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Review

Environmental Impact of Electricity Generation Technologies: A Comparison between Conventional, Nuclear, and Renewable Technologies

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Abstract: The transformation of the energy sector, based on the development of low-carbon technologies, is essential to achieve climate neutrality. The Life Cycle Assessment (LCA) is a powerful methodology for assessing the environmental impact of energy technologies, which proves to be a useful tool for policy makers. The paper is a review of the main LCA studies of power generation systems performed over the past ten years aiming at comparing the energy technologies to identify those with the lowest impact on the environment, evaluated in terms of gCO_{2eq}/kWh emissions. Screening criteria were established to include only studies of the highest qualitative significance. The authors decided to assign greater weight to emission values reported in more recent studies. For nuclear and renewable energy technologies, most of the emissions are related to the pre-operational phases. Notably, both nuclear and wind technologies, along with other renewable sources throughout their entire life cycle, exhibit significantly lower and less variable emissions compared with conventional gas- and coal-fired technologies.

Keywords: electricity generation technologies; LCA; environmental impact; nuclear energy; renewable energy; coal- and gas-fired plants

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1. Introduction

Globally, the energy sector is responsible for around three-quarters of current greenhouse gas (GHG) emissions and is the key to averting the worst effects of climate change [1,2]. The transformation of the energy sector is an essential aspect of achieving climate neutrality, mainly based on the deployment of low carbon technologies. This ongoing transformation towards renewables is not just a shift from one set of fuels to another but involves a much deeper transformation of the world's energy systems that will have major social, economic, and political consequences that go far beyond the energy sector.

On 4 November 2016, the Paris Agreement entered into force after being adopted by 196 Parties at the United Nations Framework Convention on Climate Change (UNFCCC) Conference (COP21) on 12 December 2015. The Paris Agreement's main objective is to hold "the increase in the global average temperature to well below 2 °C above pre-industrial levels"; the goal has been updated to 1.5 degrees Celsius (°C) recently [3]. This agreement requires all countries to submit Nationally Determined Contributions (NDCs) that set out their climate targets. As of September 2023, 94 countries and the European Union (EU) have legally committed to a net zero emissions target, and some countries have announced long-term strategies, although non-legally binding, to contribute to global climate neutrality [4]. This is clearly huge progress, although most of these commitments have not yet been followed by the adoption of short-term policies and measures [1]. Amongst advanced economies, the EU [5], the United States (USA) [6] and

Japan [7] have declared a commitment to become carbon neutral by 2050, while, within emerging markets, the People's Republic of China (hereinafter China) will do so by 2060 [8].

The electricity sector is expected to provide the main contribution to limiting global warming to no more than 1.5 °C [9]. In May 2021, the International Energy Agency (IEA) published its landmark report, "Net Zero by 2050: A Roadmap for the Global Energy Sector", highlighting that the electricity sector is projected to transition from being the highest-emitting sector in 2020 to becoming the first sector to achieve zero emissions by 2040 [1]. In September 2023, an update to the net zero roadmap was published by IEA [4]; although the pathway remains open it has been narrowed because global energy-related carbon dioxide emissions rose in 2022, reaching a new record of 37 gigatonnes CO_{2eq}, mainly due to the global energy crisis triggered by Russia's invasion of Ukraine. While advanced economies see an emission reduction of 4% compared to the 2019 value, for emerging markets and developing economies a 4.5% increase, with respect to the 2019 level, has been observed.

In 2022, fossil fuels still generated 60.94% of global electricity, resulting primarily from coal (35.72%) and gas (22.12%), while low carbon sources accounted for the resulting 39.06% (nuclear 9.15% and renewables 29.91%) [10]. Although demand for conventional fuels did not fall compared to 2019 levels, the last two years have also seen remarkable progress in developing and deploying some key clean energy technologies (solar photovoltaics, wind, heat pumps, and batteries). Nevertheless, much more remains to be done to align with the IEA net zero roadmap, which requires each country to strengthen its ambition and set policy packages for an effective deployment of clean energy technologies.

The Life Cycle Assessment (LCA), with its holistic approach to assess the potential impact throughout the life cycle of a system or product, is an effective methodology for assessing the environmental impact of energy technologies. The Life Cycle Assessment (LCA) is widely acknowledged as the most advanced methodology for acquiring verified and comparable information regarding the environmental performance of products, technologies, and services. This encompasses both qualitative and quantitative aspects across their entire life cycle, including raw material extraction, design and formulation, processing, manufacturing, packaging, distribution, utilization, re-use, recycling, and waste disposal.

LCA is a method for quantifying the environmental impacts of products, technologies, and services through their whole life cycle; in other words, "from cradle to grave". Enhancing comprehension of the environmental impacts during upstream and downstream phases is crucial for preventing the transfer of environmental burdens from one life cycle stage to another. It also serves to mitigate the likelihood of burden shifting from one country to another [11].

Lately, the significance of the Life Cycle Assessment (LCA) concept has grown within environmental policy, playing a pivotal role in fostering and facilitating the transition to a green economy. Outcomes derived from LCA can help decision-makers, enabling them to evaluate the multitude of environmental impacts associated with diverse energy options. This involves identifying both the advantages and disadvantages inherent in selecting from various alternatives. LCA includes four phases: definition of goal and scope, inventory analysis, impact assessment, and interpretation of results [12,13].

In the transition phase towards climate neutrality, the global energy mix must necessarily combine variable renewable energy technologies with other environmentally friendly technologies that can guarantee continuous energy production regardless of weather and climate conditions.

This paper is a comparative literature review of the main LCA studies of energy technologies (conventional and low carbon) performed over the past ten years, with the aim of highlighting the key points of these studies and providing useful suggestions for policy makers and/or stakeholders. In relation to the environmental impacts considered, the authors focused on equivalent grammes of carbon dioxide emissions for 1 kilowatt-hour of produced electricity (gCO_{2eq}/kWh).

The reviewed LCA studies (just like other studies previously carried out, including the one previously performed by some of the authors in 2010 [14]) have shown that nuclear, hydro, and wind (among renewables) are the technologies with the lowest greenhouse gas emissions, significantly lower than fossil fuels.

The purpose of the paper is to provide policymakers with a tool to quickly assess one of the parameters, such as carbon emissions throughout the life cycle, crucial in the evaluation of the energy technology mix for electricity generation to achieve the goal of zero emissions by 2050.

The most exhaustive and thorough investigations in this domain have been conducted by the UNECE (United Nations Economic Commission for Europe) and NREL (National Renewable Energy Laboratory). These studies utilized Life Cycle Assessment (LCA) to systematically compare the environmental impacts associated with various electricity generation technologies, encompassing fossil fuels, renewables, and nuclear sources.

UNECE underscores that renewable technologies consistently demonstrate significantly lower emission values, approximately an order of magnitude less than those associated with fossil technologies. This discrepancy is primarily attributed to factors such as infrastructure, capacity factor, and system lifetime. As a consequence, there are notable fluctuations in life cycle impacts influenced by variables like raw material origin, the energy mix utilized during production, and the manner of transportation during various phases of manufacturing and installation. Wind and solar technologies exhibit lower emission values compared to conventional plants, while nuclear and hydropower are also preferable over the life cycle when compared to fossil fuels. However, it is important to note that the low emission values linked to hydropower may be partially offset by the sedimentation of organic matter in reservoirs, leading to the release of biogenic greenhouse gases [15].

NREL conducted a comprehensive evaluation and standardization of numerous Life Cycle Assessments (LCAs) for electricity generation technologies. Greenhouse gas (GHG) emissions from renewable energy systems typically register lower values compared to those arising from technologies reliant on fossil fuels [16].

2. Methods

In the context of the current energy transition, modes of production (electricity and industry) may be affected by drastic changes. The energy technologies considered in this paper could show a completely different environmental profile by 2050. High differences in the environmental impacts are due to variations in raw materials origin, manufacturing, transportation, installation, and energy mix used.

The Life Cycle Assessment (LCA) methodology encompasses various methods, approaches, applications, and software packages. The inventory analysis and impact assessment phases involve several methodological decisions, including the definition of system boundaries (cradle-to-grave, cradle-to-gate, cradle-to-use, etc.), impact evaluation methods (midpoint and/or endpoint), and the selection of impact category indicators [17]. In some cases, comparison is not possible because authors choose different LCA methodologies, software, databases, system boundaries, and indicators.

This paper aims to review the main LCA studies on power generation systems published over the past ten years. The objective is to compare various energy technologies to pinpoint those with the least environmental impact.

Screening criteria were defined in order to select only the most qualitatively significant studies. Therefore, we excluded:

- studies which were not consistent with the requirements of ISO (International Organization for Standardization) standards 14040 [12] and 14044 [13];
- studies published before 2013;
- conference papers, posters and abstracts;
- papers that did not consider electricity as the final product;
- studies concerning only one phase of LCA.

In this paper, conventional and low carbon technologies were compared to identify energy technologies that can reduce global environmental impact in terms of gCO_{2eq}/kWh. Specifically, coal and natural gas power systems, hydropower, wind power (onshore and offshore), geothermal power, nuclear power, concentrated solar power (CSP), and photovoltaics (PV) were considered.

For each energy technology, carbon dioxide emission values are outlined from comparable studies, in terms of functional units, system boundary, and assumptions. For each study, the minimum and the maximum emission values or the average values for each energy technology have been considered.

The authors chose to attribute higher significance to emission values documented in more recently published studies, while assigning less weight to older studies, as delineated in Table 1. This decision was guided by the hypothesis that more recent published papers would reflect the utilization of more advanced and less impactful technologies. However, this hypothesis was not substantiated by the obtained results, likely due to two primary reasons: firstly, because even more recent studies may reference outdated research, and secondly, because emission levels vary significantly depending on the location where the energy plant is built. The operational site is a significant factor for all technologies. The diverse electricity mixes and industrial process efficiencies across different global regions impact the environmental outcomes of all systems, as energy inputs constitute a major contributor to infrastructure production [15].

Table 1. Weight given to the reviewed studies.

Year of the Study	Weight
2013–2016	0.8
2017–2019	1.0
2020–2022	1.2

When available, the data concerning the location of the examined generation plant have been included in the summary tables for various electricity generation technologies.

The mean values for each technology were calculated according to the Formula (1):

$$\frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i} = \overline{x} \quad (1)$$

where $\overline{x}$ are the mean values, x_i the value for each energy system and w_i the weights shown in Table 1.

2.1. LCA of Conventional Systems

As of December 2022, electricity generated by coal-fired power plants worldwide was 10,191 TWh (35.72% of the total) [10] and contributed about 20% of total greenhouse gas emissions, while gas power plants generated 6309 TWh (22.12% of the total) [10] and contributed about 7% of total greenhouse gas emissions [18,19].

The United Nations Economic Commission for Europe (UNECE) compares, through LCA methodology, the potential environmental impacts of the different electricity generation technologies, coal and natural gas, with and without carbon capture and storage (CCS); wind power, onshore and offshore; polycrystalline and thin-film photovoltaics; concentrated solar power; hydropower; and nuclear power [15].

Regarding coal-fired power plants, with or without CCS, the study considers:

- subcritical "pulverized coal" (PC) thermal power plants, which use finely ground coal for combustion;
- supercritical power plants, based on PC technologies, but at much higher pressures and temperatures;
- the integrated gasification combined cycle (IGCC), which relies on converting coal into a synthetic gas before combustion.

