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Review

A Review of the Life Cycle Analysis Results for Different Energy Conversion Technologies

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Abstract: Technologies that use renewable energy sources (RES) are crucial to achieving decarbonization goals, but a significant number of studies show their relatively high environmental impact during the production phase. Therefore, technologies need to be compared in terms of their life-cycle environmental impact. The life cycle analysis (LCA) methodology is well known and widely employed. However, problems related to the methodological choices prevent taking full advantage of the LCA, as the results of numerous studies are often incomparable. The presented review aims to critically compare the impact of different energy generation technologies—RES (as well as non-RES) energy generators and co-generators. The numeric results are structured and analyzed in terms of the global warming potential (GWP) and non-RES primary energy consumption. The results show that RES technologies are superior compared to conventional fossil-fuel-based systems in most cases, and the high impact during the production and installation phases is compensated in the operational phase. The high variations in GWP from similar technologies result from different methodological choices, but they also show that the wrong choice of the technology in a certain location might cause serious environmental drawbacks when the impact of the RES technology exceeds the impact of fossil fuel-based technologies. Cogeneration technologies using waste as a fuel may even have a negative GWP impact, thus showing even higher potential for decarbonization than RES technologies.

Keywords: LCA; review; energy transformation; renewable; cogeneration

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1. Introduction

Energy generation is considered a major challenge throughout the industrial evolution, especially as the global population is exponentially increasing [1]. Despite international commitments, energy-related CO_2 emissions have risen by 1% per year on average since 2010 [2], and secure, environmentally friendly, and efficient energy sources are needed now more than ever to solve the global problem of climate change. To limit the effects of the energy sector on climate change, significant reductions in CO_2 emissions can be achieved by using the appropriate technologies and policies [3], e.g., performing an energy transition of the global energy sector. Policymakers and scientists see technologies that use renewable energy sources (RES) as one of the main solutions on the road to a decarbonized energy sector. It is estimated that renewable energy and energy efficiency measures can potentially achieve 90% of the required carbon reductions by 2050 [4]. The estimates are based on the impacts of the energy conversion phase, but a significant number of studies show that the environmental impact of RES technologies during the production phase can be relatively high and cannot be neglected. Thus, to reach the deep decarbonization goals, the choice of the technology cannot be based only on the operational phase, ignoring the impacts related to the other life cycle phases of the technology. Energy conversion technologies need to be compared in terms of their life cycle environmental impacts, e.g., employing the well-known methodology of Life Cycle Analysis (LCA).

LCA is applied for two purposes: to quantify/assess the environmental performance of a product or process "from cradle to grave", and to provide general information for evaluating potential improvements of a product and/or a system. The standard methodological framework for performing the LCA consists of four main phases [5]: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation. However, the LCA detailed methodology can include several different methods, approaches, applications, and software packages. The inventory analysis and impact assessment phases are characterized by a number of methodological choices, such as system boundaries (cradle-to-grave, cradle-to-gate, cradle-to-use, etc.), impact assessment (midpoint and/or endpoint), allocation methods, and impact category indicators [6].

Although LCA methodology is widely employed in many studies analyzing energy conversion systems' life cycle impacts, problems related to methodological issues prevent taking full advantage of this method when making decisions related to the choice of cleaner energy conversion technologies. A transparent and homogeneous comparison is often not possible to make because of differences in authors' choices related to LCA methodology, software, databases, boundaries, indicators, functional units, etc. This problem was also noted by [7]. In addition, results can differ because of regional specifics, such as climate.

The breakthrough in the efficiency of energy conversion from burning fuel is undoubtedly linked to cogeneration. The combined production of electricity and heat not only increases the efficiency of energy transformation but at the same time contributes to reducing the negative impact on the environment. Most of the world's electricity is generated by burning fossil fuels (61% in total): coal (35%), natural gas (23%), and oil (3%). The rest is produced using nuclear energy (10%), hydropower (16%), and renewable energy (12%), the share of which is constantly growing, as well as other resources (about 1%) [8]. Burning renewable fuels in combined heat and power production plants further expands the environmental performance of such systems, making an overview of their LCA performance no less important than other RES technologies. The presented review aims to identify opportunities for a sustainable energy transition path, critically comparing the different energy conversion technologies on the basis of the results of the LCAs performed. Moreover, the authors aim to confirm the hypothesis that renewable energy-using technologies are not always superb in terms of their life cycle impact.

The paper consists of the following sections: (1) Introduction: a short presentation of the background of the paper and goal definition; (2) Materials and Methods: a presentation of the choices related to the reviewed energy technologies, data systematization criteria, and used functional units; (3) Results, which is divided into subsections: a review of the methodological choices used and the different energy sources technologies, comparing collected numerical values for impact categories; (4) Discussion: a critical discussion on individual technologies; and (5) Conclusions. Appendix A features a table (Table A1) with a detailed collection of data related to the methodological aspects of the LCA studies reviewed.

2. Materials and Methods

The review includes (Figure 1) literature related to renewable energy conversion systems classifying them as thermal energy generators, electrical energy generators, and co-generators (electrical + thermal), both RES and non-RES.

The review focuses on studies written in English and published in or after 2010 (with some exceptions). The literature is classified according to the energy source type: hydro, wind, solar (both PV and thermal), geothermal, waste, and cogeneration. Each source of energy is discussed in a separate section.

Methodological LCA choices, such as software, environmental impact assessment method, system boundaries, and environmental impact categories were analyzed. Moreover, the region (country) that was applied in the assessment was taken into account. Methodological choices were analyzed for all energy conversion technologies to find the tendencies, and the numeric results were systemized and analyzed for different technologies separately in terms of GWP (gCO_2 eq/kWh) emissions and non-renewable primary energy consumption (MJ/kWh). The overall number of literature sources used in the paper was 120; the number of source studies for the data collected and systemized here was 95.

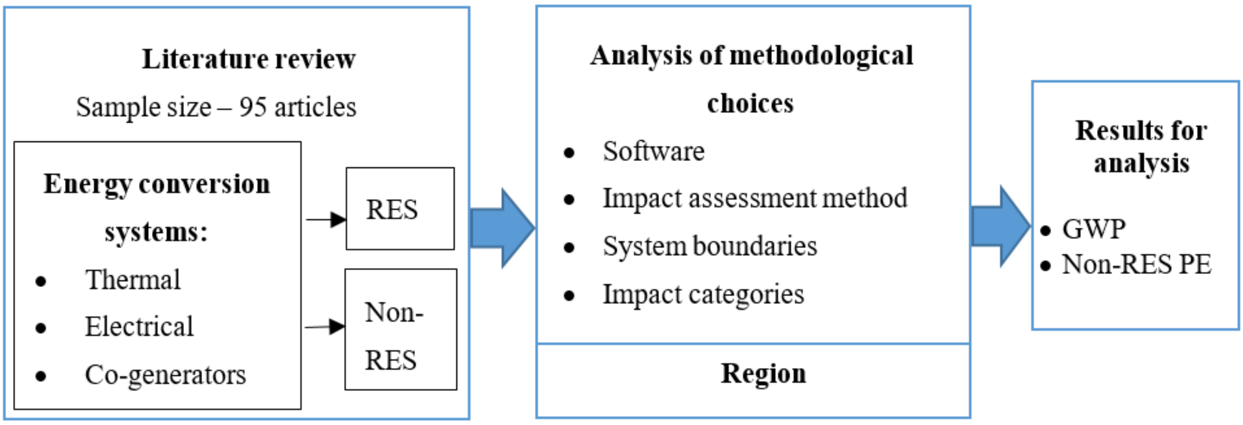

Figure 1. Overall classification of the reviewed sources presenting the results of LCA for energy conversion systems.

