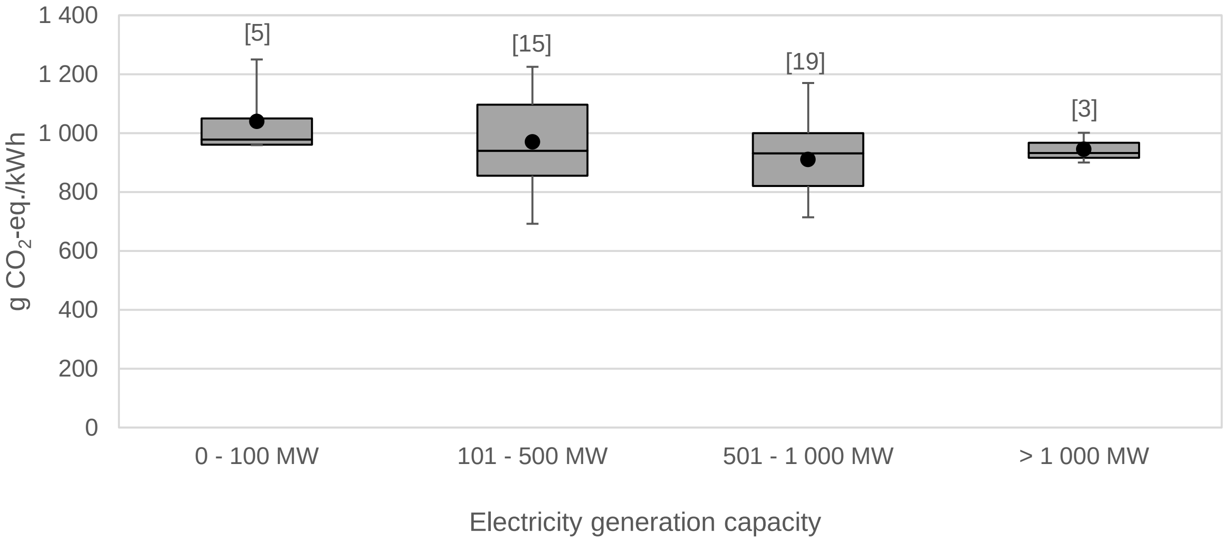


Figure 18 Summary of life cycle GHG emissions from coal power based on electricity generation capacity

As shown in Figure 18, the results range from 692 (99) to 1 250 (97) g CO_2-equivalent per kWh with the lower value representing a plant with 450 MW of electricity generation capacity and the highest value representing a plant with a capacity of 100 MW.

According to the literature review results, a significant number of studies assessing the environmental impacts of coal production over a life cycle perspective have been conducted with the aim to compare this source of energy to both renewable and non-renewable sources. However, a significant share of studies has been focused on comparing the impacts of different coal electricity generation technology options, including subcritical pulverized coal combustion (subcritical), integrated gasification combined cycle (IGCC), fluidized bed, and supercritical pulverized coal combustion (supercritical). In this sense, an overview of the GHG emissions associated with the described coal technologies is depicted in Figure 19.