Coal-fired plants highlight the highest scores, with a minimum of 751 gCO_{2eq}/kWh (IGCC, USA) and a maximum of 1095 gCO_{2eq}/kWh (pulverized coal, China). Equipped with a carbon dioxide capture facility, and accounting for the CO_2 storage, these values decrease to 147–469 gCO_{2eq}/kWh, respectively [15].

In Europe, the CO_{2eq} emissions related to 1 kWh of coal power generation, also considering the extraction phase, is 1023 gCO_{2eq}/kWh. If carbon capture and storage processes (CCS) are included, the value of CO_2eq emitted per kWh of coal power production is 369 g (−64%). European IGCC plants, which are more efficient than the former, have a lower value of greenhouse gas emissions, at 849 gCO_{2eq}/kW (279 gCO_{2eq}/kWh if the same includes CCS). Greenhouse gas emissions are almost exclusively attributed to the extraction of coal and the operation of the plant [15].

As for natural gas-fired power plants, the main technology used today is the natural gas combined cycle (NGCC), which uses the coupling of a gas turbine and a steam turbine to maximize the overall efficiency of the system.

A natural gas combined cycle plant can emit 403–513 gCO_{2eq}/kWh from a life cycle perspective, and anywhere between 49 and 220 gCO_{2eq}/kWh with CCS.

In 2020, CO_2 eq emissions related to 1 kWh of electricity generation from natural gas, in Europe, were 434 and 128 gCO_{2eq}/kWh, without and with CCS, respectively.

The operational phase is the one that contributes most significantly to the CO_2 emissions (more than 80%).

Both coal and natural gas models include methane leakage at the extraction and transportation (for gas) phases; nonetheless, direct combustion dominates the life cycle GHG emissions.

The National Renewable Energy Laboratory (NREL) published original results from the Life Cycle Assessment Harmonization Project and updated estimates of electricity generation GHG emissions factors [16]. NREL reviewed hundreds of LCA studies, concluding that renewable technologies emit less GHG than fossil fuel-based technologies.

For coal-fired plants, the median value was 1001 gCO_{2eq}/kWh, with estimates between 675 to 1689 gCO_{2eq}/kWh, while for electricity generated from gas-fired combustion turbine systems the median was 486 gCO_{2eq}/kWh, with a minimum at 307 and a maximum at 988 gCO_{2eq}/kWh [16].

Asdrubali et al. [20] reviewed about 50 papers related to electricity production from renewable energies. The paper showed that renewable technologies have considerable environmental advantages over conventional technologies. A natural gas-fired combined cycle plant shows emissions in the range of 350–410 gCO_{2eq}/kWh, while for a single cycle plant the range is between 480 and 730 gCO_{2eq}/kWh. A coal-fired plant with direct combustion has an emission range of 750–1050 gCO_{2eq}/kWh, higher than IGCC plants (660–800 gCO_{2eq}/kWh) [21], while all renewable technologies show values below 100 gCO_{2eq}/kWh.

Li et al. [22] compared wind and coal power in China. The paper finds that CO_2 emissions produced by coal-fired plants are 775.86 gCO_{2eq}/kWh (97% of which originated from the operation and maintenance phase), significantly higher than those produced by a wind power plant (31.36 gCO_{2eq}/kWh).

Agrawal et al. [23] used LCA for assessing GHG emissions for a natural gas combined cycle (NGCC) thermal power plant and a coal thermal power plant in India. The total GHG emissions from the NGCC thermal power plant was 584 gCO_{2eq}/kWh, whereas for coal-fired power plant, it was 1127 gCO_{2eq}/kWh.

Akber et al. [24] analysed the electricity sector in Pakistan, adopting an integrated approach of life cycle assessment. They evaluated all operational generation sources from a sustainable development perspective in order to optimize the future energy mix. The findings of the study can be summarized in the following values for coal-fired and gas-fired plants, respectively: 790.11 gCO_{2eq}/kWh and 531 gCO_{2eq}/kWh.

Rasheed et al. [25] analysed the life cycle impacts of a recent coal-fired power plant located in Pakistan, based on a "gate to gate" approach. The climate change potential of the plant was found to be 741 gCO_{2eq}/kWh. The power generation phase accounts for 84% of the overall CO_2 emissions.

Šerešová et al. [26] assessed the environmental impacts of both non-renewable and renewable source in the Czech Republic, based on their entire life cycle (construction, renovation, operation and decommissioning phases). The highest impact on the climate change category was found for coal-fired plants (1004 gCO_{2eq}/kWh), while for gas-fired plants the value was less than half (440 gCO_{2eq}/kWh). Almost all the impacts associated with fossil fuels are linked to the operational phase.

Malode et al. [27] reviewed LCA studies for India's coal-fired power plants. Emission values lie within the range 898–1129 gCO_{2eq}/kWh. The study concludes that in the "climate change" category renewables and nuclear sources have significantly lower impacts.

The following tables summarize the results of the analysed studies. Specifically, Table 2 summarizes greenhouse gas emissions (in gCO_{2eq}/kWh) for coal-fired and gas-fired plants found in the published works and Table 3 shows the mean values for conventional systems calculated, taking into account the weight given according to the year of the study, as indicated in Table 1.

Table 2. List of LCA results found in the literature for coal-fired plants.

Published Works	Year of the Study	Plant Type	gCO_2eq/kWh
UNECE [15]	2021	IGCC (USA); pulverized coal (China) IGCC with CCS (USA); pulverized coal with CCS (China) IGCC (Europe); pulverized coal (Europe) IGCC with CCS; pulverized coal with CCS Natural gas combined cycle (NGCC) Natural gas combined cycle with CCS	751–1095 147–469 849–1023 279–369 403–513 49–220
NREL [16]	2021	Coal-fired Gas-fired combustion turbine	675–1689 307–988
Asdrubali et al. [20]	2015	Gas-fired combined cycle Gas-fired single cycle Coal-fired with direct combustion IGCC	350–410 480–730 750–1050 660–800
Li et al. [22]	2020	Coal-fired (China)	775.86 (mean)
Agrawal et al. [23]	2014	NGCC (India) Coal-fired (India)	584 (mean) 1127 (mean)
Akber et al. [24]	2017	Coal-fired (Pakistan) Gas-fired (Pakistan)	790.11 (mean) 531 (mean)
Rasheed et al. [25]	2021	Coal-fired (Pakistan)	741 (mean)
Šerešová et al. [26]	2020	Coal-fired (Czech Republic) Gas-fired (Czech Republic)	1004 (mean) 440 (mean)
Malode et al. [27]	2020	Coal-fired (India)	898–1129

Table 3. CO_2 equivalent emissions related to 1 kWh for several conventional systems weighted according to the year of the study.

Plant Type	Weighted Mean of the Minimum Values	Weighted Mean of the Mean Values	Weighted Mean of the Maximum Values
Coal-fired	753.9		1215.4
Coal-fired with CCS	379.0	899.8	678.3
Gas-fired		316.0	
Gas-fired with CCS	49.0		220.0

Table 3 shows that emissions from gas-fired plants are about half of those from coal-fired plants. Emissions from coal-fired plants with CCS are 65% lower than those from coal-fired plants without CCS (316.0 versus 899.8 gCO_{2eq}/kWh), whereas gas-fired plants with CCS show 87% lower emissions for minimum values (49 versus 379.0 gCO_{2eq}/kWh) and 68% lower emissions for maximum values than gas-fired plants without CCS (220.0 versus 678.3 gCO_{2eq}/kWh).

2.2. LCA of Renewable Energy Systems

As of 31 December 2022, according to the International Renewable Energy Agency (IRENA), worldwide renewable generation capacity was 3372 GW, accounting for 40% of global installed power capacity [28]. Hydropower still accounts for the largest renewable power source in terms of installed capacity, followed by solar and wind. In 2022, the global installed capacity of hydropower (excluding pumped hydro) achieved a milestone of 1256 GW, constituting 37% of the total capacity derived from renewable sources. Solar reached 1053 GW (almost entirely PV for 1047 GW, with a very small part being CSP—6.5 GW), representing 31% of total renewable capacity. Wind accounted for 27% of total renewable capacity, with a total installed capacity of 899 GW. The rest of the renewable capacity includes 149 GW of bioenergy, 15 GW of geothermal, and 524 MW of marine energy.

UNECE is the most comprehensive and up-to-date source of data, since it covers almost all energy technologies and dates back to 2022. In 2022, the organization published a report [29] aimed to evaluate the life cycle environmental impacts of energy technologies for power generation. The report highlights that renewable technologies exhibit substantially lower emission values by about an order of magnitude than fossil technologies, to be attributed mainly to infrastructure, capacity factor, and system lifetime. This leads to considerable variations in life cycle impacts due to raw material origin, energy mix used for production, the mode of their transport during various phases of manufacturing and installation, etc. Wind and solar show lower emission values than conventional plants; nuclear and hydropower technologies are also deemed more advantageous than fossil fuels over the entire life cycle. However, low emission values associated with hydropower can be partially counterbalanced by the sedimentation of organic matter in the reservoirs, resulting in the release of biogenic greenhouse gases.

The National Renewable Energy Laboratory (NREL) assessed and harmonized hundreds of LCAs of electricity generation technologies. GHG emissions from renewable energy systems are usually lower than those from fossil fuel-based technologies [16].

Asdrubali et al. [20] reviewed about 50 papers related to electricity generation from renewable energy sources. The paper showed that renewable technologies have considerable environmental advantages over conventional technologies (emission values below 100 gCO_{2eq}/kWh).

Motuziene et al. [30] issued a review of life cycle analysis results for hydropower, wind, geothermal, and solar PV energy conversion technologies. Hydropower plants, besides accounting for the largest share of renewable energy production in the world, have a lower global warming potential (GWP) than other renewable sources.

2.2.1. Hydropower

Globally, hydropower is the largest renewable technology in terms of installed capacity, with 1256 GW (37%) [28]. Run-of-river hydropower plants are characterized by smaller size and capacity, while a hydropower plant with a reservoir provides more energy and can potentially store energy by pumping water from a lower reservoir to a higher one.

UNECE [29] reports that hydropower shows significant variability, as emissions exhibit significant site-specific characteristics, ranging from 6 to 147 gCO_{2eq}/kWh. The report also performed a LCA study for a 360 MW reservoir plant located in Europe with an associated GHG emission mean value of 10.7 gCO_{2eq}/kWh. The main GHG emissions are from transportation during construction (more than 80%), followed by materials of the dams and turbines. However, it should be noted that biogenic emissions from sediment accumulating in reservoirs can be very relevant in tropical areas.

Motuziene et al. [30] found high values in hydropower systems with high dams and large reservoirs (152–237 gCO_{2eq}/kWh) because the dams were built using huge amounts of concrete and steel and thus emissions. Run-of--river plants show very low values of GHG emissions (2.06–13 $gCO_{2eq/}$kWh) because of their much smaller dam heights, reservoir sizes, and flooded land areas. The paper also highlighted intermediate values in a couple of cases (both run-of-river). The first one was a 3-kW hydroelectric plant in Thailand (52.7 gCO_{2eq}/kWh) and the second one refers to five large-scale plants (120–790 MW) in Myanmar showing GHG values in the range 31.17–39.23 gCO_{2eq}/kWh.

Ding et al. [31] analysed the top five energy technologies for electricity generation in China: thermal, nuclear, hydro, wind, and solar photovoltaics. For hydropower, they found the GWP value of 15.68 gCO_{2eq}/kWh.

Asdrubali et al. [20] examined eleven case studies including reservoir and run-of-river plants. GWP values were in the range 2.2–74.8 gCO_{2eq}/kWh. After the harmonization procedure, the GWP median value was 11.6 gCO_{2eq}/kWh.