3. Results of the Review

3.1. Methodological Aspects of the Studies Reviewed

As was already mentioned, different methodological choices make it difficult to transparently and correctly compare the results of the LCA studies on energy technologies. The methodological aspects of the studies are systemized in detail in Appendix A (Table A1), and Figure 2 summarizes the general aspects of the choices related to the impact assessment methodologies used by the authors, the boundaries of the studies, the LCA software used, and the impact categories. The choices related to functional units were not analyzed in the study. The most commonly used functional unit according to a review performed by Muteri et al. [9] is kWh of produced electricity, and it was further used in this review. As seen from the figure (Figure 2a), most studies used CML methods, yet the ReCiPe method is popular as well. In general, it is obvious that there is not one strongly dominant method. Figure 2b shows boundaries used in the LCA studies and here, the boundaries that are used most commonly are from cradle-to-grave (full life cycle of the system) and from cradle-to-gate. The leading software used in the reviewed studies is SimaPro (Figure 2c); in terms of impact assessment, the most popular category, which is also compared in this study, is still global warming (Figure 2d).

The least unification in LCA methodology is related to the impact assessment methods. Each of them uses different assumptions, thus causing additional uncertainties of the results, and comparison becomes merely indicative. A higher degree of unification in the LCA methodology of energy using systems would be beneficial.

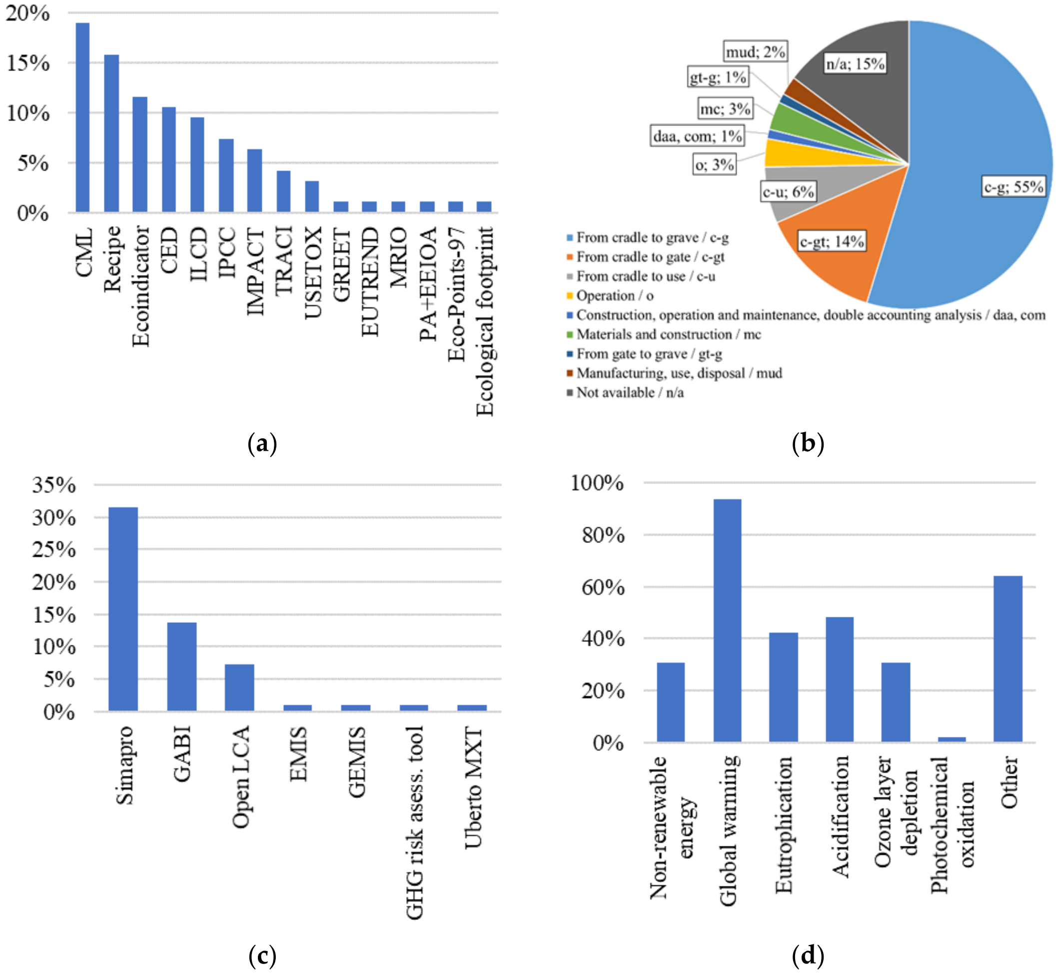

Figure 2. Methodological aspects used in reviewed studies: (**a**) impact assessment methodologies; (**b**) boundaries; (**c**) LCA software; (**d**) impact categories.

3.2. Hydro Energy

Electricity generated in hydropower stations accounts for the largest share of the world's renewable energy conversion. In 2019, this share was 60% [10]. It is widely agreed that this technology is among the "greenest" used for power generation. In addition to the papers' aim to compare GHG emissions for different energy conversion technologies, it also merits to compare results within the same technologies provided by different studies. As expected, the results showed a high level of variation. The widest dispersions can be found in review papers, e.g., in [11,12], and this is logical, taking into account the nature of such papers.

Table 1 summarizes the results obtained from different studies on hydro energy life cycle impact in terms of GHG emissions (a visual representation of the results is provided in Figure 3, together with other reviewed technologies). Looking at the hydropower results on the chart (see Figure 3), three relative zones can be distinguished: "upper", "middle", and "bottom". The clear "upper" zone (3 points over 100 gCO_2 eq/kWh.e) corresponded to [11–13] (in a descending order of GHG emissions). The highest values (237, 160, and 152 gCO_2 eq/kWh.e) referred to the cases with high dams and large reservoirs. The dams were constructed using very large amounts of concrete and steel with a high rate of embodied energy and, consequently, emissions. The reservoirs in this case usually are large, flooded land areas, with biomass decaying under the water and releasing GHG (CO_2 and CH_4) for the years. Moreover, this share of emissions is even more important because it contributes to such a large dispersion of results, as is shown in [12]. This paper also emphasizes the need to distinguish between "net" and "gross" emissions from flooded land because natural ponds (such as lakes and rivers) also emit some amount of GHG into the atmosphere. Emissions from flooded land presented in [13] as "biogenic" are in line with [12], and they were approximately equal to 160 gCO_2 eq/kWh.e (85 gCO_2 + 3 gCH4 × 25) with "a multiplicative uncertainty factor of 2".