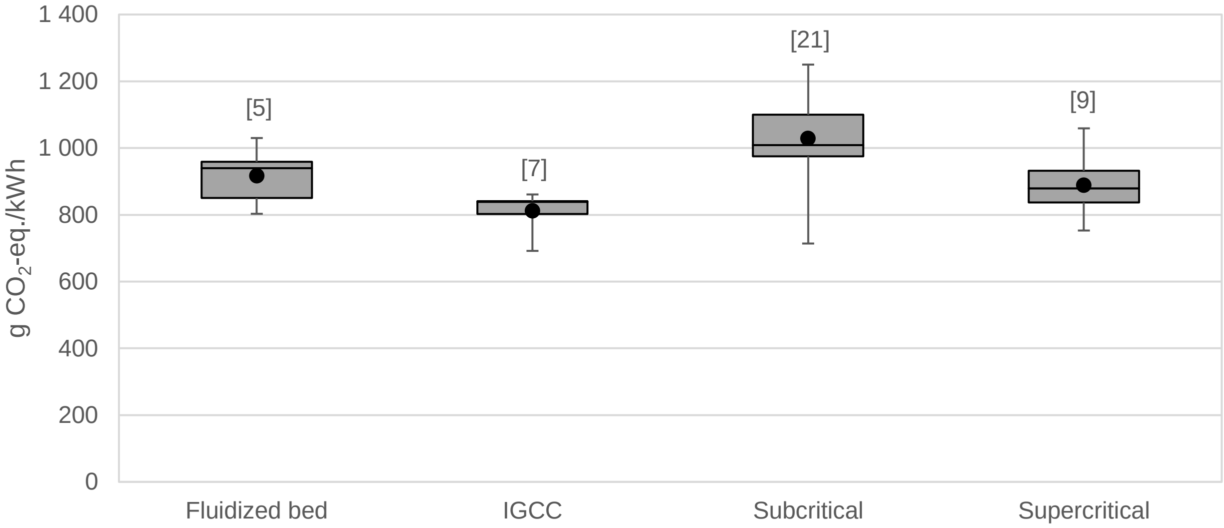


Figure 19 Summary of life cycle GHG emissions from coal power based on technology

As shown in Figure 19, subcritical technology presents in average a higher contribution to GHG emissions, with values ranging from 714 (41) to 1 250 (97) g CO_2-equivalent per kWh and a mean value of 1028 g CO_2-equivalent per kWh. On the other hand, IGCC technology presents the lowest contribution to GWP with values ranging from 692 (99) to 861 (100) g CO_2-equivalent per kWh. This is in line with previous findings (48,97,100), and shows that the GHG emissions from thermal power plants are most sensitive to the efficiency of the plant (hence technology options). This is reasonable as the operation phase (combustion of coal) contributes between 80 % and 90 % to the life cycle GHG emissions.

3.2.2 Natural Gas

To assess the life cycle GHG emissions of natural gas, the second largest non-renewable source of grid-supplied electricity in Denmark, 20 LCA studies, published between 2003 and 2013, were considered (17,41,66,87,97,99,100,102–112). The reference unit used corresponds to 1 kWh of natural gas.

The considered studies comprised a cradle-to-grave analysis, i.e. impacts related to the extraction of raw materials through combustion and to plant decommissioning were considered in the analysis. Further, most of the considered studies assessed the GHG emissions by using the IPCC emission factors. The assumed lifetime ranged between 15 and 30 years. It should also be noticed that the assessed studies only consider the natural gas electricity generation by means of a combined cycle technology.

Figure 20 shows a summary of the GHG emissions from the investigated LCAs of natural gas power categorised into electricity generation capacity. These are grouped into three categories depending on the plant electricity generation capacity.

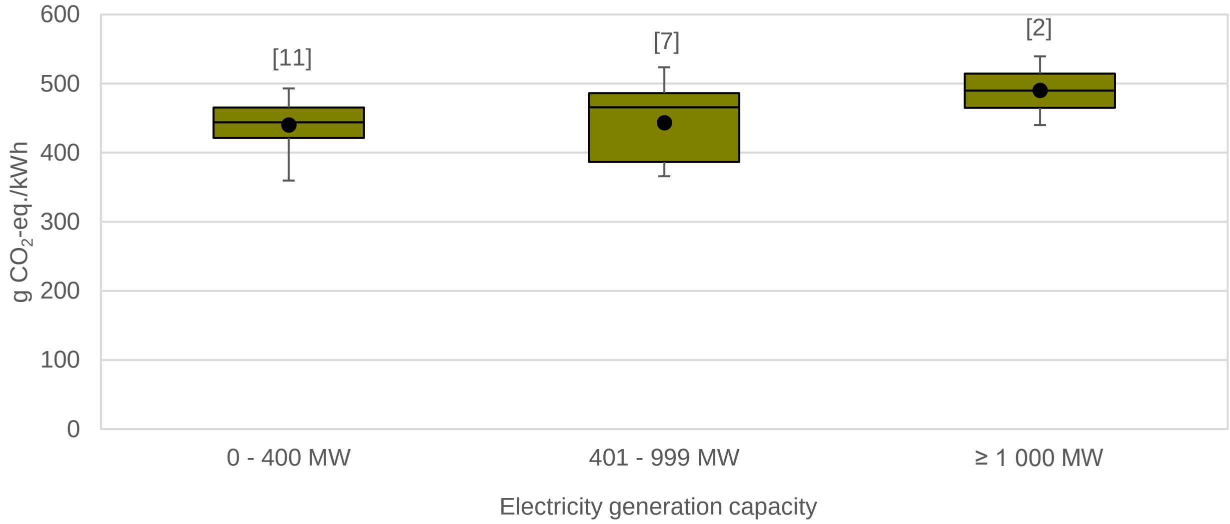


Figure 20 Summary of life cycle GHG emissions from natural gas power based on electricity generation capacity

The results depicted in Figure 20 show that it is hard to range the GHG emissions according to the capacity of the plants. This is reasonable as the operation phase (combustion of gas) is the activity that contributes most to the life cycle GHG emissions (approximately 80%). Hence, GHG emissions from thermal power plants are sensitive to the efficiency of the plant.