Hertwich [32] assessed emissions from the degradation of biogenic carbon in hydropower reservoirs and, after a literature review, estimated life cycle average GHG emissions to be 85 gCO_{2eq}/kWh.

Veran-Leigh and Vazquez-Rowe D. [33] performed a LCA of three recently built hydropower plants located in the Peruvian Andes. All three plants are of the run-of-river type, with capacities of 172, 220, and 18.4 MW, respectively. GHG emissions were found in the range 2.06–2.42 gCO_{2eq}/kWh.

Briones Hidrovo et al. [34] carried out an analysis of environmental performance of dam and run-of-river hydropower plants situated in Ecuador, through the LCA combined with reservoir GHG emissions approach. The run-of-river plants showed better environmental performance than the dam ones. Very high values were found for GHG emissions from dam plants (547 gCO_{2eq}/kWh), mainly ascribed to the reservoir, while the run-of-river plants recorded much lower values of 2.6 gCO_{2eq}/kWh.

Mahmud et al. [35] compared the environmental impact of hydropower plants in alpine and non-alpine regions of Europe using LCA. The functional unit chosen was 1 MJ of produced energy. The results of the analysis highlighted that reservoir hydropower plants in alpine regions showed significantly lower GWP values (0.107 gCO_{2eq}/kWh) than non-alpine plants (1.41 gCO_{2eq}/kWh). The values have been converted by the authors to make them consistent with the functional unit commonly chosen in all other studies.

Wang et al. [36] evaluated and compared the environmental impacts of three technologies (hydro, nuclear, and wind) in China using LCA. As far as concerns hydropower, a 252 MW pumped storage plant has been considered (dam on river with reservoir, https://globalenergyobservatory.org/geoid/44147, accessed on 27 October 2023). They found a value of 3.4 $\pm$ 0.3 gCO_{2eq}/kWh for GWP, lower than the other two energy sources, about 90% arising from the manufacturing phase.

Li et al. [37] studied the carbon footprint of the second and the third largest hydropower plants in China. GHG emissions of the two plants are 7.60 $\pm$ 1.09 gCO_{2eq}/kWh and 9.12 $\pm$ 1.36 gCO_{2eq}/kWh, respectively. GHG emissions during the dam decommissioning phase constituted a significant portion (around 50%) of the overall life cycle GHG emissions. This was closely followed by emissions during the construction phase, constituting over 25% of global emissions. NREL evaluated and harmonized hundreds of LCAs of electricity generation technologies [16]. GHG emissions from hydropower plants are significantly lower than fossil fuel plants and rather like other renewable energy sources. The median value of GHG emissions found for hydropower was 21 gCO_{2eq}/kWh; specifically, 13 gCO_{2eq}/kWh for reservoir and 23 gCO_{2eq}/kWh for run-of-river plants.

Paulillo et al. [38] studied the environmental impact of geothermal energy with LCA. A comparison was then made with photovoltaics and hydropower. For the latter, the median value of 24 gCO_{2eq}/kWh was found.

Akber et al. [24] evaluated the sustainability of all electricity generation sources in Pakistan in order to optimize the future energy mix. Hydropower is found as the most sustainable option, showing the lowest environmental impact. The values found for GWP are 8.78 and 12.83 gCO_{2eq}/kWh for run-of-river and reservoir, respectively.

Šerešová et al. [26] assessed the environmental impacts of several energy sources in the Czech Republic, based on their entire life cycle. The renewable sources examined were wind, photovoltaics, and hydro. Regarding the latter, the authors assessed many case studies, covering different types of plants. Their environmental impact on the climate change category was on average equal to 22 gCO_{2eq}/kWh. The utilization of electricity from the grid during the operational period constitutes the predominant contribution to the climate change category, accounting for approximately 80%, while the construction phase accounts for 20%. The impact of the decommissioning phase is marginal because it was assumed that only the technological components of the power plant would be dismantled, while the water-related elements would be preserved to maintain flow regulation.

Table 4 summarizes the results of the analysed studies for hydropower.

Table 4. List of LCA results found in the literature for hydropower plants.

Published Works	Year of the Study	Plant Type	gCO_2eq/kWh
UNECE [29]	2022	Reservoir Reservoir (Europe)	6–147 10.7 (mean)
Motuziene et al. [30]	2022	Reservoir Run-of-river Run-of-river (Thailand) Run-of-river (Myanmar)	152–237 2.06–13 52.7 (mean) 31.17–39.23
Ding et al. [31]	2019	Not specified (China)	15.68 (mean)
Asdrubali et al. [20]	2015	Reservoir and run-of-river	2.2–74.8 11.6 (mean)
Hertwich [32]	2013	Reservoir	85 (mean)
Veran-Leigh and Vazquez-Rowe D. [33]	2019	Run-of-river (Peruvian Andes)	2.06–2.42
Briones Hidrovo et al. [34]	2017	Reservoir (Ecuador) Run-of-river (Ecuador)	547 (mean) 2.6 (mean)
Mahmud et al. [35]	2019	Reservoir (Europe)	0.107–1.41
Wang et al. [36]	2019	Reservoir (China)	3.1–3.7
Li et al. [37]	2017	Reservoir (China)	6.51–10.48
NREL [16]	2021	Reservoir Run-of-river	13 (mean) 23 (mean)
Paulillo et al. [38]	2019	Not specified	24 (mean)
Akber et al. [24]	2017	Reservoir (Pakistan) Run-of-river (Pakistan)	12.83 (mean) 8.78 (mean)
Šerešová et al. [26]	2020	Not specified (Czech Republic)	22 (mean)

Table 5 shows that emissions from reservoirs are much higher than the run-of-river plants due to greater biogenic GHG emissions.

Table 5. CO_2 equivalent emissions related to 1 kWh for hydropower plants weighted according to the year of the study.

Plant Type	Weighted Mean of the Minimum Values	Weighted Mean of the Mean Values	Weighted Mean of the Maximum Values
Reservoir	31.1	126.2 ° (26.0)	74.4
Run-of-river	12.3	23.2	19.2
Not specified	2.2	18.8	74.8

° This higher value comes from the high value for reservoirs in Ecuador found in the paper of Briones-Hidrovo et al. [34]. Excluding this value, the weighted mean would be 26.0.

2.2.2. Wind

At the end of 2022, onshore wind was the third largest source of renewable electricity after hydropower and solar photovoltaics, with 835.6 GW of installed capacity. Onshore wind power holds a dominant position in the wind market (93%), while offshore wind power accounted for a global capacity of only 63.2 GW (7%) [28].

According to UNECE, in Europe in 2020 mean emission values were 12.4 and 14.2 gCO_{2eq}/kWh for onshore and offshore plants, respectively. These values were obtained by performing a LCA on updated life cycle inventories of wind technology [29].

Wang et al. [36] evaluated and compared the environmental impacts of three technologies (hydro, nuclear, and wind) in China using LCA. As far as concerns wind power, the study selected a wind power project sited in Inner Mongolia (an onshore plant) as the reference case study. The plant has a capacity of 49.5 MW. This plant produces 28.6 ± 3.2 gCO_{2eq}/kWh for GWP throughout its life cycle, approximately 65% arising from the manufacturing stage.

Alsaleh and Sattler [39] carried out a complete LCA for large onshore wind power plants in the USA. They found a mean GWP of 18 gCO_{2eq}/kWh, more than 80% attributable to raw material acquisition and manufacturing phases.

Xu et al. [40] used simplified LCA models to assess the GHG emissions from onshore wind power plants in China. They found a GHG mean value of 19.88 gCO_{2eq}/kWh, with all values in the range 13.59–34.50 gCO_{2eq}/kWh. The geographical position stands out as a predominant factor influencing GHG emission values.

Teffera et al. [41] evaluated the environmental impacts associated with wind power systems in Ethiopia. The functional unit chosen in this study is the generation of 1 kWh of average electricity from all three wind plants connected to the national grid system. The average GHG emission intensity of the three wind power systems was 33.6 gCO_{2eq}/kWh. The pre-operational phases account for approximately 88% of the total CO_2 emissions.

Bonou et al. [42] assessed the environmental impact of four wind power plants in Europe: two onshore (2.3 and 3.2 MW turbine) and two offshore (4 and 6 GW turbine). The GHG emissions were less than 7 gCO_{2eq}/kWh for onshore and 11 gCO_{2eq}/kWh for offshore power plants. The majority of impacts stem from the extraction and production of materials, with this phase contributing more than 79% and 70% to the CO_2 emissions from onshore and offshore power plants, respectively.

Kadiyala et al. [43] reviewed 29 LCA studies on wind power plants. The mean life cycle GHG emissions for onshore plants were: 38.67 gCO_{2eq}/kWh (horizontal axis onshore turbine–small capacity), 11.75 gCO_{2eq}/kWh (horizontal axis onshore turbine–intermediate capacity), 15.98 gCO_{2eq}/kWh (horizontal axis onshore turbine–large capacity), and 46.4 gCO_{2eq}/kWh (vertical axis onshore turbine–small capacity). The mean life cycle GHG emissions for offshore plants were 12.9 gCO_{2eq}/kWh (horizontal axis offshore turbine–small capacity). The horizontal axis onshore turbine–intermediate capacity showed the minimum GHG emission value.

Asdrubali et al. [20] examined 20 case studies regarding wind power. All the wind power plants were comparable in size, with a minimum capacity value of 0.25 MW and a maximum of 6 MW. GWP values were found between 6.2 and 46 gCO_{2eq}/kWh, almost all referring to onshore plants. After the harmonization procedure, the GWP median value was 9.4 gCO_{2eq}/kWh. The construction phase was the biggest contributor to the overall GHG value.

Li et al. [44] performed a LCA on an onshore 40 MW wind plant. The GHG emissions intensity was found to be 16.4–28.2 gCO_{2eq}/kWh.

Li et al. [22] used a LCA to compare emissions from wind and coal power plants. As far as regards wind energy, a wind farm consisting of 33 1.5 MW wind turbines (for an installed capacity of 49.5 MW) is the case study under examination. The emissions from wind turbines were found to be 31.36 gCO_{2eq}/kWh, 91% of which originated from the pre-operational phases.

Khoie et al. [45] studied the carbon intensity of a 1.3 MW wind turbine situated in Texas (USA). The carbon emission intensity of this turbine was 14.45 gCO_{2eq}/kWh. The transportation phase was the third contributor to the total CO_2 emissions (16%), after the manufacturing phase (41%) and raw materials (38%).

Vélez-Henao et al. [46] carried out a LCA of an onshore 19.5 MW wind power plant to assess its environmental performance. The wind power plant showed a low GWP value (12.93 gCO_{2eq}/kWh), even lower than other analogous studies, probably due to the high wind speed considered in this study and to the high-capacity factor of the wind plant (42%).

Xie et al. [47] assessed the environmental impact of three wind power plants during their entire life cycle by using LCA. Their total electricity generation was 455.8 GWh. The results showed that the average CO_{2eq} emission factor was 3.9 g/kWh, 60% of which originated from the pre-operational phases.

Nugent and Sovacool [48] analysed 41 LCA studies about solar PV and wind energy. As regards wind energy, 22 studies were taken into account, most of which refer to onshore plants. They found an extremely low value of 0.4 gCO_{2eq}/kWh and a high value of 364.8 gCO_{2eq}/kWh. The study reported a mean value of 34.11 gCO_{2eq}/kWh, 95% of which originated from the pre-operational phases. This also occurs because of the assumption of a negative value for CO_2 emissions during the decommissioning phase in this study, wherein recycling is considered as a strategy to mitigate future greenhouse gas production.