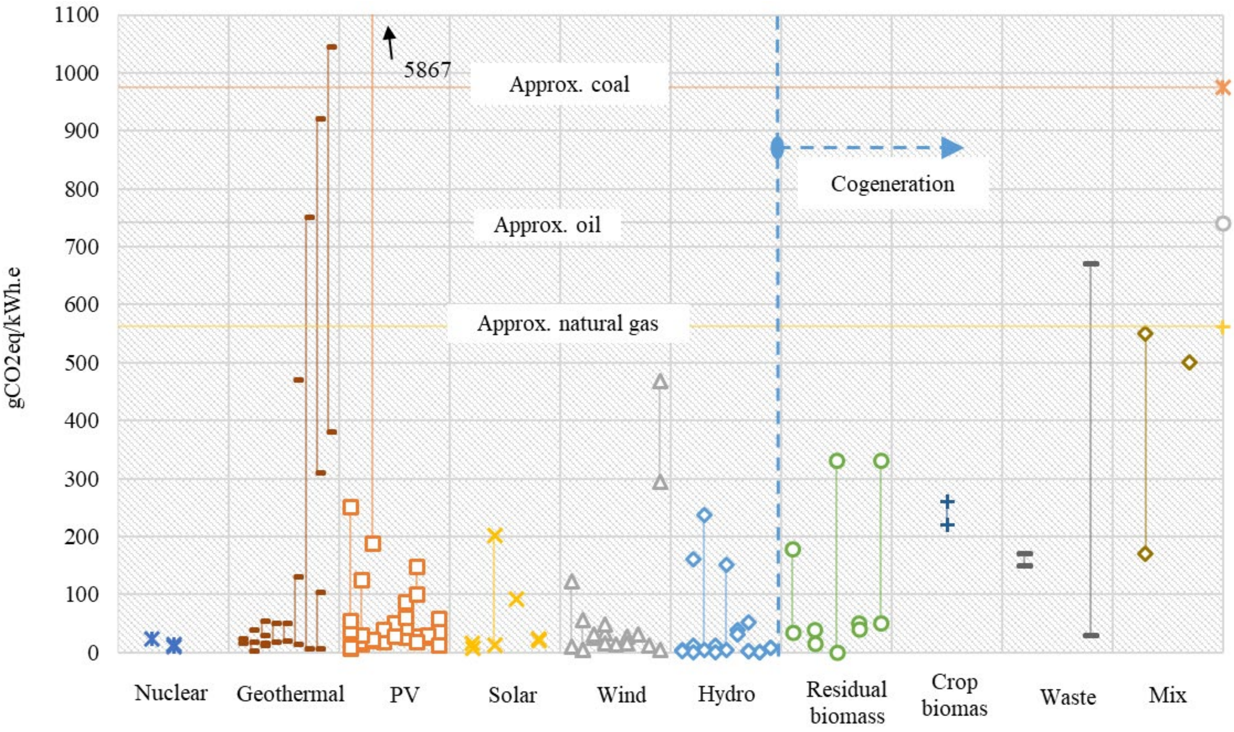

Figure 3. Comparison of GWP of different energy conversion technologies.

The "bottom" zone in Figure 3 (points with values below 20 gCO_2 eq/kWh.e) corresponded to the results of [14–17], as well as the lower parts of [11,12]. All these sources, except for [17], refer to the "run-off-river" cases or reservoir cases excluding emissions from flooded land. In the "run-off-river" cases, the height of dams; reservoir sizes; flooded land areas; and, consequently, biogenic GHG emissions usually are much smaller, and this could explain the large differences between the "upper" and the "bottom" parts of hydropower results (see Figure 3). In this logical sequence, the results of [17] stand out strongly compared to other results referring to the cases with high dams and large reservoirs. Some circumstances, such as the immense capacity of power stations and the pre-impoundment clearance of reservoir areas, could explain this gap, but this case still requires more attention.

Table 1. LCA impact of the hydropower.

Source	Country, Comments	gCO_2 eq/kWh.e
[11]	review	3.7–237
[13]	bGHG only	160
[12]	review, incl. dams	4.5–152
[18]	Thailand, micro	52.7
[19]	Myanmar, large scale, ROR	31.17–39.23
[12]	review, ROR	0.3–13
[12]	review, not incl. dams	avg. 2.9 (0.2–11.2)
[17]	China, mega scale	7.6–9.12
[16]	China	3.1–3.7
[14]	Peru, Andes, ROR	2.06–2.42
[15]	Europe, alpine non-alpine	0.107–1.41

The "middle" zone also contained two atypical cases. Both cases were drastically different in terms of power generation capacity, although both fell into the "run-off-river" category. Pascale et al. [18] presented a 3 kW community hydroelectric system located in rural Thailand, and this "micro" scale probably is the main cause of higher emissions. Aung et al. [19] presents the results of five large-scale hydropower stations with a capacity of 120 to 790 MW. These stations also appear unusual because of the combination of "run-off-river" type with large dams and reservoirs.

3.3. Wind Energy

The amount of global wind energy conversion takes second place among renewable energy sources, standing at about 20% [10]. Like hydropower, wind energy is also considered as one of the "greenest".

Among the results presented in Table 2 (also see the visual presentation of results in Figure 3), [20] is a clear exception with approximately 10 times the values of other sources, ranging from 295.2 to 468 gCO_2 eq/kWh.e. It seems that there is a problem with the conversion of units because these figures are not in line even with the data in the review part of this source. The second highest value of 123.7 gCO_2 eq/kWh.e is presented in [11], although there are no details provided other than a reference to the source itself. The next two points in descending order represent upper parts of quite large intervals. The 55.4 gCO_2 eq/kWh.e value [12] refers to a small turbine (30 kW) with a capacity factor of between 0 and 15%. The 42.75 gCO_2 eq/kWh.e value [21] represents the worst case of six scenarios with different life-spans, capacity factors, replacement rates of parts, transport routes, and waste management options.

Table 2. LCA impact of wind energy.

Source	Country, Comments	gCO_2 eq/kWh.e
[20]	onshore	295.2–468
[11]	review	9.7–123.7
[12]	review	4.6–55.4
[21]	Ethiopia	33.6 (15.72–42.75)
[16]	China	25.4–31.8
[22]	China, onshore	16.4–28.2
[23]	China	31.36
[24]	USA, onshore	14.45
[25]	Colombia, Higher wind speed	12.93
[26]	China, onshore	3.9

The remaining points lie (also see Figure 3) in the relatively compact zone between 3.9 and 31.8 gCO_2 eq/kWh.e. A closer look at this zone revealed some differences; however, there was no clear trend. These results confirm some already known facts that larger wind farms with larger turbines and especially with greater capacity factor values produce lower GHG emissions per energy unit generated. Another obvious fact that is mentioned in almost all of the sources reviewed is that the main part of GHG emissions is generated during the manufacturing phase of wind farms.

3.4. Solar Energy

Solar energy is used to generate electricity and thermal energy. Therefore, these technologies are further discussed separately as photovoltaics and solar thermal collectors.

3.4.1. Photovoltaics

Over the decades, solar PV has been one of the most rapidly developing, mature, and cost-competitive renewable energy technologies [27]. The total cumulative installed capacity for PV at the end of 2020 reached at least 760.4 GW [28]. Solar PV is seen as the second most promising source after wind, and it has 21% of the total CO_2 emission reduction potential from renewables and energy efficiency measures by 2050.

Over the last four decades, a range of viable PV technologies has been proposed, spanning from conventional single-crystal (s-Si) and multi-crystalline silicon (m-Si) to second-generation panels such as amorphous silicon (a-Si), cadmium telluride (CdTe), and cadmium indium gallium selenium (CIGS). More recently, much research and development have gone into third-generation PV technologies including dye-sensitized (DSC), perovskite, quantum dot (QD), and organic (OPV) cells, for instance [29], and a variety of technologies are expected to continue to characterize the PV technology portfolio. First-generation technologies still account for the majority of global annual production [30]. Newer technologies still have barriers that need to be addressed and overcome (durability, price).

Different environmental impact categories of the PV technology strongly vary because of the different component materials, module efficiencies, manufacturing methods, locations, and modes of disposal used in their life cycle. The environmental impacts of some technologies from different generations are compared in [31], where the second-generation a-Si PV technology seems to be among the most sustainable, taking into account the overall effect in nine different impact categories. The thin-film technologies seem more environmentally efficient, and Bergesen et al. [32] estimates that they have the potential to reach GWP values of 6–7 gCO_2 eq/kWh.e. A study by Krebs-Moberg et al. [33] also confirms that m-Si has the highest environmental impacts and that organic thin-film panels have the best life cycle environmental performance.

The concerns about air pollution stemming from PV-system components in all the life cycle stages of the system must be treated with caution [34]; however, most of the CO_2 emissions are attributable to the manufacturing processes of the PV modules [35,36], and multi-Si production is the most contributing phase in terms of the energy demand and environmental impacts [37,38].