3.3 Results overview

This Section presents an overview of the impacts towards GWP for the considered electricity generation technologies. To summarize the main findings of this report, Figure 21 depicts the variation of results associated with the assessed technologies over a life cycle perspective. It should be noticed that hydropower pumped storage technology was excluded due to the high level of uncertainty associated with its impact, as previously referred in Section 3.1.4. The results are further depicted in Table 1 by presenting minimum, maximum, and mean values. In addition, results regarding the most contributing life cycle phase and its associated variation towards GWP are also presented. The results are shown in g CO_2-equivalent per kWh.

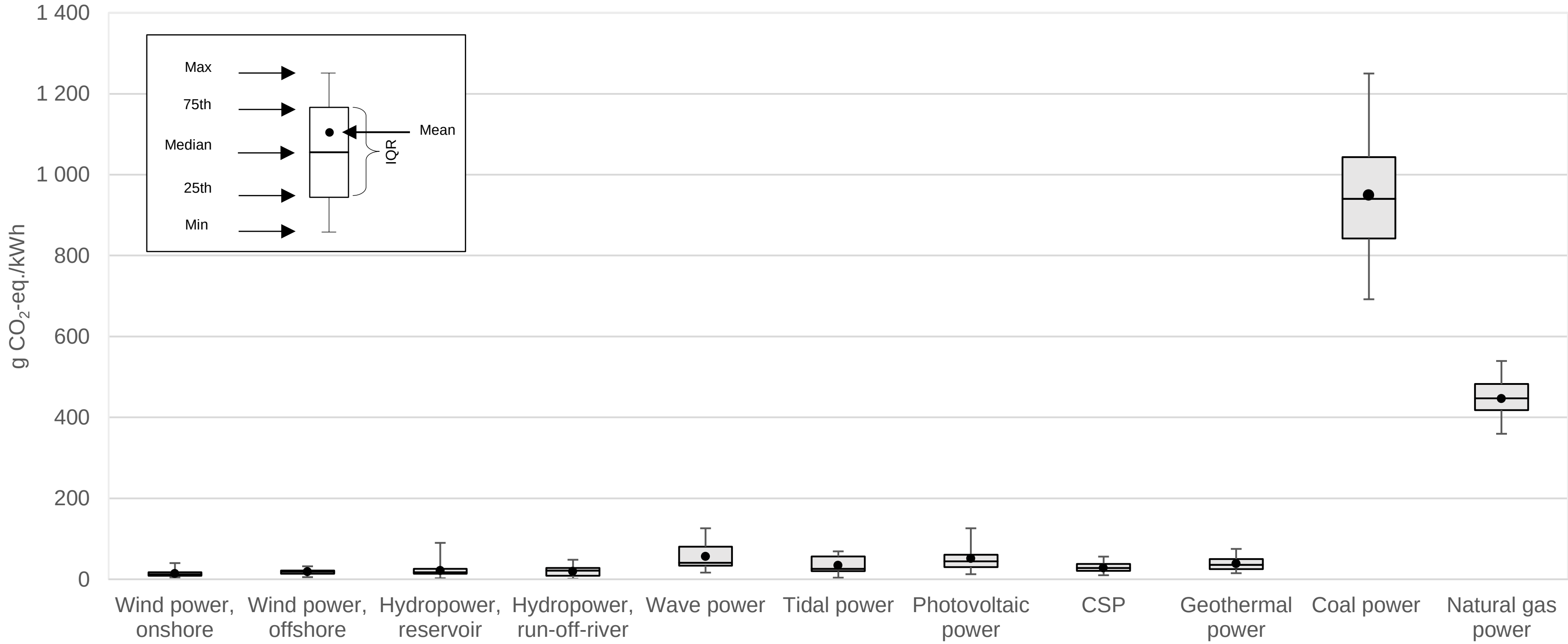


Figure 21 Summary of the GHG emissions for the considered electricity generation technologies