NREL evaluated and harmonized hundreds of LCAs of electricity generation technologies [16]. GHG emissions from wind power plants are much lower than fossil fuel plants and comparable to other renewable energy sources. The median values of GHG emissions found were 12 gCO_{2eq}/kWh for onshore plants and 19 gCO_{2eq}/kWh for offshore plants.

Basosi et al. [49] used a LCA to compare the environmental performances of three Italian renewable power plants: geothermal, solar PV, and wind. The three power plants have comparable capacity (about 20 MW). The onshore wind power plant is composed of nine wind turbines, each with a capacity of 2 MW, and had a full-load operability of 2337 h/year in the period 2016–2018. GWP for the wind power plant was estimated at 13.4 gCO_{2eq}/kWh.

Paulillo et al. [38] studied the environmental impact of geothermal energy with LCA, but also compared it with the environmental impact of other renewable energy sources. For onshore wind power plants, the median GWP value considered in the paper was 11 gCO_{2eq}/kWh.

Šerešová et al. [26] assessed the life cycle performances of different energy sources in the Czech Republic, based on their entire life cycle. Renewable sources examined were wind, solar (PV) and hydro. Regarding wind power, the authors assessed two case studies, one older and one newer. Their environmental impact on the climate change category was on average equal to 19 gCO_{2eq}/kWh, more than 80% attributable to the construction phase.

Akber et al. [24] evaluated the sustainability of all electricity generation sources in Pakistan in order to optimize the future energy mix. The GWP value found for wind power was 11.38 gCO_{2eq}/kWh.

Brussa et al. [50] carried out a LCA of an around 3 GW project for a floating offshore wind farm, composed of 190 wind turbines (15 MW size) for almost 3 GW of installed capacity, which will be placed about 60 km off the west coast of Sicily in the Mediterranean

Sea. LCA showed for this project a GWP value of 31.3 gCO_{2eq}/kWh, more than 75% arising from the pre-operational phases.

Garcia-Teruel et al. [51] performed a LCA to assess the environmental impact of two (one existing and one under construction) floating offshore wind parks placed off the coast of Scotland. The authors find GWP values in the range 25.6–45.2 gCO_{2eq}/kWh, depending on the O&M strategy chosen.

Table 6 shows summarized results found in the literature for wind power plants.

Table 6. List of LCA results found in the literature for wind power plants.

Published Works	Year of the Study	Plant Type	gCO_2eq/kWh
UNECE [29]	2022	Onshore (Europe) Offshore (Europe)	12.4 (mean) 14.2 (mean)
Wang L. et al. [36]	2019	Onshore (China)	25.4–31.8
Alsaleh and Sattler [39]	2019	Onshore (USA)	18 (mean)
Xu et al. [40]	2022	Onshore (China)	19.88 (mean) 13.59–34.50
Teffera et al. [41]	2013	Onshore (Ethiopia)	33.6 (mean)
Bonou et al. [42]	2019	Onshore (Europe) Offshore (Europe)	7 (mean) 11 (mean)
Kadiyala et al. [43]	2017	Onshore Offshore	11.75–46.4 12.9 (mean)
Asdrubali et al. [20]	2015	Onshore and offshore	9.4 (mean) 6.2–46
Li et al. [44]	2021	Onshore	16.4–28.2
Li et al. [22]	2020	Onshore	31.36 (mean)
Khoie et al. [45]	2021	Onshore	14.45 (mean)
Vélez-Henao et al. [46]	2021	Onshore	12.93 (mean)
Xie et al. [47]	2020	Onshore	3.9 (mean)
Nugent and Sovacool [48]	2014	Onshore	34.11 (mean)
NREL [16]	2021	Onshore Offshore	12 (mean) 19 (mean)
Basosi et al. [49]	2020	Onshore (Italy)	13.4 (mean)
Paulillo et al. [38]	2019	Onshore	11 (mean)
Šerešová et al. [26]	2020	Onshore (Czech Republic)	19 (mean)
Akber et al. [24]	2017	Onshore (Pakistan)	11.38 (mean)
Brussa et al. [50]	2023	Offshore (Italy)	31.3 (mean)
Garcia-Teruel et al. [51]	2022	Offshore (Scotland)	25.6–45.2

The analysis of the aforementioned papers reveals that larger wind farms, equipped with bigger turbines, and particularly those with higher capacity factor values, yield lower CO_2 emissions. The primary portion of emissions is generated during the pre-operational phases.

Two primary factors contribute to the diminished environmental impact per kWh generated by wind systems: scaling capacity and increase in size of the wind turbine. At the device scale, wind turbines have become increasingly efficient due to their larger size, particularly their height and diameter. Height is crucial as it allows for the capture of more wind energy at higher wind shear factors and hub heights. Diameter is associated with the area swept by the blades and the kinetic energy harnessed by the turbine. The technological learning encompasses the experience accumulated over time (proportional to cumulative installed capacity), leading to enhanced design and manufacturing efficiency, as well as technological advancements such as the utilization of less and more efficient materials for the blades. Collectively, these two factors have been estimated to reduce the life cycle environmental impacts of wind power by 14% for every doubling in capacity.

Table 7 shows that emissions from wind technologies are very similar, with slightly higher values for offshore plants due to the platform impact on the environment.

Table 7. CO_2 equivalent emissions related to 1 kWh for wind power plants weighted according to the year of the study.

Plant Type	Weighted Mean of the Minimum Values	Weighted Mean of the Mean Values	Weighted Mean of the Maximum Values
Onshore	16.6	16.4	34.9
Offshore	25.6 +	18.1	45.2 +
Onshore and offshore	6.2 °	9.4 °	46 °

+ Calculated on a single value basis (Garcia-Teruel et al. [51]). ° Calculated on a single value basis (Asdrubali et al. [20]).

2.2.3. Photovoltaics

At the end of 2022, solar PV was the second largest source of renewable electricity after hydropower, with 1046.6 GW of installed capacity (31%) [28].

Over the past decade, photovoltaic (PV) technology has matured and emerged as the fastest-growing source of electricity production from renewable energies. PV involves the conversion of light into electricity through semiconductors, which exploit the photoelectric effect. The primary types of PV cell and module technologies include crystalline silicon (mono and multi), thin-film (Copper Indium Gallium Selenide (CIGS), Cadmium Telluride (CdTe), amorphous silicon (a-Si), perovskite), and multi-junction (utilizing multiple p-n junctions of different semiconductor materials to absorb various wavelengths of light) modules. The PV systems can be ground-mounted or roof-mounted (building-mounted or building-integrated). Based on how the generated electricity is managed, PV systems can be categorized as grid-connected or stand-alone. These systems come in various main types: residential, commercial, or utility-scale. The fundamental components of a PV system include photovoltaic modules, the tracking system, the balance of the system, and the inverter.

The PV sector achieved its initial terawatt milestone in the spring of 2022, with a cumulative installed PV capacity of 1 terawatt peak and an annual production of solar cells and modules ranging between 200 to 230 gigawatts peak (GWp). The forthcoming terawatt milestone, reaching 1 terawatt peak of annual production, is anticipated within the next 5 to 7 years, and it is projected to escalate to a 2 terawatt peak by the beginning of the next decade. This advancement aims to curtail worldwide greenhouse gas (GHG) emissions, aligning with the objective of limiting the global temperature increase to 1.5 °C by the mid-century, as outlined in the 2016 Paris Agreement. According to the IEA [4], to achieve net-zero emissions by 2050, nearly 90% of global electricity generation in 2050 should derive from renewable sources, with solar PV and wind jointly constituting almost 70%, with an annual capacity addition of 630 GWp between 2030 and 2050.

A quintupling of annual solar cell production within the next 5 to 7 years, followed by a tenfold increase at the beginning of the next decade, poses significant challenges for the PV industry and necessitates corresponding research efforts. Across the entire PV value chain, spanning from raw material extraction to the recycling or re-use of solar system components, the PV sector must actively diminish its environmental impact and transition towards sustainability and circularity. According to the International Technology Roadmap for Photovoltaic (ITRPV) 14th edition (VDMA, 2023), crystalline silicon technology accounts for 95% of global PV module production. Of these, over 95% are monocrystalline (mono c-Si) modules, while the remaining ones are multicrystalline (multi c-Si) modules. Multicrystalline silicon panels, which accounted for the largest market share of manufactured PV until 2015, are to some extent cheap to manufacture, but less efficient than monocrystalline silicon ones [19]. Thin-film panels are lighter than crystalline silicon ones, and flexible, but they show a meaningfully lower efficiency than crystalline modules. Furthermore, thin-film technologies require critical raw materials like cadmium, indium, tellurium, with all that this entails.

According to UNECE, solar PV technologies produce GHG emissions ranging from 8.0 to 83 gCO_{2eq}/kWh, depending on technology and installation type. Thin-film PV systems show noticeably lower GHG values than silicon-based ones [29]. Specifically, GHG emissions for the various technologies can be found in Table 8. The pre-operational phases contribute to over 90% of the global emissions in the case of multi-Si modules. Extensive work on LCA assessment has been carried out within the Task 12 (PV Sustainability) of the PVPS (Photovoltaic Power Systems) TCP (Technology Collaboration Programme) of the IEA. Task 12 is operated jointly by the National Renewable Energy Laboratory (NREL) and University of New South Wales (UNSW), with support from the United States Department of Energy (DOE) and UNSW. In 2020, Task 12 published a report "Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems" [52] that provides life cycle inventories (LCIs), which are often the greatest barrier for conducting LCA. In 2022, Task 12 reported updated GWP values for solar PV [53]. The carbon emissions associated with the generation of 1 kWh of solar electricity from PV systems, reported in Table 8, are in the range of 25.5–44.0 (gCO_{2eq}/kWh). It is worth noting that the study also reported that GHG emissions associated with the generation of 1 kWh of solar PV electricity, produced by a rooftop residential PV system in Switzerland, using mono-crystalline technology, jumped from 121 to 43 gCO_{2eq}/kWh from 1996 to 2021. The improvements are not only due to the increase in yield, but also due to technological advancements in PV manufacturing.

NREL examined many LCAs of electricity generation technologies [16]. GHG emissions for all PV technologies were in the range 11–226 gCO_{2eq}/kWh, with a median value of 43 gCO_{2eq}/kWh. Specifically, median values for thin film technologies were: 37 (a-Si), 25 (CdTe), and 41 (CIGS) gCO_{2eq}/kWh. Median values for crystallin silicon were: 64 (mono-Si) and 56 (multi-Si) gCO_{2eq}/kWh.

Asdrubali et al. [20] examined 33 case studies regarding PV applications. GWP values were found between 9.4 and 167 gCO_{2eq}/kWh. After the harmonization procedure, the GWP median value was 29.2 gCO_{2eq}/kWh.

Li et al. [44] performed a LCA on an onshore 40 MW wind plant and compared its environmental performance with other renewable and fossil technologies. They considered reference GWP values for photovoltaics in the range 16–40 gCO_{2eq}/kWh.

Paulillo et al. [38] studied the environmental impact of geothermal energy with LCA, but also compared it with the environmental impact of other renewable energy sources. They found a median GWP value for photovoltaics equal to 48 gCO_{2eq}/kWh.

Šerešová et al. [26] assessed the environmental performance of several energy sources in the Czech Republic, based on their entire life cycle. Regarding PV, they studied five case studies related to differently located plants (roof-mounted, ground-mounted) that used different PV technologies (mono-Si, multi-Si, CdTe). They found a GWP mean value of 11 gCO_{2eq}/kWh, more than 60% arising from the construction phase, specifically the production of construction materials.