The life cycle impact of a photovoltaic installation is strongly related to the geographical features of the location where it is installed. Both solar radiation levels and outside temperatures play a role in the efficient electricity generation of the module, and there are multiple studies to prove it. In cold climate zones, solar radiation is lower, but at the same time, the efficiency of PV panels increases due to the lower ambient temperature [39]. Parisi et al. [40] have demonstrated how irradiation influences GWP for different PV technologies at different radiation levels. Low radiation levels, e.g., for North Europe, may have almost twice the impact compared to Southern countries. Akinyele et al. [41] found even three times higher GWP values for locations with the lowest solar radiation levels. The results of a comparative LCA depend also on the local electricity mix used in the life cycle stages of the assessed products [42].

Muteri et al. [9] reviewed 39 LCA studies relating to the different types of grid-connected PV systems (from first to third generation) and have provided a summary of information and critical analysis. The review showed that, even when similar modules are examined, it is difficult to compare different studies because of different methodological approaches, as well as factors such as different configurations of the modules, installations, and efficiencies. Therefore, following the aim of the review, we purposefully searched life cycle assessment results—GWP and non-RES PE of the PV technologies, wherein the functional unit is kWh.e. The results are summarised in Table 3.

As is seen from the table, most of the PV technologies have very low environmental impacts compared to traditional fossil fuel sources (see Figure 3). Perovskite solar cells show extreme variations in the GWP impact category, but the value of 5867 gCO_2 eq/kWh.e suggests that it should not be treated as a bad technology because the authors [49] only performed a sensitivity analysis assuming different lifetimes and solar radiation levels, and this is the result of the worst case scenario. In general, Perovskite cells are seen as a new and promising technology, offering superior technical performance at a low cost.

Table 3. LCA impact of the PV technologies.

Source	Technology	Country	gCO_2 eq/kWh.e	MJ/kWh.e
[35]	Silicon solar modules	China	60–87	
[36]	Sc-Si and mc-Si with power conditioning system and BOS	Korea	25–41.8	0.35–0.56
[43]	CIGS/Si, CZTS/Si, and AZTS/Si tandem solar modules	n/a	25–29	
[44]	Concentrated solar power plant	China	35	0.514
[45]	Sc-Si PV	Brazil	14.54–18.68	
[34]	Poly-Si, a-Si, CdTe, CuInSe2 (CIS)	Greece	12.28–58.81	
[37]	mc-Si	China	51	0.041–0.87
[46]	Mono-Si, Poly-Si; Fin films: a:Si, CdTe, CIGS, Zn_3P_2, CZTS	United States	18–38	
[32]	Thin-film PV technologies: CIGS and CdTe	United States	20–22	
[40]	DSSC system	North/Central/South Europe	30–125	
[47]	Perovskite	USA	99–147	
[48]	Perovskite	South Europe	35–37	3.98–4.15
[49]	Perovskite	Europe, USA	187–5867	
[50]	OPV	Germany, South Europe	5.8–8.2	

PV systems might also be efficiently integrated with other systems, e.g., Yan et al. [51] presented parametric LCA for the tri-generation system—a combined cooling, heating, and power system with renewable energy and energy storage. They compared the influence of various sizes of solar PV arrays and batteries in such a system and discovered a potential decrease in GWP of up to 46%.

It is obvious from the above that solar technologies impact varies, but it can be minimized with proper selection of the technology, taking into account location specifics, with proper selection of elements and with efficient integration with other systems.

3.4.2. Solar Thermal Collectors

Solar thermal technologies are used in all regions of the world to provide low- and medium-temperature heat, especially when used in domestic applications, but it is still a niche market for industrial processes [52]. Solar systems are considered to be attractive investments, due to their long lifetime of more than 25 years and relatively small maintenance cost. However, the real potential of solar technologies lies in the improvement of their efficiency so that they can achieve satisfactory environmental performance when compared to other renewable energy systems [53].

Compared to what is needed to achieve the Paris Agreement goals, the installation speeds of solar thermal collectors are inadequate. For instance, IRENA's 1.5 °C pathway requires the global solar thermal capacity to increase from around 4 GW in 2018 to 890 GW in 2030 and 1290 GW in 2050 [10]. In this way, solar thermal technologies—and their applications—are thus far at the stage of development.

The literature review of solar thermal technologies demonstrated that even though the publications covered vacuum and flat-type solar collectors, the focus mainly lay on the latter [52,54,55]. Vacuum tube collectors show higher efficiency and are much less affected by variation in the ambient temperature, but as the price is almost 45% higher, it is the flat-type collectors that are the principal option in southern climates [56].

During the last few years, these solar thermal technologies have been taking a large leap towards the improvement of energy efficiency, the minimization of materials used in the production stage, recycling, and the reduction of environmental burdens [57].

In contrast to the widely discussed solar PV technologies, there have been a limited number of life cycle analyses looking specifically at solar thermal technologies [56], with most research papers concentrating on economic analysis [58].

The results of certain LCA studies show that almost all of the environmental impact of solar thermal technologies is produced during the production phase, while in the operation stage, the emissions were negligible [56,57,59].

Moreover, solar thermal systems show their weaknesses in the acidification and eutrophication impact categories, mainly due to the metals used to produce their main components: collector, tank, and copper tubes [59].

In summary, as there was a limited number of publications on solar thermal technologies, and Table 4 presents life cycle assessment results—GWP of the solar thermal technologies for three cases. In all of them, the analysis was covered in southern climates, and thus the variation of the results was moderate (Figure 3). No results for functional unit non-RES PE were found by us.

Table 4. LCA impact of the solar thermal technologies.

Source	Technology	Country	gCO_2 eq/kWh.t
[56]	PV and solar thermal (flat and vacuum collectors)	Greece	22.2–23.8
[59]	Flat-plate solar collectors for DHW	Spain	92.4
[55]	Flat-plate collectors for space heating and DHW	Greece	8–16

Nevertheless, a review by Kylili et al. [52] proved that the geographical location has a decisive impact on GWP. Life cycle assessment results for various European cities (Athens, Barcelona, Milan, Frankfurt, Copenhagen, Oslo) presented a significant difference, with higher latitude locations showing more than twice the GWP values compared to lower latitudes.

3.5. Geothermal Energy

Geothermal energy is an important energy resource, largely contributing to limiting the use of fossil fuels. It can be employed for both electricity and direct uses [60]. Geothermal energy can be directly utilized for space heating and cooling, greenhouse heating, aquaculture, bathing, district heating, and industrial uses. The direct utilization of geothermal energy by countries worldwide is reviewed in detail in the study of [61]. Indirect utilization is when geothermal energy is converted into electricity by using different technologies. Geothermal plants tend both to run trouble-free at nearly full capacity for most of their lifetimes and to serve the baseload power demand well [62]. In 2020, the volume of generating energy from geothermal technologies was 94 TWh. Nevertheless, geothermal technology is still not on track to reach the required annual 13% increase in generation over 2021–2030, corresponding to ≈3.6 GW of average annual capacity additions [63]. Different technologies, such as dry steam; binary cycle; and single flash, double flash, and triple flash enhanced geothermal systems, are employed to generate heat from geothermal sources. The energy conversion technology used for exploiting geothermal systems depends on different aspects, such as the reservoir properties (e.g., geological, geophysical, geochemical, physicochemical, and thermodynamic) [64]. In terms of this technology, geological areas with very high geothermal gradients hold the greatest appeal [65]. At sites with less favorable conditions, only certain plant designs can make up for the energy and material input to exploit the energy potential provided by geothermal reservoir [66,67]. Moreover, the type of technology and the characteristics of the wells must be treated with caution [67].

With some exceptions, geothermal systems are considered one of the least GHG-emitting renewable technologies [62]. The authors compared the energy conversion impact from different energy sources using the GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model. The results show that the biggest impact in geothermal power plants is made during the construction phase. Comparisons of three different types of plants are presented in Figure 4, where EGS is the enhanced geothermal system, and HT–Binary and HT–Flash are hydrothermal binary and hydrothermal flash plants, respectively.