Figure 21 shows that among the reviewed renewable technologies, wave and photovoltaic power present in average the highest contribution to GHG emissions with 55.9 and 50.9 g CO_2-equivalent per kWh, respectively. The Figure also shows that the referred technologies present a high variation in results, with wave power presenting a contribution to GHG emissions between 16.5 and 126.0 g CO_2-equivalent per kWh, while photovoltaic power presents a contribution between 12.5 and 126.0 g CO_2-equivalent per kWh. On the other hand, wind power presents in average the lowest contribution to GHG emissions (14.4 g CO_2-equivalent per kWh for onshore locations and 18.4 g CO_2-equivalent per kWh for offshore locations), being closely followed by hydropower (21.4 g CO_2-equivalent per kWh for reservoir plants and 19.1 for run-of-river plants). It is also important to notice that both technologies present significant variations in results, with reservoir plants presenting a variation in GHG emissions from 2.4 to 90.0 g CO_2-equivalent per kWh, for example.
Nonetheless, it is important to notice that in comparison with the non-renewable technologies, the considered renewable technologies present a much lower impact towards GWP.

Table 1 Summary of findings

	Electricity generation technology				
Parameters	Wind power	Hydropower	Wave power	Tidal power	Photovoltaic power
Number of studies	54	94 (excluding pumped storage)	11	13	45
Variations in GHG emissions [g CO_2-eq./kWh]	4.6-40.0[a] 5.2-32.0[b]	2.4-90.0[c] 1.2-48.2[d]	16.5-126.0	3.9-69.0	12.5-126.0
Mean in GHG emissions [g CO_2-eq./kWh]	14.4[a] 18.4[b]	21.4[c] 19.1[d]	55.9	33.9	50.9
Most contributing life cycle phase	Infrastructure	Infrastructure	Infrastructure	Infrastructure	Infrastructure
Variations in contribution	85-99%	48-99%[c] 10-99%[d]	85-95%	97-99%	93-99%
Most contributing activity	Material production	Construction of dams and tunnels[c] Building construction and production of equipment[d]	Material production	Material production	Material production

[a] Onshore, wind power
[b] Offshore, wind power
[c] Reservoir, hydropower
[d] Run-of-river, hydropower

Table 2 Summary of findings (continued)

	Electricity generation technology			
Parameters	CSP	Geothermal power	Coal power	Natural gas power
Number of studies	29	13	42	20
Variations in GHG emissions [g CO_2-eq./kWh]	10.0-56.0	15.0-75.0	692.0-1 250.0	359.6-539.5
Mean in GHG emissions [g CO_2-eq./kWh]	27.9	38.1	948.9	446.1
Most contributing life cycle phase	Infrastructure	Infrastructure	Operation	Operation
Variations in contribution	59-70%	55-78%	80-90%	80-82%
Most contributing activity	Material production	Well drilling	Combustion	Combustion

4 Conclusion

The aim of this report is to assess the GHG emissions from both renewable and non-renewable electricity generation technologies over a life cycle perspective. This has been done by performing a literature review of LCA studies that assessed the GHG emissions of the considered electricity generation technologies.

According to this report findings, wave and photovoltaic power present the highest contribution to GHG emissions for the considered renewable electricity generation technologies, with an average value of 55.9 and 50.9 g CO_2-equivalent per kWh, respectively. Wind power, on the other hand, presents the lowest contribution to GHG emissions with an average contribution of 14.4 and 18.4 g CO_2-equivalent per kWh for onshore and offshore locations, respectively. Hydropower presents the second lowest contribution to GHG emissions with reservoir plants presenting an average contribution of 21.4 g CO_2-equivalent per kWh and run-of-river plants an average contribution of 19.1 g CO_2-equivalent per kWh. Nonetheless, in comparison with the non-renewable technologies, renewable technologies present much lower GHG emissions.

The results show that for renewable technologies, infrastructure is the most contributing life cycle phase to the total impacts towards GWP, with a contribution up to 99%, while from non-renewable technologies the operation phase is the most contributing one, with a contribution ranging from 80% to 90%.

The results also show that the GHG emissions might present significant variations within the same technology. As discussed throughout the report, such variations may be linked to differences according to “real variations”, such as local conditions (e.g. wind and solar conditions), national/regional energy mixes used for the manufacturing of materials, etc. However, the differences might be increased by varying methodological assumptions, such as data sources and degree of specific data used for the assessment, the assumed technologies’ lifetime, end-of-life assumptions, as well as the energy mixes considered for the production and assembly phases in the analysis.