Ali et al. [54] assessed the environmental impact of electricity generation from 120 distributed PV systems in USA with LCA. Two kinds of photovoltaic modules are used: mono-Si and multi-Si, mainly ground-mounted. GWP values are in the range 25.2–88.5 gCO_{2eq}/kWh, with a mean value of 45.6 gCO_{2eq}/kWh. The variation in GHG is mainly due to the type of module used and to the capacity factors. Multi-Si modules show lower GWP values than mono-Si ones. Furthermore, GWP values decrease as the capacity factor increases. Around 80% of the emissions stems from the upstream (pre-operational) phase.

Table 8. List of LCA results found in the literature for solar photovoltaics.

Published Works	Year of the Study	Technology Type	gCO_2eq/kWh
UNECE [29]	2022	Multi-Si (ground-mounted) Multi-Si (roof-mounted) CdTe (ground-mounted) CdTe (roof-mounted) CIGS (ground-mounted) CIGS (roof-mounted)	23–82 37 (mean) 23–83 37 (mean) 8–28 12 (mean) 10–35 15 (mean) 7.4–27 11 (mean) 9.2–34 14 (mean)
IEA PVPS TCP [53]	2022	Mono-Si Multi-Si CIGS CdTe	42.9 (mean) 44.0 (mean) 35.4 (mean) 25.5 (mean)
NREL [16]	2021	All technologies a-Si CdTe CIGS Mono-Si Multi-Si	11–226 43 (mean) 37 (mean) 25 (mean) 41 (mean) 64 (mean) 56 (mean)
Asdrubali et al. [20]	2015	Not specified	29.2 (mean)
Li et al. [44]	2021	Not specified	16–40
Paulillo et al. [38]	2019	Not specified	48 (mean)
Šerešová et al. [26]	2020	Mono-Si (Czech Republic) Multi-Si (Czech Republic) CdTe (Czech Republic)	11 (mean)
Ali et al. [54]	2022	Mono-Si (USA) and Multi-Si (USA)	25.2–88.5 45.6 (mean)
Ludin et al. [55]	2018	Mono-Si Multi-Si a-Si CdTe CIS DSSC Perovskite QDSSC	5.6–87.3 6.04–81 8.1–57 8.9–66 33–95 9.8–25 56.65–497.2 2.89–5
Bergesen et al. [56]	2014	CdTe (ground-mounted) (USA) CIGS (ground-mounted) (USA)	20 (mean) 22 (mean)
Stylos and Koroneos [57]	2014	Multi-Si	51.68–58.81
Hou et al. [58]	2016	Crystalline silicon Multi-Si (China) Mono-Si	60.1 (large scale) 81 (distributed) 65.2 (large scale) 87.3 (distributed)
Kim et al. [59]	2014	Mono-Si (Korea) Multi-Si (Korea)	31.5 (mean) 41.8 (mean)

Table 8. *Cont.*

Published Works	Year of the Study	Technology Type	gCO_2eq/kWh
Fu et al. [60]	2015	Multi-Si (China)	50.9 (mean)
Lunardi et al. [61]	2018	Si and tandem solar modules	25–29
Collier et al. [62]	2014	Mono-Si Multi-Si a-Si CdTe CIGS Zn_3P_2 CZTS	35 (mean) 29 (mean) 19 (mean) 18 (mean) 36 (mean) 30 (mean) 38 (mean)
Celik et al. [63]	2016	Mono-Si Multi-Si a-Si CdTe CIS Perovskite	23 (mean) 20 (mean) 12 (mean) 12 (mean) 17 (mean) 99–147
Zhang et al. [64]	2015	Mono-Si Multi-Si a-Si CdTe DSSC Perovskite	29–45 23–44 18–50 14–35 19–120 60.1–5480

Ludin et al. [55] examined LCA studies concerning several solar PV technologies. GHG emissions rate was in the range 29–671 gCO_{2eq}/kWh for mono-Si and 12.1–569 gCO_{2eq}/kWh for multi-Si. A detailed analysis of the tables in the paper showed that the highest values refer to older studies. Thus, considering only studies from 2013 onwards, the values for mono-Si ranged between 5.6 and 87.3 gCO_{2eq}/kWh and for multi-Si between 6.04 and 81 gCO_{2eq}/kWh. Most of the emissions arise from the production phase. For thin film technologies the following values for GHG were found: 8.1–57 gCO_{2eq}/kWh (a-Si), 8.9–66 gCO_{2eq}/kWh (CdTe), 33–95 gCO_{2eq}/kWh (CIS). For dye-sensitized solar cells (DSSC), GHG values were in the range 9.8–25 gCO_{2eq}/kWh, for perovskite the range was between 56.65 and 497.2 gCO_{2eq}/kWh, while for quantum dot sensitized solar cells (QDSSC) GHG emissions were in the range 2.89–5 gCO_{2eq}/kWh. All data are reported in Table 8, but emissions related to DSSC, QDSSC, and perovskite are not considered in Table 9, being the analysed solar cells not commercially available yet.

Table 9. CO_2 equivalent emissions related to 1 kWh for solar photovoltaic technologies weighted according to the year of the study.

Plant Type	Weighted Mean of the Minimum Values	Weighted Mean of the Mean Values	Weighted Mean of the Maximum Values
Mono-Si	31.1	35.5	74.3
Multi-Si	30.8	36.4	71.2
Mono and Multi-Si	25.1	45.6	61.5
a-Si	12.5	24.7	53.9
CdTe	9.9	17.4	40.4
CIGS	8.3	26.3	30.5
CIS	33.0 °	17.0 °	95.0 °
Not specified	16.0	39.6	40.0

° All the values in the line are calculated on a single-item basis.

Bergesen et al. [56] performed a LCA on two thin-film technologies (CIGS and CdTe) in the USA. They found GHG emissions equal to 20 CO_{2eq}/kWh for ground-mounted CdTe and 22 CO_{2eq}/kWh for ground-mounted CIGS.

Stylos and Koroneos [57] performed a LCA on multi-Si modules. They took into account four scenarios: the base case (representing the present state-of-the-art technology), the improved case (technology that will be available within next two years), the forward case (technology available within the next 5 years), and an application of a commercially available module. They found GHG emissions values between 51.68 and 58.81 gCO_{2eq}/kWh for currently commercially available modules, and lower values for modules available within future years (12.28–19.49 gCO_{2eq}/kWh). GHG emissions will decrease over time due to improvements in production processes.

Hou et al. [58] performed a LCA on large scale and distributed grid-connected PV systems equipped with crystalline silicon modules in China. They found GHG emissions ranging from 60.1–87.3 gCO_{2eq}/kWh, with very little differences between multi-Si and mono-Si, in favour of multi-Si, and larger differences between large scale and distributed PV, in favour of large scale. Specifically, the mean value for large scale multi-Si was 60.13 gCO_{2eq}/kWh and for distributed multi-Si was 81 gCO_{2eq}/kWh; for large scale mono-Si it was 65.2 gCO_{2eq}/kWh and for distributed mono-Si it was 87.3 gCO_{2eq}/kWh. Over 35% of the emissions originate from the production phase.

Kim et al. [59] assessed the environmental performances of crystalline silicon systems in Korea using LCA. The GWP for mono-Si was 31.5 gCO_{2eq}/kWh, while for multi-Si they found the value of 41.8 gCO_{2eq}/kWh. The majority of CO_2 emissions were attributed to the manufacturing processes of the PV module.

Fu et al. [60] performed a LCA of multi-Si modules, the most widespread PV technology in China before 2015. They calculated a GWP mean value for the PV technology equal to 50.9 gCO_{2eq}/kWh, highlighting that the most critical phase is the module production, which contributes to about 50% of the global emissions.

Lunardi et al. [61] assessed the environmental performances of Si and tandem solar modules. GWP values for these modules were between 25 and 29 gCO_{2eq}/kWh. The primary impact arises from the production of solar-grade silicon. All data are reported in Table 8, but emissions related to the tandem structure are not considered in Table 9, being the analysed module not commercially available yet.

Collier et al. [62] used LCA to assess the environmental impact of new thin film technologies: Zn_3P_2 and CZTS (copper zinc tin sulphide). Their environmental impact was compared with commercial thin-film technologies (a-Si, CdTe, and CIGS) and a crystalline silicon one. They found the GWP values shown in Table 8, ranging from 18 to 38 gCO_{2eq}/kWh. The primary impacts stemmed from electricity consumption during manufacturing, contributing to more than 50% for each technology. Values associated with novel thin-film technologies (Zn_3P_2 and CZTS) are not considered in Table 9, being the analysed structure not commercially available yet.

Celik et al. [63] used LCA to assess the environmental impact of perovskite PV cells and to compare it with the environmental impact of silicon-based cells. They found GWP values for perovskite cells in the range 99–147 gCO_{2eq}/kWh. These values are higher than GWP values for mono-Si and multi-Si, respectively, equal to 23 and 20 gCO_{2eq}/kWh. The higher values for perovskite cells are mainly due to their lower average value of lifetime (5 years versus 30 years assumed for Si cells) and their lower efficiency. The paper also reports GWP values for a-Si (12 gCO_{2eq}/kWh), CdTe (12 gCO_{2eq}/kWh), and CIS (17 gCO_{2eq}/kWh) cells.

Zhang et al. [64] performed a LCA to assess the environmental impact of titanium dioxide nanotube perovskite solar cells, based on laboratory-scale data, and compared them with those of commercial solar cells. Results showed that GHG emissions of perovskite solar cells varied over a very wide range compared to commercial ones. This range is between 60.1 and 5480 gCO_{2eq}/kWh. The environmental performances of perovskite solar cells could be reduced as a result of an improvement in their conversion efficiency and an increase in lifetime. GHG emissions for considered commercial solar cells are: 29–45 gCO_{2eq}/kWh (mono-Si), 23–44 gCO_{2eq}/kWh (multi-Si), 18–50 gCO_{2eq}/kWh (a-Si), 14–35 gCO_{2eq}/kWh (CdTe), and 19–120 gCO_{2eq}/kWh (DSSC). Raw material extraction (pre-operational phase) is the phase with the most substantial environmental impact, contributing to over 69% of the overall CO_2 emissions. All data are reported in Table 8, but emissions related to non-commercial products are not considered in Table 9.

Table 8 summarizes the results for solar photovoltaics found in published works.

Low emission mean values are associated with commercial thin-film technology (ranking from CdTe, CIS, a-Si, and CIGS), due to the lower thermal budget needed for module manufacturing (without any crystallisation process and direct module production by omitting the cell-to-module step) and less material usage. CdTe panels face restrictions due to legislation on how to handle the Cd in the decommissioning phase. The main differences between CIS and CIGS are due to the usage of gallium (Ga). High emission values are associated with a-Si due to its lower efficiency and lifetime. Wafer-based technology (mono-Si and multi-Si) shows higher emission values due to the manufacturing process (purification, ingot growing, wafering, cell, etc.. . .). Nevertheless, a reduction of almost 35% of the emission value has been observed during the last decades because of the increase in yield, but also due to technological advancements in manufacturing (less material usage: wafer thickness reduction and lower content of metals).

2.2.4. Concentrated Solar Power

At the end of 2022, global concentrated solar power accounted for 6.5 GW, less than 0.2% of the global renewable generation capacity [28].