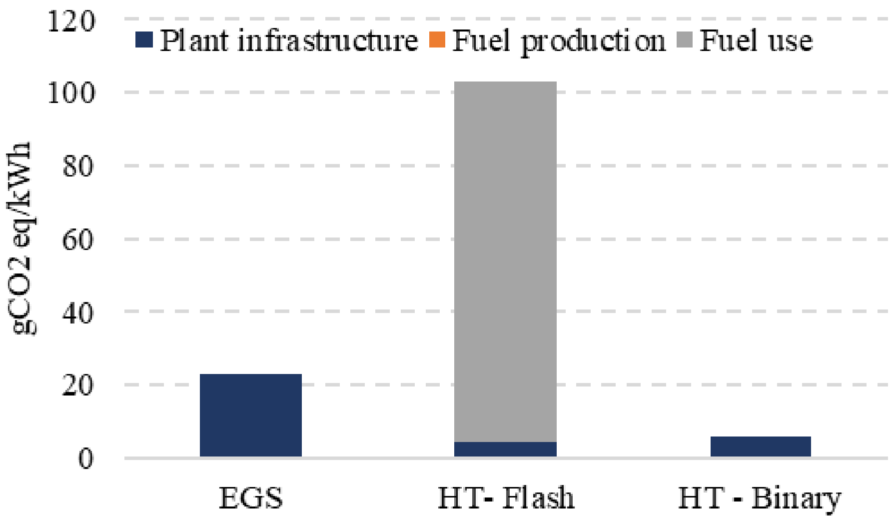

Figure 4. GHG emissions (gCO_2 eq/kWh) by the life cycle stage for various power-generating technologies (Source: [62]).

The authors of the review [64] on different geothermal technologies' life cycle impact results have concluded that most of the LCA studies report global warming, which is mostly caused by the fuel consumption in the construction and operation stages. The results from this study show that the available information about geothermal power production's life cycle environmental impacts is still scarce.

Geothermal plants' contribution to global warming also depends on whether an emission treatment system and substitution of natural emissions are applied or not. Basosi et al. [60] calculated that an existing plant with an AMIS® emissions treatment system emits approx. 0.47 kg CO_2 eq/kWh, and without an emission treatment system, slightly less. Meanwhile, when an emission treatment system is applied together with a 40% substitution of natural emissions, GWP is only 0.3 kg CO_2 eq/kWh.e.

It is also estimated by some studies that the plants that provide electrical power have larger impacts across all impact categories analyzed, compared to plants that provide both power and heat [66,68]. However, [69] notes that this also highly depends on the heat and electricity mix in the region. Meanwhile, [66] emphasizes that for net power and district heat production, the main aspects of environmentally sound plants are the enhancement of the reservoir productivity, reliable design of the deep wells, and an efficient utilization of the geothermal fluid. It must be also noted that there are allocation difficulties related to impacts associated with joint production processes for electricity and heat [70]; therefore, most of the authors of the studies reviewed only addressed the impacts of producing electricity, despite the fact that the plant also generates heat.

The results of different LCA studies show that the construction phase of the plant is largely responsible for the environmental impacts of the geothermal plant [69,70]. However, Ruzzenenti et al. [68] concluded that the materials and energy used for the drilling, cementation, casing, and development of the wells almost offset the benefits provided by the use of non-fossil resources.

Most of the studies reviewed (Table 5) show low GWP impact results compared to conventional fossil-fuel systems, despite the fact that there have been high variations and values found, depending on the region. As a case in point, for power plants analyzed by [68,69], located in Italy, GWP reaches impacts that are similar to the fossil fuel power plants. Moreover, in some cases and depending on the configuration of the plant, there are high variations of the GWP, such as in a power plant located in Germany [66]. Very high environmental performance is noticed in a geothermal plant located in Iceland [70–72], where in some cases it can also be achieved by employing a carbon capture and storage technology [70]. Icelandic rocks are primarily igneous and contain lower amounts of carbonates [73]; this does not only mean lower greenhouse gas emissions, but also enables permanent disposal through mineralization of captured CO_2, as demonstrated by the CarbFix project [74]. Enhanced geothermal systems (EGS) also show considerably better GWP results for different regions, namely, the U.S., Germany, and Iceland, as presented in [62,69,72,75,76]; they also showed that using refrigerants with low global warming potential ensures minimal effects.

Table 5. LCA impact of geothermal technologies.

Source	Technology	Country	gCO_2 eq/kWh.e	gCO_2 eq/kWh.t	MJ/kWh.e
[62]	EGS, geothermal flash, hydrothermal binary	U.S.	5.7–103		
[60]	Plant with AMIS® emissions treatment system	Italy	470		
[67]	Four plants: 1 single flash and 3 steam with entrained water separated at the wellhead	Italy	380–1045		
[68]	Small combined geothermal heat and power plant	Italy	309–921		
[66]	Binary plants	Germany	7–750	7–650	
[76]	Hydrothermal binary plant	Germany	38.2		0.185
[77]	Binary power plants: various geothermal ORC power plant concepts and working fluids	Germany	13.2–130.1		
[69]	Enhanced geothermal systems (EGS)	Germany	29.5–54.9	2.7–9.2	
[75]	Enhanced geothermal systems (EGS)	Germany, Switzerland	16.9–49.8		
[70]	Double flash combined heat and power with and without CCS (carbon capture and storage)	Iceland	11.2–15.9		
[72]	Enhanced geothermal systems (EGS)	Iceland	1.6–17.4		
[71]	Double-flash combined heat and power plant	Iceland	15–24		

However, there are studies, such as [67], that prove that CO_2 emissions from geothermal energy may be of the same order of magnitude as those from fossil power plants and that demonstrate that geothermal electricity conversion is not exempt from environmental drawbacks. Thus, geothermal systems must be designed carefully with environmental consideration throughout the whole life cycle of the system. For this purpose, even a simplified life cycle assessment (LCA) method to assess the environmental impacts of deep geothermal energy plants—those that are in the pipeline or already in operation—has been developed to help geothermal project developers evaluate the environmental performance of their project, in particular against fossil alternatives (https://www.geoenvi.eu/lca-for-geothermal/, accessed on 9 September 2022).

3.6. Waste

The European Union adopted the Circular Economy Package in 2018, wherein the waste-to-energy (WtE) sector plays a crucial role towards a resource-efficient, low-carbon, circular economy. WtE has several purposes: to reduce the amount of waste sent to landfills by producing usable energy: heat and/or electricity [78].

Waste can be classified as organic and non-organic, while the main technologies used for WtE are direct combustion, thermochemical, physiochemical, and biochemical processes.

According to this review and in the context of LCA, much attention is paid to biochemical–anaerobic digestion processes for food waste [79,80] and municipal waste [81]. This is a tested technology for waste management that has a global application, but it has been given less attention recently in terms of thermal treatment [82].

The LCA modeling techniques applied in the research outlined a large degree of variability in technological systems, with different system boundaries, functional units, impact categories, and geographical features complicating the comparison. Nevertheless, the most widely assessed impact categories are global warming [83–85], eutrophication/acidification [86], toxicity, etc. (Table 6).

Table 6. Assessed impact categories in the investigated studies [82].

LCIA-Category	Share
Global warming	98%
Eutrophication/acidification	79%
Toxicity	57%
Respiratory effects	57%
Energy/resources	52%
Ozone depletion	33%
Land use	12%

In this research, we found a problem with the comparability of the WtE LCA results due to different functional units. Most researchers choose the input-based approach with a specific amount of solid, food, or other waste as the functional unit [79,80,85]. It was only in a few cases that the authors followed the output-based approach, wherein the results were presented towards the amount of useful products [86].