When implementing renewable electricity technologies into the future smart energy systems, critical parameters for choosing technology according to GHG emissions, should be based on both local conditions (where the plant is assumed to be built) as well as impacts from production/building phase (infrastructure impact). This means that it is important to be aware about the origin of the raw materials (what is the relevant electricity mix used?), the transport of the raw materials to the assembling plant (what is the travelled distance?) and what is the type of transport used, including vehicle’s size class, category, capacity, type of fuel and its average consumption?), the location of the assembling plant (what are the energy requirements and their sources? How are the waste fractions handled and further treated?), what are the end-of-life options, etc. Furthermore, local parameters such as wind and sun conditions for the plants should be considered, as these are critical in order to utilize the installed electricity technology (and thus the already invested impacts) as much as possible.

Finally, it should be emphasised that this report assesses the considered technologies only from a greenhouse gas perspective which means that other environmental impact categories are not included.

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Appendix 1: Impact assessment methodologies

A description of the main characteristics of the impact assessment methodologies considered by the assessed studies may be found in Table 1 (1-3).

Table 1: Main characteristics of the different impact assessment methodologies

IPCC	All Life Cycle Impact Assessment (LCIA) methodologies have the Climate Change impact category, and they all use the Global Warming Potentials (GWPs) developed by the IPPC. However, there are some differences in the use of GWP's: • IPCC periodically publishes updates, and not all methodologies use the latest characterization factors (2013 IPCC version); • IPCC publishes GWP's for different timeframes. The 500-year perspective is considered sufficiently long to assess the majority of the damage caused by the substances with the long atmospheric residence times, while the 100- and 20-year timeframes capture partially the impact of substances with a long lifetime. In some circles, the 100-year timeframe is used as this is the basis adopted for the Kyoto Protocol. There is a wide consensus on the use of IPCC's GWP's for characterisation at midpoint level, being thus considered representative for all midpoint methods currently used in LCA. The total number of substances covered are 212.	
CML 2001	Purpose	Providing best practice for midpoint indicators operationalising the ISO14040 series of Standards.
	Midpoint/endpoint	Midpoint.
	Regional validity	Global for Climate Change impact category.
	Temporal validity	Present time.
	Time horizon	100 years for Climate Change impact category (GWP100).
	Number of substances covered	Approximately 800 substances, often with characterisation factors for more than one impact category, or more than one compartment within an impact category. Climate Change impact category: 183 substances.

Eco-Indicator 99	Purpose	Simplifying the interpretation and weighting of results. One of the intended applications was the calculation of single-point eco-indicator scores that can be used as a general purpose impact assessment method in LCA.
	Midpoint/endpoint	Endpoint method. Midpoints are not separated.
	Regional validity	Global for Climate Change impact category.
	Temporal validity	Present time.
	Time horizon	Short (approx. 100 year) for individualist perspective, long/indefinite for other perspectives.
	Number of substances covered	Approximately 391, depending on the perspective.
EDIP	Purpose	Supporting LCA of industrial products to support environmental analysis and synthesis in product development covering the three areas: Environment, resources and working environment.
	Midpoint/endpoint	Midpoint.
	Regional validity	Global for Climate Change impact category.
	Temporal validity	Present time.
	Time horizon	100 years for Climate Change impact category (GWP100).
	Number of substances covered	Approximately 500 substances, often with characterisation factors for more than one impact category, or more than one compartment within an impact category. Climate Change impact category: 96 substances.
Impact 2002+	Purpose	Providing combined midpoint/damage approach, linking all types of life cycle inventory results via 14

		midpoint categories to four damage categories: human health, ecosystem quality, climate change, and resources.
	Midpoint/endpoint	Midpoint and endpoint.
	Regional validity	Europe for the basic version. A multi-continental version of this model has been made available for the assessment of emission inventories taking place in all the continents.
	Temporal validity	Linear modelling independent of temporal constraints.
	Time horizon	500 years for Climate Change impact category (GWP500).
	Number of substances covered	Approximately 1500 substances, often with characterisation factors for more than one impact category, or more than one compartment within an impact category. Climate Change impact category: 83 substances.
ILCD	The ILCD 2011 Midpoint method was released by the European Commission, Joint Research Centre in 2012. It supports the correct use of the characterisation factors for impact assessment as recommended in the ILCD guidance document "Recommendations for Life Cycle Impact Assessment in the European context - based on existing environmental impact assessment models and factors" (2). Time horizon: 100 years for Climate Change impact category (GWP100). Number of substances covered: Climate Change impact category comprises 104 substances.	

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