Up to now, concentrated solar thermal technologies have developed to a commercial scale but have played only a small role in decarbonising the energy system. Global CSP market growth remains modest and on current trends may not reach levels foreseen by the IEA roadmaps. Nonetheless, considerable potential exists, although the development of the market relies on the design of effective auctions which can potentially reward the flexibility that the technology provides. As a technology, over the last 10 years CSP has made big steps forward in terms of cost reduction and in establishing a track record as a reliable option (benefiting from the good performance of the Spanish fleet and that of some recent international projects). However, to become more competitive, further standardisation in design and manufacturing can be key to attracting the levels of investment needed to bring deployment rates back on track. R&D has a major role to play in this; as shown by the PV sector, mass-production processes can accommodate major innovations and cost cutting. Digitisation in all phases needs also be fully embraced.

Concentrated Solar Power (CSP) plants generate electricity in a manner analogous to conventional power stations, employing high-temperature steam or gas to propel a turbine. However, in CSP plants, the hot fluid is generated through the concentration of solar radiation rather than the combustion of fossil fuels. A noteworthy characteristic of CSP plants is the potential integration of a thermal storage system, enabling electricity production even in the absence of sunlight. CSP technology provides reliable and flexible electrical production for utilities and grid operators, contingent upon Direct Normal Irradiance (DNI) values exceeding 2000 $kWh/m^2/y$.

There are four primary commercial technologies: parabolic troughs and linear Fresnel systems, which employ line concentration, and central receivers (or towers) and parabolic dishes, which utilize point concentration. These technologies vary in terms of optical design, receiver shape, the nature of the transfer fluid, and the ability to store heat before converting it into electricity. The two predominant designs currently in use are parabolic trough power plants and central receiver tower systems.

CSP can be synergistically integrated with other power generation technologies, either for solar-assisted power generation or in hybrid configurations, including photovoltaic systems.

A comprehensive review of the scientific literature about environmental performances of CSP plants published in recent years was carried out by Guillen-Lambea and Carvalho [65]. Only seven studies out of 96 passed the screening criteria adopted by the authors in order to obtain high quality studies. GWP values of the seven studies, most of which referred to CSP parabolic trough with molten salt-based thermal energy storage (TES), were in the range 26–60 gCO_{2eq}/kWh. The contribution of pre-operational phases to global emissions ranges from 52% to 80%. Differences are due to the different energy mix (plants are located in Spain, USA, United Arab Emirates, and South Africa), sizes of the plants, DNI values, and the lifetime of the CSP plants. Higher values were found for synthetic molten salt compared with mined salt.

Gasa et al. [66] carried out a LCA of a CSP tower plant with molten salt storage and compared it with a reference CSP plant without storage. They concluded that CSP with storage showed a lesser environmental impact than CSP without storage (9.8 g CO_{2eq}/kWh versus 31 g CO_2 eq./kWh). They also found that the component with the highest impact was the solar field, followed by the heat transfer fluid and the thermal energy storage.

Ko et al. [67] performed a LCA of a CSP tower plant with molten salt as the heat transfer fluid and storage medium. The case study was a tower plant with a 12 h heat storage. They found a GWP value of 24.3 g CO_{2eq}/kWh, 50% of which stems from the construction phase.

Gasa et al. [68] analysed the environmental impact of four CSP tower plants, with molten salt thermal energy storage systems, having different storage capacities. As the storage capacity increases, environmental impact decreases. GWP value decreased from 14.21 g CO_{2eq}/kWh (3 h storage capacity), to 12.26 g CO_{2eq}/kWh (6 h), to 10.99 g CO_{2eq}/kWh (9 h), and to 9.95 g CO_{2eq}/kWh (17.5 h). Nearly all environmental impacts are generated during the pre-operational phase, with values ranging from 66.7% (3 h storage capacity) to 80% (9 h), and up to 93.3% (17.5 h).

Li et al. [69] used LCA to evaluate environmental performances of a 10 MW CSP in tower configuration in China with 15 h storage capacity. CO_2 emissions during the whole life cycle of the plant reported in this study were 35 gCO_{2eq}/kWh. The production of components is the primary source of CO_2 emissions.

Whitaker et al. [70] performed a LCA of a power tower concentrating solar power (CSP) facility, located in the USA. It is a dry-cooled, 106 MW_{net} facility using mined nitrate salts as the heat transfer fluid and storage medium, with a storage system operating for six hours. The plant showed GHG emissions of 37 gCO_{2eq}/kWh, slightly less than 50% arising from the pre-operational phase.

Asdrubali et al. [20] examined 15 case studies regarding concentrated solar power; nine referred to parabolic trough applications and six to central tower plants. GWP values were found between 14.2 and 203 gCO_{2eq}/kWh. After the harmonization procedure, the GWP median value for CSP was 30.9 gCO_{2eq}/kWh.

UNECE compares, through LCA methodology, the potential environmental impacts of different electricity generation technologies. As far as concerns CSP, trough and tower designs have been investigated. For the CSP trough power plant in Europe, a value of 42 gCO_{2eq}/kWh was found for GWP (30% of which stems from the construction phase), while for the tower design GWP value was almost half and equal to 22 gCO_{2eq}/kWh, probably because of its higher efficiency due to its load factor being higher than the parabolic trough one [29].

NREL examined hundreds of LCAs of electricity generation technologies [16]. GHG emissions from CSP plants are in the range 11–241 gCO_{2eq}/kWh, with a median value of 28 gCO_{2eq}/kWh for trough and tower configurations. Specifically, median values for parabolic trough, tower, and parabolic dish were: 26, 38, and 15 gCO_{2eq}/kWh. Although all emission values are reported in Table 10, in Table 11 the authors do not include the value related to the parabolic dish because commercial plants utilizing this technology are not currently operational.

Table 10. List of LCA results found in the literature for CSP power plants.

Published Works	Year of the Study	Plant Type	gCO_2eq/kWh
Guillen-Lambea and Carvalho [65]	2021	Parabolic trough with storage	26–60
Gasa et al. [66]	2021	Tower plant with storage Tower plant without storage	9.8 (mean) 31 (mean)
Ko et al. [67]	2018	Tower plant with 12 h storage	24.3 (mean)
Gasa et al. [68]	2022	Tower plant with 3 h storage Tower plant with 6 h storage Tower plant with 9 h storage Tower plant with 17.5 h storage	14.21 (mean) 12.26 (mean) 10.99 (mean) 9.95 (mean)
Li et al. [69]	2019	Tower plant with 15 h storage (China)	35 (mean)
Whitaker et al. [70]	2013	Tower plant with storage (USA)	37 (mean)
Asdrubali et al. [20]	2015	Parabolic trough and tower plants	30.9 (mean)
UNECE [29]	2022	Parabolic trough with storage Tower plant with storage	42 (mean) 22 (mean)
NREL [16]	2021	Parabolic trough with storage Tower plant with storage Parabolic dish	26 (mean) 38 (mean) 15 (mean)

Table 11. CO_2 equivalent emissions related to 1 kWh for CSP power plants weighted according to the year of the study.

Plant Type	Weighted Mean of the Minimum Values	Weighted Mean of the Mean Values	Weighted Mean of the Maximum Values
Parabolic trough with storage	26.0 °	33.2	60.0 °
Tower plant with storage		20.5	
Tower plant without storage		31°	

° Calculated on a single-item basis.

Table 10 shows the results of the analysed studies for CSP power plants.

Table 11 shows that emissions from CSP technologies are very similar, with a slightly higher values for parabolic trough plants due to the lower solar-to-electricity efficiency.

As the storage capacity of a CSP plant expands, there is a corresponding escalation in the environmental impacts incurred during the manufacturing and disposal phases. Nevertheless, the impacts arising in the operational phase diminish as the augmented storage capacity mitigates the necessity for drawing electricity from the grid. The reported value of 60 gCO_{2eq}/kWh is due to considered low plant lifetime (20 years).

2.2.5. Geothermal

As of 31 December 2022, global geothermal capacity accounted for almost 15 GW, about 0.44% of the global renewable generation capacity [28].

A natural hydrothermal geothermal reservoir is characterized by porous and permeable rocks saturated with hot water or steam, possessing both an ample heat supply and a reliable recharge mechanism. Geothermal energy can be found at various depths and temperatures.

Three primary power plant technologies are used to convert the energy in geothermal resources to electricity: dry steam, flash/double steam, and the binary cycle [71]. In the first, steam is piped directly from underground wells to the power plant, where it is fed into a turbine/generator. This typology is not considered in the review because it is less common. Dominant water tanks are used to power systems in single or double flash. In the binary cycle, geothermal fluid is used to vaporize, through a heat exchanger, a second liquid, with a lower boiling point than water.

The Organic Rankine Cycle (ORC) is a technology that converts low-temperature heat sources into mechanical energy and can be employed to generate electrical energy within a closed-loop system.

Enhanced geothermal systems (EGS) improve the permeability of geothermal systems through hydraulic, chemical, and thermal stimulation through pumping of the water into the rock fractures, thereby creating an artificial reservoir.

Basosi et al. [49] compared the environmental performances of three Italian renewable power plants (geothermal, solar, and wind) using LCA. The three power plants have similar capacity (about 20 MW). The geothermal power plant is equipped with an AMIS® emissions treatment system, which reduces H_2S and Hg, with calculated efficiencies of 99.8 and 82.2, each in order, but not CO_2 emissions. The GWP value found for this real case study (with AMIS®) was 477 gCO_{2eq}/kWh, while the value found for the plant without AMIS® was 301 gCO_{2eq}/kWh.

Asdrubali et al. [20] examined 20 case studies regarding geothermal power. GWP values showed considerable variability and were in the range 16.9–142.0 gCO_{2eq}/kWh. This variability depends substantially on the technology characteristics. After the harmonization procedure, the GWP median value for geothermal was 33.6 gCO_{2eq}/kWh.

Pratiwi et al. [72] evaluated the environmental impact of a geothermal plant in France. The environmental impact varies greatly according to geography and geology. The emissions calculated for the French geothermal plant were in the range 6.97–9.15 gCO_{2eq}/kWh throughout its 25-year lifetime. The authors also evaluated emissions for a future plant. This will show emissions between 2.69 and 4.39 gCO_{2eq}/kWh and between 29.53 and 54.92 gCO_{2eq}/kWh, based on heat and electricity production shares. Usually, geothermal binary technology is characterized by low CO_2 emissions, but there are some exceptions such as binary plants in Turkey (7 MW_e) with emissions of 400–1100 gCO_{2eq}/kWh, ascribable to carbonate-dominated metamorphic rocks in the reservoir.

Karlsdottir et al. [73] used LCA to assess the environmental impact originating from the generation of 1 kWh of energy in an Icelandic geothermal combined heat and power plant (CHP) using high temperature geothermal energy. The plant operates in a double flash cycle. The GWP values are mainly due to the operational phase of the plant. They found the following values for GWP: 15.9 gCO_{2eq}/kWh for the plant without CCS and 11.4 gCO_{2eq}/kWh for the plant with CCS.

Paulillo et al. [38] studied the environmental impact of geothermal energy with LCA. The case study they took into account was an Icelandic combined heat and power double flash geothermal plant. The life cycle emissions of GHG for the functional unit of the case study plant were in the range 18–24 gCO_{2eq}/kWh for single flash configuration and in the range 15–23 gCO_{2eq}/kWh for double flash configuration.