The critical review of WtE also stated the major challenges in comparability LCA: while most of the studies analyzed followed an input-based approach (80%), some of them did not clearly state their functional unit, and/or the functional unit could not be retrieved [82].

The analysis of the cogeneration processes using waste appeared to be more informative for the purposes of comparison of the functional units for gCO_2 eq/kWh or MJ/kWh; as a result, some of the data are presented in the following section.

3.7. Cogeneration

Usually, during the cogeneration process, two types of products are produced: electricity and heat. Different allocation methods are used to distribute the environmental impact between these two products on the basis of energy, exergy, the value of emissions, fuel chargeable to power, shared emissions, and other methods. Variations of up to 88% were identified among the most common methods applied to the allocation of resources and emissions [87]. In some cases, in addition to energy flows, some other co-products can include, for example, combined synthetic natural gas and electricity production from lignocellulosic biomass [88], electricity and cold [89], and electricity and hydrogen [90,91]. Due to electricity cogeneration from excess heat occurring in the production of gas, both gas and the electricity are potential products, with their relative amount depending on the process design. The exergy allocation method is often referred to as the most objective and more precise [87,89,92]. The problem related to electrical and thermal energy allocation in the cogeneration process can be avoided by choosing the primary energy as the functional unit [93]. The case of co-processing sewage sludge and the organic fraction of municipal solid waste shows that anaerobic co-digestion provides better performance than dark co-fermentation, mainly because of the higher energy recovery for electricity and thermal energy production [94]. In looking for better options of cogeneration of waste products, recovery of used cooking oil in cogeneration plants has in general lower values in terms of environmental impacts than its employment in biodiesel production [95]. The effective integration of traditional and renewable sources and the proper operation of thermal storage units increase the system flexibility and sustainability, helping to deal with the intermittent nature of the solar source [96].

A summary of the LCA results for cogeneration technologies is presented in Table 7. The nature of the indicators is very different and depends on the priorities of the authors, the specifics of the technology, and the functional unit chosen (electricity and/or thermal output). The ranges of the indicator values are also very wide. They depend mainly on the type of the primary energy source (RES or Non-RES) and the cogeneration technology. Unfortunately, no clear trends in the dependencies of the indicators were observed in the studies examined.

Table 7. LCA impact of the cogeneration technologies.

Source	Technology	Country	Energy Source	gCO_2 eq/kWh.e	gCO_2 eq/kWh.t	MJ/kWh.e	MJ/kWh.t
[92]	CH4-fueled combined liquid fuel and power co-production based on chemical looping combustion and CO_2 storage	China	Natural gas	52 ÷ 57 [1]			
[97]	Micro cogeneration systems with fuel cell, Stirling, and reciprocating engine configurations	Germany	Natural gas	260 ÷ 520			
[98]	A bioenergy power plant integrated with a juice factory Residual biomass (citrus peel)	Italy	Residual biomass	−330 ÷ 1		−7.53 ÷ −2.06	
[99]	Biomass direct combustion steam turbine cogeneration	Turkey	Residual biomass	40 ÷ 50	10	0.67	0.16
[100]	A biomass combustion cogeneration (heat and power) plant and a district heating plant	Italy	Residual and crop biomass		50 ÷ 330		1.01 ÷ 4.27
[101]	Electricity generation from the combined use of energy cane locally cropped with imported pellet	France	Crop biomass	220 ÷ 260		2.20 ÷ 2.55	
[69]	Geothermal heat and/or power plants	France	Geothermal sources	20 ÷ 50	3 ÷ 9		
[94]	Biogas turbine and internal combustion engine cogeneration	Italy	Waste			8.63	4.27
[93]	Municipal solid bio-waste combustion/gasification with electricity recovery, anaerobic digestion with energy cogeneration from biogas/biomethane	Italy	Waste	−30 ÷ 670		−0.07 ÷ 2.7	
[102]	Electricity import, supply of biomass, and CHP	Denmark	Country mix	170 ÷ 550		2.1 ÷ 8.1	
[103]	Hungarian grid	Hungary	Country mix	500		12.2	
[69]	Electricity supply system	France	Geothermal sources	20 ÷ 50	3 ÷ 9		
[94]	CH4-fueled combined liquid fuel and power co-production based on chemical looping combustion and CO_2 storage	Italy	Waste			8.63	4.27
[93]	Micro cogeneration systems with fuel cell, Stirling, and reciprocating engine configurations	Italy	Waste	−30 ÷ 670		−0.07 ÷ 2.7	
[102]	A bioenergy power plant integrated with a juice factory Residual biomass (citrus peel)	Denmark	Country mix	170 ÷ 550		2.1 ÷ 8.1	
[103]	Biomass direct combustion steam turbine cogeneration	Hungary	Country mix	500		12.2	

[1] with carbon capture and utilization.

3.8. Results for Different Energy Conversion Technologies

All results from the previous section related to separate energy conversion sources were consolidated into one comparative graph (Figure 3).

No comparison of the non-RES primary energy demand for different sources was made because of the limited amount of data available. The sufficient amount of GWP indicators, wherein the functional unit is kWh of produced electricity, makes it possible to present differences and ranges for different technologies, comparing them to fossil-fuel-based energy conversion systems (coal, oil, and natural gas). Some values of RES generators are even higher than the traditional fossil-fuel-based technologies, pointing to some design drawbacks or worst-case scenarios. Most of the values are in a range from 0 to 100 gCO_2 eq/kWh.e, proving that RES technologies, if carefully designed with the environmental issues in mind, have a high potential to replace conventional technologies and lead to the global decarbonization goals.

4. Discussion

This review aimed to identify any opportunities for comparing environmental impacts of different power generation technologies using the results of the previously performed LCAs. The paper further compared different RES-based technologies—hydro, wind, solar (PV and thermal collectors), geothermal, and waste—with the results of cogeneration technology as an alternative, an efficient way to transform energy with a smaller environmental impact. The comparison was made using kWh of converted energy as a functional unit. The impact was assessed in terms of GWP (global warming potential), which is the most common indicator in similar studies, and demand for non-RES primary energy. There are many differences in the methodological approaches in different LCA studies, which were systematized in Annex A; for numerical comparison, only studies that involved the same functional units were used. Each of the technologies was reviewed separately, and the data were structured and compared to the other alternative technologies as the final result of the review paper.

Electricity generated in hydropower stations takes the biggest share of the world's renewable energy conversion, and in most cases has the smallest global warming potential (GWP) compared with other RES. However, two typical cases can be distinguished, each with its own level of GWP. In the case of high dams and large reservoirs, the expected GWP value is between 140 and 240 gCO_2 eq/kWh.e, and in the run-off-river case, it is below 15 gCO_2 eq/kWh.e. Such significant differences occur depending on whether biogenic GHG emissions are included in the assessment or not.

Wind energy is the second largest source of RES energy. The reviewed literature confirms the already-known facts that larger wind farms with larger turbines, especially those that have greater capacity factors, produce lower GHG emissions per energy unit. Another obvious fact mentioned in almost all of the studies reviewed is that the main part of GHG emissions is generated during the manufacturing phase of wind farms. The GWP effect of wind power generation is comparable to PV and hydro energy. The approximate average value derived from the sources reviewed can be estimated as 25 ± 10 gCO_2 eq/kWh.e. Any values outside this interval usually are associated with scenarios that are based on near-marginal favorable or unfavorable assumptions.

Solar PV technologies are some of the most rapidly developing RES technologies, where different generations of solar cells are applied and developed. Despite their relatively high environmental impacts during the production stage, these technologies have a small overall impact during the whole life cycle, compared to the conventional fossil-fuel-based systems. Some of the PV technologies, such as thin-film technologies, seem extremely environmentally efficient and are estimated to have the potential to reach GWP values of 6–7 gCO_2 eq/kWh. This level of impact is hundreds of times lower compared, e.g., to coal power plants. However, it is important to note that geographic features of a photovoltaic installation have a significant effect on the electricity generation, and therefore it is also an important factor when it comes to assessing the sustainability of the PV technologies within their life cycle, as low radiation levels, such as those that exist in Northern Europe, may double or triple the impacts.