Sigurjónsson et al. [74] performed a LCA of two enhanced geothermal systems, the first located in Iceland and the second in France. Furthermore, the study considered a range of installed capacity, 5–30 MW in Iceland, and 40.1–80.3 MW in France. The GHG emissions of the two geothermal systems were in the range 1.6–17.4 gCO_{2eq}/kWh for the Icelandic case (85% stems from operational emissions, namely the CO_2 released from the borehole, originating from the geothermal reservoir), and in the range 6.9–13.9 gCO_{2eq}/kWh for the French one (50% from the borehole construction phase).

Lacirignola and Blanc [75] examined the environmental impact of enhanced geothermal systems using LCA. EGS systems, despite the great amount of energy and materials they require in the construction phase, show environmental performances like other renewables. They analysed ten case studies of EGS located in Central Europe. GHG emissions were in the range 16.9–49.8 gCO_{2eq}/kWh.

Menberg et al. [76] carried out a LCA to evaluate the environmental performance of a binary geothermal plant located in Germany. The GHG value found for this plant was 38.2 gCO_{2eq}/kWh. The main contribution to this value comes from the refrigerant used as a working fluid (64%).

Heberle et al. [77] performed a LCA for geothermal power generation by binary power plants. This paper considers the replacement of traditional working fluids with lower environmental impact ones. The use of R1233zd as a working fluid instead of R245fa results in a reduction of the GWP value from 78 to 13.2 gCO_{2eq}/kWh. In this latter case, 95% of the emissions originate from the pre-operational phase. NREL evaluated and harmonized hundreds of LCAs of electricity generation technologies [16]. GHG emissions from geothermal power plants are in the range 5.6–245 gCO_{2eq}/kWh, with a median value of 37 gCO_{2eq}/kWh. Specifically, median values for EGS binary, hydrothermal (HT) flash and HT binary plants were: 32, 47, and 11 gCO_{2eq}/kWh.

Motuziene et al. [30] performed a review of life cycle analysis results for renewable energy conversion technologies. As far as concerns geothermal energy, they found that the highest impact to GHG emissions came from the construction phase. Geothermal systems exhibit a low environmental impact in comparison to conventional fossil fuel systems, although the degree of impact varies significantly based on the region and the specific system employed. Notably, geothermal power plants in Iceland and the utilization of enhanced geothermal systems (EGS) with additional technologies, such as carbon capture and storage, combined heat and power production, or the integration of refrigerators with low GWP values, contribute to minimizing environmental effects.

Table 12 shows the results found in the analysed studies for geothermal systems. Table 13 shows CO_2 equivalent emissions related to 1 kWh for geothermal systems weighted according to the year of the study.

Among the five geothermal power generation technologies examined, HT single and double flash plants have the weighted average of similar minimum and maximum values.

The high emission value associated with the binary plant does not depend on the technology used but on the location. Indeed, in the Italian plants, during the operation phase, non-condensable gases are emitted and not captured in the atmosphere; furthermore, the composition of the geofluid varies with location and depth. However, when an emission treatment system is applied (AMIS), a 40% decrease in GHG is observed as a compensation of natural emissions.

Table 12. List of LCA results found in the literature for geothermal systems.

Published Works	Year of the Study	Plant Type	gCO_2eq/kWh
Basosi et al. [49]	2020	Binary (Italy)	477 (with AMIS® system) 301 (without AMIS® system)
Asdrubali et al. [20]	2015	Not specified	33.6 (mean) 16.9–142
Pratiwi et al. [72]	2018	EGS (France)	6.97–9.15
Karlsdottir et al. [73]	2020	HT double flash	15.9 (without CCS) 11.4 (with CCS)
Paulillo et al. [38]	2019	HT single flash HT double flash	18–24 15–23
Sigurjónsson et al. [74]	2021	EGS (Iceland) EGS (France)	1.6–17.4 6.9–13.9
Lacirignola and Blanc [75]	2013	EGS	16.9–49.8
Menberg et al. [76]	2021	Binary with ORC	38.2
Heberle et al. [77]	2016	Binary with ORC	13.2
NREL [16]	2021	EGS HT single flash Binary	37 (mean) 32 (mean) 47 (mean) 11 (mean)

Table 13. CO_2 equivalent emissions related to 1 kWh for geothermal systems weighted according to the year of the study.

Plant Type	Weighted Mean of the Minimum Values	Weighted Mean of the Mean Values	Weighted Mean of the Maximum Values
EGS	7.3	32.0 *	20.6
Binary		263.0	
HT single flash	18.0	47.0 *	24.0
HT double flash	15.0	13.7 °	23.0
Binary with ORC		28.2	
Not specified	16.9	35.6	142.0

* Only one value. ° Mean of two values: one without CCS and one with CCS.

Geothermal binary (ORC) plants offer an effective solution to avoid CO_2 emissions to the atmosphere. The CO_2 is compressed at the outlet of the ORC vaporizer and reinjected along with the liquid into the reinjection well.

2.3. LCA of Nuclear Systems

According to the International Atomic Energy Agency (IAEA) [78] (pp. 9–10), as of 31 December 2022 there were 411 nuclear power plants in operation all over the world with a total electricity generating capacity of 371 GW. Light water reactors (LWRs) are by far the most prevalent with 333.2 GW installed capacity (90% of total installed capacity: 78% pressurized water reactors (PWR) and 12% boiling water reactors (BWR)).

As reported by IAEA, the nuclear power fleet generated about 2486.8 TWh of low-emission electricity during 2022 (excluding Ukrainian reactors), accounting for about 10% of electricity generation globally.

Essentially, two fuel cycle types are used nowadays, the "open" and the "partially closed", also called "once through cycle" and "twice through cycle" (TTC), each in order. A distinction should be made between the "partially" closed fuel cycle as it applies to thermal reactors, which is limited to twice-through, and the "fully" closed cycle, which applies to fast reactors. In this review the term "closed" fuel cycle refers to the "partially" closed cycle (TTC).

In 2021, Joint Research Centre (JRC), the European Commission's science and knowledge service, carried out a review on the 'do no significant harm' (DNSH) aspects of nuclear energy, by examining the entire life cycle of nuclear energy also in terms of environmental impact, also focusing on the management of high-level radioactive waste and spent nuclear fuel [79]. Most of the LCAs consulted are complete, as they include all the phases including the disposal phase. The JRC study analysed many LCA studies from the last two decades. Three references were given more weight for their comprehensiveness. All the three studies are very recent. These studies resulted in the following values for GHG emissions: 5.3 gCO_{2eq}/kWh for PWR reactors (mixed cycle), 5 gCO_{2eq}/kWh for III generation EPR (European Pressurized water Reactor) reactors (open cycle), and 4.6 gCO_{2eq}/kWh for EPR (closed cycle).

In 2022 UNECE [29] estimated a range of 5.1—6.4 gCO_{2eq}/kWh for GHG emissions for nuclear power. These values were calculated for conventional reactors in operation as of 2020, typically PWR and BWR, and considering the full nuclear power fuel cycle (uranium mining and milling, uranium conversion and enrichment, fuel fabrication, power generation, and waste management and disposal). The first phases (from mining to fuel fabrication) are often called "front end", whereas "back end" includes the reprocessing of irradiated fuel (not included in this study) and waste management and disposal. It was found that front end phases contribute most to the environmental impact of nuclear power. Life cycle emissions from nuclear power are estimated at 5.5 gCO_{2eq}/kWh on a global average. The study also analysed small modular reactors (SMRs), namely advanced reactors with a power capacity less than 300 MW, that can be manufactured and then easily shipped and installed on any site. UNECE focused on water-cooled SMRs (the most advanced design for SMRs), also considering that there is a paucity of scientific literature on the subject. The values found for GHG emissions form SMRs were in the range 4.6–8.4 gCO_{2eq}/kWh. Front-end processes are the primary contributors to the overall CO_2 emissions (more than 60%).

Pomponi and Hart [80] studied the life cycle GHG emissions associated with new nuclear reactors in Europe. The nuclear power plant at Hinkley Point C will include two EPR units of 1.6 GWe each, operating for 60 years with a 92% load factor, producing 1560 TWh of electricity. EDF (Electricitè de France), the company developing the power station, reports that the "total life cycle emissions of Hinkley Point C will be just 5 gCO_{2eq}/kWh". The paper investigates the greenhouse gas emissions by using three methods: process-based, input-output, and a simplified LCA. The analysis suggests that the GHG emissions associated with future nuclear power plants will be higher than 5 gCO_{2eq}/kWh. They will be very close to previous findings from other studies on the carbon intensity of nuclear power. The results range from 8 to 64 gCO_{2eq}/kWh, and the mean values for the three methods are 16.97, 24.89, and 27.63 gCO_{2eq}/kWh, respectively.

Kadiyala et al. [81] examined published LCAs identifying a quite significant range of variations. They reviewed 26 nuclear power generation LCA studies (49 case representations). Most of these studies defined the system boundary conditions including all the life cycle phases of nuclear power plants. The paper highlights that the centrifuge enrichment method produces lower GHG emissions than the gaseous diffusion enrichment method. This study does not include small modular reactors (SMRs). They found the following mean life cycle GHG emissions for several reactors: 6.26 (fast breeder reactor—FBR), 28.2 (high water reactor—HWR), 11.87 (PWR), 14.52 (BWR) gCO_{2eq}/kWh.

Poinssot et al. [82] performed a LCA of the whole French nuclear fuel cycle. In 2014 the French utility EDF operated 58 PWRs sited in 19 different locations, with a capacity of 63 GW for an overall production of about 400–420 TWh/year. Calculations were performed by means of the Nuclear Energy Life Cycle Assessment Simulation tool (NELCAS), especially developed for the French nuclear fleet. GHG emissions for the French overall fuel cycle are assessed to be 5.29 gCO_{2eq}/kWh. In France, exhausted nuclear fuel is recycled to recover uranium and plutonium.

Nian et al. [83] proposed a methodology based on the principle of energy balance, able to standardize all LCA methodologies related to power generation. An average carbon emission factor of 25.03 gCO_{2eq}/kWh has been obtained for a reference LWR plant sited in Singapore (1000 MW installed capacity; 70% loading factor; 33% average thermal efficiency; 60 years lifetime; 45,000 MWD/t U burn-up).

The paper of Carless et al. [84] deals with the LCA of small modular reactors (SMRs). The study, aiming at assessing the environmental performance of SMRs, states that the mean life cycle GHG emissions of the Westinghouse SMR are 9.1 gCO_{2eq}/kWh (5.9–13.2 gCO_{2eq}/kWh), whereas the GHG emissions from the Westinghouse AP1000 are 8.4 gCO_{2eq}/kWh (5.5–12.1 gCO_{2eq}/kWh). A once-through nuclear fuel cycle is assumed, as well as gas centrifugation being assumed to be the only allowed enrichment method (40 times less energy intensive than gaseous diffusion). The O&M phase takes into account also GHG emissions from tasks such as employees' travel to work.

Ding et al. [31] considered the top five energy technology for electricity generation in China: thermal, nuclear, hydro, wind, and solar photovoltaics. The system boundary included all life cycle stages from extraction of raw materials to power transport. The study does not include the decommissioning phase and that is why it was not included in Table 14. GWP values of 6.36 gCO_{2eq}/kWh are reported for nuclear power.

Table 14. List of LCA results found in the literature for nuclear power plants.

Published Works	Year of the Study	Plant Type	gCO_2eq/kWh
UNECE [29]	2022	PWR and BWR (LWR) Water-cooled SMR	5.1–6.4 4.6–8.4
JRC [79]	2021	PWR EPR (open cycle) EPR (closed cycle)	5.3 (mean) 5 (mean) 4.6 (mean)
Pomponi and Hart [80]	2021	EPR (France)	5 (mean) 8–64 16.97, 24.89 and 27.63 (mean values)
Kadiyala et al. [81]	2016	FBR HWR PWR BWR	6.26 (mean) 28.2 (mean) 11.87 (mean) 14.52 (mean)
Poinssot et al. [82]	2014	PWR (France)	5.29 (mean)
Nian et al. [83]	2014	LWR (Singapore)	25.03 (mean)
Carless et al. [84]	2016	SMR PWR (AP1000)	5.9–13.2 9.1 (mean) 5.5–12.1 8.4 (mean)
Koltun et al. [85]	2018	IV generation GT-MHR	9.57 (w/recycling) (mean) 9.87 (w/o recycling) (mean)
Portugal Pereira et al. [86]	2014	PWR (Japan)	16.95 (mean)
Wang et al. [36]	2019	PWR (China)	10.9–13.9
NREL [16]	2021	LWR PWR BWR HWR FBR	13 (mean) 14 (mean) 21 (mean) 57 (mean) 0.87 (mean)

Koltun et al. [85] performed a LCA of a IV generation nuclear power plant. A high-temperature helium-cooled reactor and gas turbine technology with a modular helium reactor (GT-MHR) is used as an example. The study is actually a hybrid LCA, since it also considers the impact of accidents and incidents (AI) at nuclear power generation facilities. The functional unit for the LCA study for nuclear power was 1 MWh, but the results were normalized to 1 kWh of produced electricity as functional unit in order to compare it with all other studies. The power plant under consideration produces 26.8 PJ of electrical energy per annum (average) over 60 years. Databases of European conditions were used, assuming that all the material needed to build the nuclear reactor was produced there, and then transported to Australia, where the reactor was assumed to be built. The calculated GHG emissions are 9.57 gCO_{2eq}/kWh and 9.87 gCO_{2eq}/kWh with and without recycling, respectively, excluding the impact of accidents and incidents. It should be noted that front-end operations contribute about one-third of the total CO_2 emissions.

Portugal Pereira et al. [86] evaluated the effects of four alternative electricity generation scenarios in Japan after Fukushima. The use of LCA methodology allows to assess scenarios in terms of non-renewable energy (NRE) consumption, global warming potential (GWP), terrestrial acidification potential (TAP), and particulate matter formation (PMF). Emissions from energy technologies were calculated using the GEMIS (Global Emission Model for Integrated Systems) software. The functional unit was 1 kWh of produced electricity. The global warming potential of nuclear power was 16.95 gCO_{2eq}/kWh for PWR reactors, of which 13.80 gCO_{2eq}/kWh were from upstream processes.

Wang et al. [36] evaluated and compared the environmental impacts of three technologies (hydro, nuclear, and wind) in China using LCA. The results showed the greatest environmental impact for wind power technology, followed by nuclear power and hydropower. In terms of global warming potential, GWP, values for nuclear power in the range of 12.4 ± 1.5 gCO_{2eq}/kWh have been reported. The manufacturing stage contributes for at least 30% of the global CO_2 emissions. The decommissioning phase is most relevant for nuclear power in terms of environmental impacts, compared to other technologies.

Also, NREL reviewed many LCAs of nuclear power plants [16]. GHG emissions from nuclear power plants were in the range 0.78–220 gCO_{2eq}/kWh, with a median value of 13 gCO_{2eq}/kWh for light water reactors. Specifically, median values for PWR, BWR, HWR (Heavy Water Reactor), FBR (Fast Breeder Reactor) plants were: 14, 21, 57, and 0.87 gCO_{2eq}/kWh.

Table 14 shows the results of the analysed studies for nuclear power plants.

Table 15 shows that emissions from nuclear power plants are very low and for some systems are less than 10 gCO_{2eq}/kWh, thus positioning it as the energy technology with the lowest emissions. Several studies highlighted that pre-operational phases (i.e., front-end processes) significantly contribute to the overall CO_2 emissions (at least 30%). Also, estimated emissions for Generation IV reactors are below 10 CO_{2eq}/kWh. Higher values were found for HWR, a not widely spread kind of reactor.

The findings of the reviewed papers highlighted that enrichment through the gaseous diffusion process demands a high amount of energy input. Notably, the gaseous diffusion process has been phased out and replaced by the centrifuge enrichment process, which is up to 50 times less energy-intensive than the gaseous diffusion process. CO_2 emissions are significantly impacted by the energy consumed in mining and enrichment processes. Therefore, lower values have been observed in countries with an energy mix dominated by renewable sources rather than fossil fuels. There is a growing interest in SMRs and their applications. Several countries regard SMRs as a potentially valid nuclear option in climate change mitigation. Currently, there are few studies available on SMRs that appear promising in terms of reducing CO_2 emissions for several reasons: extended refueling cycles, heightened thermal efficiency, enhanced construction efficiency via modularity, decreased construction time and mass production, and simplified decommissioning.

Table 15. CO_2 equivalent emissions related to 1 kWh for several nuclear systems weighted according to the year of the study.

Plant Type	Weighted Mean of the Minimum Values	Weighted Mean of the Mean Values	Weighted Mean of the Maximum Values
LWR	5.1	17.8 *	6.4
PWR	8.0	10.5	13.1
BWR		18.4	
FBR		3.0	
HWR		45.5	
SMR	5.1	9.1 **	10.3
EPR (III gen)	8.0	14.0	64.0
GT-MHR (IV gen)	9.6		9.9

* The mean value refers to a value from a 2014 paper and a value from a 2021 paper, while min and max refer to values from a 2022 paper. ** The mean is calculated from a single item.

3. Conclusions

This review aimed at comparing the environmental impact of different electricity generation technologies using LCA carried out in the last ten years. Conventional, renewable, and nuclear technologies have been compared. The functional unit chosen in almost all LCA studies was 1 kWh of produced electricity. Data were converted when a different functional unit was chosen. The environmental impact was assessed in terms of GHG (gCO_{2eq}/kWh) emissions.

The paper shows that both renewable energy technologies and nuclear power can contribute to the EU's goal of zero emissions by 2050 by choosing the most appropriate energy mix, depending on the country's geographical and geological characteristics. A summary of the gCO_{2eq}/kWh associated with each technology considered in this study is shown in Table 16. We have also reported the values of the standard deviation, which are rather high due to the limited number of data points and their wide dispersion.

Table 16. CO_2 equivalent emissions related to 1 kWh for all the technologies considered in this study weighted according to the year of the study.

	Weighted Mean of the Minimum Values	**SD of the Weighted Mean of the Minimum Values**	**Weighted Mean of the Mean Values**	**SD of the Weighted Mean of the Mean Values**	**Weighted Mean of the Maximum Values**	**SD of the Weighted Mean of the Maximum Values**
FOSSIL						
Coal-fired	753.9	246.7	899.8	183.6	1215.4	619.1
Coal-fired with CCS			316.0	136.8		
Gas-fired	379.0	83.4			678.3	361.9
Gas-fired with CCS	49.0				220.0	
HYDROPOWER						
Reservoir	31.1	79.7	26.0	27.2	74.4	129.2
Run-of-river	12.3	20.3	23.2	27.3	19.2	22.9
Not specified	2.2		18.8	5.6	74.8	
WIND						
Onshore	16.6	5.7	16.4	8.6	34.9	6.8
Offshore	25.6		18.1	10.7	45.2	
Onshore and offshore	6.2		9.4		46.0	
PHOTOVOLTAICS						
Mono-Si	31.1	23.5	35.5	24.1	74.3	26.1
Multi-Si	30.8	17.0	36.4	18.7	71.2	25.8
Mono and multi-Si	25.1	3.7	45.6		61.5	54.6
a-Si	12.5	4.5	24.7	18.7	53.9	12.0
CdTe	9.9	1.4	17.4	7.8	40.4	16.8
CIGS	8.3	1.5	26.3	14.9	30.5	5.9
CIS	33.0		17.0		95.0	
Not specified	16.0		39.6	17.4	40.0	
CONCENTRATED SOLAR POWER						
Parabolic trough with storage	26.0		33.2	13.4	60.0	
Tower plant with storage			20.5	11.4		
Tower plant without storage			31.0			

Table 16. *Cont.*

	Weighted Mean of the Minimum Values	SD of the Weighted Mean of the Minimum Values	Weighted Mean of the Mean Values	SD of the Weighted Mean of the Mean Values	Weighted Mean of the Maximum Values	SD of the Weighted Mean of the Maximum Values
			GEOTHERMAL			
EGS	7.3	4.8	32.0		20.6	13.1
Binary			263.0	282.4		
HT single flash	18.0		47.0		24.0	
HT double flash	15.0		13.7	3.8	23.0	
Binary with ORC			28.2	24.9		
Not specified	16.9		35.6	12.4	142.0	
			NUCLEAR			
LWR	5.1		17.8	3.1	6.4	
PWR	8.0	4.6	10.5	4.5	13.1	3.0
BWR			18.4	9.6		
FBR			3.0	2.8		
HWR			45.5	32.4		
SMR	5.1	0.6	9.1		10.3	0.3
EPR (III generation)	8.0		14.0	12.7	64.0	
GT-MHR (IV generation)	9.6				9.9	

Specifically, nuclear systems and wind are the technology with the lowest emissions, followed very closely by hydro, photovoltaics, CSP, and geothermal, with mean values between 18.8 and 26 gCO_{2eq}/kWh for hydro (see note on Table 5), 17 and 45.6 gCO_{2eq}/kWh for PV, 20.5 and 33.2 for CSP, and 13.7 and 47 gCO_{2eq}/kWh for geothermal (excluding the higher value for binary systems not associated with the technology but with a specific location). Nevertheless, all the emission values identified for renewables are at least one order of magnitude, and in some cases two orders of magnitude, lower than those exhibited by fossil technologies. As far as concerns PV systems, a fivefold increase in annual solar cell production within the next 5 to 7 years and a 10-fold increase by the beginning of the next decade will have severe consequences for the PV industry and the research needed to enable it. Along the whole PV value chain, the PV sector must reduce its environmental footprint and become truly sustainable and circular.

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Abbreviations

a-Si	amorphous silicon PV technology
BWR	boiling water reactor
CCS	carbon capture and storage
CdTe	cadmium telluride PV technology
CHP	combined heat and power
CIGS	copper indium gallium selenide
CIS	copper indium selenide
CSP	concentrated solar power
CZTS	copper zinc tin sulfide
DNI	direct normal irradiance
DNSH	do not significant harm
DSSC	dye sensitized solar cell
EDF	Electricitè de France
EGS	enhanced geothermal systems
EPR	European pressurized water reactor
FBR	fast breeder reactor
GEMIS	global emission model for integrated systems
GHG	greenhouse gas
GT-MHR	gas turbine modular helium reactor
GWP	global warming potential
HT	hydrothermal
HWR	heavy water reactor
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IGCC	integrated gasification combined cycle
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
ITRPV	International Technology Roadmap for Photovoltaic
JRC	Joint Research Centre
LCA	life cycle assessment
LWR	light water reactor
NDC	nationally determined contributions
NGCC	natural gas combined cycle
NRE	non-renewable energy
NREL	National Renewable Energy Laboratory
ORC	organic Rankine cycle
PC	pulverized coal
PMF	particulate matter formation
PV	photovoltaics
PVPS	photovoltaic power systems
PWR	pressurized water reactor
QDSSC	quantum dot sensitized solar cell
SMR	small modular reactor
TAP	terrestrial acidification potential
TCP	Technology Collaboration Programme
TTC	twice through cycle
UNECE	United Nations Economic Commission for Europe

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