Solar thermal systems are also presented as clean energy conversion systems with quite a long lifetime of more than 25 years and relatively small maintenance costs. LCA studies show that here, the production stage plays the largest role, producing almost all of the environmental impact for different types of solar collectors. Meanwhile, the results for the operation stage are insignificant. The review also proved that the geographical location has a decisive impact on energy and GWP, with northern locations presenting up to twice the GWP values and as much as half the GWP and energy savings of southern locations.

As most of the studies on geothermal system LCA covered in this review showed, these systems have low GWP impact results compared to the conventional fossil fuel systems, despite the high variation and values depending on the region and the type of the system. In particular, low impacts are found in geothermal power plants in Iceland and when enhanced geothermal systems (EGS) are employed with the application of different additional technologies, such as carbon capture and storage, combined heat and power production, or the use of refrigerators with low GWP impacts. These plants may reach extremely low GWP values of less than 2 gCO_2 eq/kWh. However, there are studies that prove that emissions of CO_2 from geothermal energy sources may have the same order of magnitude as fossil fuel power plants, demonstrating that geothermal electricity conversion is not exempt from environmental drawbacks. Thus, geothermal systems must be designed carefully with environmental factors in mind throughout the whole life cycle of the system.

The review of LCA studies of waste-to-energy (WtE) systems identified many differences in system boundaries, functional units, impact categories, and geographical features. Therefore, a problem was found with the comparability of WtE LCA results, as in most cases the functional unit was found to be a specific amount of waste. Thus, the analysis of using waste as a fuel in cogeneration processes was shown to be more informative and could present some results for GWP (gCO_2 eq/kWh) emissions and non-renewable energy consumption (MJ/kWh).

LCA results for cogeneration technologies have a strong variation due to the allocation of the environmental impact between different products such as electricity, heat, cold, synthetic natural gas, hydrogen, and recovery of used cooking oil. Moreover, LCA results for GWP strongly depend on the type of the primary energy source (RES or Non-RES) and the cogeneration technology. For cogeneration plants using natural gas as fuel, the GWP is $260 \div 520$ CO_2 eq g/kWh.e. Meanwhile, for plants using residual waste, it can even be negative: $-300 \div 1$ CO_2 eq g/kWh.e. The negative impacts are found when residual materials (residual biomass, bio-waste) were considered more dangerous to the environment than the energy conversion process as such.

5. Conclusions

In conclusion, of the review, RES technologies can be said to be clearly superior to the conventional fossil-fuel-based systems in most cases (Figure 3), and, despite the high impact during the production and installation phases, their impacts are compensated with miniscule impacts during the operational phase. High variations in GWP results occur because of different methodological choices, but they also show that inappropriate technology deployed in a certain location might be the reason for serious environmental issues when the impact of the RES technology excels over fossil-fuel-based technologies. Thus, RES systems must be designed carefully with environmental factors in mind through the whole life cycle of the system, taking into account the specifics of the location, such as solar radiation, external temperatures, and geological properties. The initial hypothesis raised by us that renewable-energy-using technologies are not always superb in terms of their life cycle impact was confirmed. This critical review might be beneficial for policymakers when making decisions on decarburization of the energy sector.

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List of Acronyms

a-Si	amorphous silicon PV technology
CCS	carbon capture and storage
CdTe	cadmium telluride PV technology
CED	cumulative energy demand
CExC	cumulative exergy consumption
c-g	from cradle to grave
c-gt	from cradle to gate
CHP	combined heat and power
CIGS	cadmium indium gallium selenium PV technology
CML	impact assessment method by Institute of Environmental Sciences at Leiden University
com	construction, operation, and maintenance
c-u	from cradle to use
daa	double accounting analysis
DSC	dye-sensitized PV technology
DHW	domestic hot water
EGS	enhanced geothermal systems
FU	functional unit
GHG	greenhouse gas
gt-g	from gate to grave
GWP	global warming potential
HT	hydrothermal plant
ILCD	International Reference Life Cycle Data System
IPCC	intergovernmental panel on climate change
kWh.e	kilowatt hours of electricity
kWh.t	kilowatt hours of thermal energy
LCA	life cycle assessment
LC-TEC	The Thermo Ecological Cost Life Cycle Assessment
mc	materials and construction
m-Si	multicrystalline silicon PV technology
mud	manufacturing, usage, disposal
non-RES	non-renewable energy sources
o	operation
OPV	organic cell PV technology
ORC	organic Rankine cycle
PA + EEIOA	process analysis + env extended IO analysis
PE	primary energy
PV	photovoltaics
QD	quantum dot PV technology
ReCiPe	impact assessment method by RIVM and Radboud University, CML, and PRé Consultants
RES	renewable energy sources
ROR	run-off-river
s-Si	conventional single-crystal PV technology
WtE	waste to energy

Appendix A

Table A1. Methodological aspects of the reviewed LCA studies.

Source	Energy Sources		Converted Energy		Software	Impact Assessment Method	Boundaries	Impact Categories						
	RES	Non-RES/Fossil	Electricity	Heat				Non-Renewable Energy	Global Warming	Eutrophication	Acidification	Ozone Layer Depletion	Photochemical Oxidation	Other
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
[104]	+		+		n/a	ESA ReCiPe	daa, com							+
[105]	+		partly		n/a	n/a	n/a		+					+
[18]	+		+		n/a	n/a	c-g	+	+	+	+	+	+	+
[13]	+		+		n/a	Biogenic GHG only as input to LCA	n/a		+					
[12]	+		+		n/a	n/a			+					
[19]	+		+		n/a	LCI, LCIA	c-g		+		+		+	+
[14]	+		+		SimaPro v8.3.0.0	ReCiPe	n/a		+					+
[15]	+		+		SimaPro 8.5 (ecoin vent)	ReCiPe 2016, Impact 2002+, Eco-points 97	c-g		+					+
[106]	+		+		Umberto NXT; (ecoinvent v3.2)	ReCiPe, IPCC	c-g	+	+	+				+
[107]	+		+		n/a	n/a	n/a							+
[17]	+		+		GHG Risk Assess ment Tool	LCA ISO/TS 14067	c-g		+					
[16]	+		+		SimaPro	CML2001	n/a		+	+	+			+
[21]	+		+		SimaPro 8.0.3.14 (Ecoinvent 3.01)	ReCiPe 2008	c-g		+					+
[24]	+		+		n/a	PA + EEIOA	mc		+					+
[22]	+		+		n/a	n/a	c-g		+					
[23]	+	+	+		n/a	n/a	n/a		+					
[25]	+		+		n/a	ILCD	n/a		+					+
[26]	+		+		n/a	n/a	c-g		+					

Table A1. *Cont.*

Source	Energy Sources		Converted Energy		Software	Impact Assessment Method	Boundaries	Impact Categories						
	RES	Non-RES/Fossil	Electricity	Heat				Non-Renewable Energy	Global Warming	Eutrophication	Acidification	Ozone Layer Depletion	Photochemical Oxidation	Other
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
[108]	+		+		Simapro	Eco-indicator 99; + "original"	n/a							+
[20]	+		+		n/a	n/a	c-g		+					
[109]	+	+	+		SimaPro	CML 2001	o		+		+	+		
[110]	+		+	+	SimaPro 8.2	n/a	c-g		+		+	+		+
[111]	+	+	+		n/a	CML-IA baseline V3.02/EU25	c-g		+					
[112]	+			+	SimaPro 8	ReCiPe, USEtox, and Ecological footprint	c-g		+	+	+	+	+	+
[113]	+		+	+	n/a	n/a	c-u		+					
[35]	+		+		n/a	n/a	c-g		+					
[36]	+		+		SimaPro 7.1	IPCC 1996 GWP 100a	c-g	+	+					
[43]	+		+		GaBi	IPCC, USEtox, EUTREND, CML 2002	c-g		+	+				+
[44]	+		+		n/a	MRIO-LCA	c-g	+	+					
[7]	+		+	+	openLCA® 1.6.3	Matrix-based LCA method	c-gt	+						
[51]	+	+	+	+	Simapro 8	TRACI 2.1 LCIA model	c-g		+	+	+	+		+
[36]	+		+		SimaPro 7.1	IPCC 1996 GWP 100a	c-g	+	+					
[45]	+		+		GaBi 4.0	Ecoinvent 1.01 CML 2001 CED	c-u		+					
[34]	+		+		GaBi	Eco-Indicator '95	c-u		+					
[37]	+		+		GaBi 4.3	CML 2001	c-g	+	+	+	+	+	+	+
[42]	+		+		SimaPro 7.1.8	CML 2001	mud		+	+	+	+	+	+
[46]	+		+		GaBi	TRACI 2.1	c-gt	+	+					+

Table A1. *Cont.*

Source	Energy Sources		Converted Energy		Software	Impact Assessment Method	Boundaries	Impact Categories						
	RES	Non-RES/Fossil	Electricity	Heat				Non-Renewable Energy	Global Warming	Eutrophication	Acidification	Ozone Layer Depletion	Photochemical Oxidation	Other
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
[32]	+		+		n/a	Traci1.0 ReCiPe 2008	mud		+	+	+		+	Etc
[40]	+		+		SimaPro	ReCiPe 2008, CED	c-gt		+					
[29]	+		+		openLCA v1.4.2	ReCiPe v1.0.5, CED	c-g		+	+	+	+	+	+
[47]	+		+		GaBi 6.0	TRACI ReCiPe	c-gt		+	+	+			+
[48]	+		+		SimaPor	n/a	c-gt	+	+	+				+
[49]	+		+		GaBi 6.0	ILCD	c-gt		+	+	+	+	+	+
[33]	+		+		SimaPro 8.5.2.0	ReCiPe	c-g		+	+	+	+		+
[50]	+		+		EMIS v5.7	IPPC 2007 CED ReCiP USEtox EPB	c-gt		+					+
[60]	+		+		OpenLCA	ILCD 2011 Midpoint + ReCiPe 2016	c-g		+	+	+	+	+	+
[67]	+				SimaPro	CML 2002	c-u		+		+			+
[66]			+	+	n/a	CED	c-g		+	+	+			+
[68]	+		+	+	SimaPro	CML 2011 CED	n/a		+	+	+			+
[62]	+		+	+	n/a	GREET	c-u		+					
[71]	+		+	+	Gabi	ILCD	c-g		+	+	+	+	+	+
[76]	+		+	+	n/a	IMPACT 2002+	c-g	+	+	+	+			
[77]	+		+	+	n/a	CED	c-g		+	+	+			+
[70]	+		+	+	SimaPro	CML-IA CED	c-gt		+	+	+	+	+	+
[72]	+		+	+	n/a	IPCC 2013	gt-g		+					

Table A1. *Cont.*

Source	Energy Sources		Converted Energy		Software	Impact Assessment Method	Boundaries	Impact Categories						
	RES	Non-RES/Fossil	Electricity	Heat				Non-Renewable Energy	Global Warming	Eutrophication	Acidification	Ozone Layer Depletion	Photochemical Oxidation	Other
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
[69]	+		+	+	OpenLCA	ILCD 2011	c-g		+					
[75]	+		+		n/a	IMPACT 2002 + LCI	c-g		+	+	+			+
[94]	+		+	+	n/a	CML-IA baseline V3.02/ EU25	n/a	+	+					+
[114]		+	+	+	n/a	Mix	c-g		+	+	+		+	+
[102]	+	+	+		n/a	n/a	n/a	+	+	+	+	+	+	+
[92]		+	+		n/a	n/a	c-gt		+					
[98]	+		+		OpenLCA 1.10.1	ILCD 2018	c-g	+	+	+	+	+	+	+
[89]		+	+	Cold	SimaPro 8.0	IPCC 2013 GWP 20a	c-gt		+					
[115]	+	+	+	+	n/a	LC-TEC	c-g	+	+					
[101]	+		+		SimaPro 8.1	CML IA baseline V3.02; Re-CiPe Midpoint (E) V1.12	c-g	+	+	+	+		+	+
[91]		+	+	H2	n/a	Manual	c-g	+	+					
[116]		+		+	SimaPro 7.1	Eco-Indicator 99	c-g	+	+	+	+	+		+
[93]	+		+	+	Ecoinvent	Impact 2002+	c-g	+	+					+
[97]		+	+	+	n/a	n/a	c-g		+		+			
[69]	+		+	+	OpenLCA	ILCD 2011	c-g		+					
[96]	+	+	+	+	n/a	Manual	c-g		+					
[117]	+	+	+	+	n/a	ILCD	c-g	+	+	+	+		+	+
[99]	+		+	+	SimaPro V8.1.1.16	CML IA baseline V3.03	c-g	+	+	+	+	+	+	+
[118]		+	+	+	n/a	Manual	c-g		+					
[103]	+	+	+		OpenLCA, Ecoinvent v3.2	Cumulative energy demand, CML, ReCiPe	c-g	+	+	+	+	+	+	+

Table A1. *Cont.*

Source	Energy Sources		Converted Energy		Software	Impact Assessment Method	Boundaries	Impact Categories						
	RES	Non-RES/Fossil	Electricity	Heat				Non-Renewable Energy	Global Warming	Eutrophication	Acidification	Ozone Layer Depletion	Photochemical Oxidation	Other
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
[95]	+		+	+	n/a	CML-IA, CExC	c-gt		+					+
[100]	+		+	+	SimaPro 8	ReCiPe (I) 2016	c-gt	+	+	+	+	+	+	+
[54]	+			+	SimaPro 7.3:	CED; Greenhouse Gas Protocol; Eco-indicator 99	n/a		+					+
[119]	+			+	n/a	EcoIndicator 99, Egalitarian Approach	c-g				+			+
[52]	+			+	GaBi	n/a	c-u	+	+	+	+	+	+	+
[53]	+			+	SimaPro 8.5	ILCD, Impact 2002+, CED, Eco-points 97, Eco-indicator 99 and IPCC	c-g		+	+	+	+		+
[56]	+		+	+	Simapro	n/a	c-g		+	+	+			+
[110]	+			+	SimaPro 8.2	n/a	c-g	+	+	+	+	+		+
[57]	+			+	n/a	Eco-indicator'95	c-g	+	+	+	+	+		+
[59]	+			+	Gabi	n/a	c-g	+	+	+	+	+	+	
[55]	+			+	GEMIS	EcoIndicator 99	c-g		+	+		+		+
[58]	+		+	+	n/a	EcoIndicator 95	c-gt		+					+
[79]	+		+		Gabi 4.0	CML 2001	n/a		+		+	+	+	+
[84]	+		+		SimaPro 8.05	Eco-indicator 99	o		+		+			+
[83]	+		+		SimaPro 8.02	Impact 2002+	c-g	+	+					+
[86]	+		+	+	n/a	ReciPe v1.12	c-g	+			+	+		+
[120]	+		+		SimaPro7.7.3	Ecoindicator99 2.09	c-g	+	+	+	+	+		+
[81]	+		+		Gabi 4.0	CML method	o		+	+	+	+	+	
[80]	+				n/a	Classic LCA	mc		+					+
[85]	+		+		GABI 4.0	CML 2001	mc		+		+			

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