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Life cycle assessment of electricity production from renewable energies: Review and results harmonization

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A B S T R A C T

A significant number of Life Cycle Assessment (LCA) analyses of renewable energy technologies is available in the literature, even though there is a lack of consistent conclusions about the life cycle impacts of the different technologies. The reported results vary consistently, according to the size and the technology of the considered plant, thus limiting the utility of LCA to inform policy makers and constituting a barrier to the deployment of a full awareness on sustainable energies. This variability in LCA results, in fact, can generate confusion regarding the actual environmental consequences of implementing renewable technologies. The article reviews approximately 50 papers, related to more than 100 different case studies regarding solar energy (Concentrated Solar Power, Photovoltaic), wind power, hydropower, and geothermal power. A methodology for the harmonization of the results is presented. The detailed data collection and the results normalization and harmonization allowed a more reliable comparison of the various renewable technologies. For most of the considered environmental indicators, wind power technologies turn out to be the low end while geothermal and PV technologies the high end of the impact range where all the other technologies are positioned.

Contents

1. Introduction

Over the past 40 years the world energy final consumption approximately doubled and the growth in global energy demand, in a scenario with no change in government policies, is projected

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Nomenclature

AP	Acidification Potential
a-Si	Amorphous Silicon
CdTe	Cadmium Telluride
CE	Conversion Efficiency
CED	Cumulative Energy Demand
CF	Capacity Factor
CIGS	Copper Indium Gallium Selenide
CSP	Concentrated Solar Power
$D_{i,harm}$	Harmonized data related to the environmental indicator i
$D_{i,pub}$	Published data related to the environmental indicator i
D_i	Lifetime harmonized data related to the environmental indicator i
DNI	Direct Normal Irradiance
EP	Eutrophication Potential
EPBT	Energy Pay-Back Time
GHG	Greenhouse Gas
GWP	Global Warming Potential
IPCC	International Panel on Climate Change
IQR	Inter Quartile Range
ISO	International Organization for Standardization
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCA	Life Cycle Assessment
LCSA	Life Cycle Sustainability Assessment
LU	Land Use
ME	Module Efficiency
Mono-Si	Monocristalline Silicon
Multi-Si	Multicristalline Silicon
POCP	Photochemical Ozone Creation Potential
PR	Performance Ratio
PV	Photovoltaic
SE	Solar-to-electric Efficiency
SF	Solar Fraction
WC	Water Consumption

to rise sharply over the coming years [1]. The total primary energy supply reached the value of 13,113 Mtoe in 2011 [2]; fossil fuels remain the main source of energy supply, with a share of 81.9% of total final consumption in 2010, even though the contributions of renewables are increasing.

In this context, the environmental impact associated to different energy technologies is becoming more and more a key issue to support policy decisions; carbon footprinting, other GHG accounting approaches and Life Cycle Assessment (LCA) are commonly used in this regard [3–6].

Evaluation approaches with a single indicator, such as Carbon Footprint, are certainly more attractive than LCA due to their simplicity [7], but may result in oversimplification. With particular regard to electricity generation technologies, recent studies [8] confirm that focusing only on GHG emissions may lead to wrong conclusions concerning their environmental consequences. As a matter of fact, many renewable energy technologies do have an impact on water, ground, wildlife, landscape, therefore the mere evaluation of CO_2 emissions results limitative. Thus, a range of key indicators must be considered to evaluate the sustainability of energy generation technologies [9] and a LCA approach is desirable to avoid impact shifting from one life cycle phase to another [10]. In this regard, also the utilization of a Life Cycle Sustainability Assessment (LCSA) model is considered a valid supporting tool [11].

Several literature studies deal with LCA of renewable energy technologies as well as with the review of literature results [8,12–17]. Although different tools to ensure a correct implementation of LCA have been developed [18–20], the individual interpretation of methodological aspects plays a key role, generating different and inconsistent results. Furthermore, renewable energies plants are characterized by a wide range of power, technologies, configurations, and applications. This article focuses on the set of environmental indicators generally used to carry out LCA of power plants, in order to take into account all the issues related to the electricity production with the most common renewable energy technologies (solar, wind, hydro, geothermal). Bioenergies were excluded because of the great number of existing typologies (biofuels, biogas, solid biomass) and technologies (direct combustion, co-combustion with fossil fuels, gasification) and, therefore, because of the consequent impossibility to obtain a significant number of data for each one of these typologies. Literature regarding wave power, even if many projects have been implemented leading to interesting insights and innovations [21], did not allow to obtain a significant number of data about environmental impacts. Therefore, also this renewable technology was excluded from the study.

The article also proposes a simple and straightforward methodology to harmonize the LCA studies results on the basis of the main parameters on which the output of each renewable energy power plant depends (e.g. resource availability, capacity factor, efficiency, and lifetime). The main purpose of the article is therefore to suggest a methodological approach to perform a more reliable comparison of the various renewable technologies, thus making the best use of LCA results to inform policy makers.

2. Life cycle assessment methodology

LCA methodology allows the evaluation of the environmental impact of products and services across all life cycle stages, modeling their interaction with the environment and accounting for all steps from raw material extraction to final disposal or recycling. According to LCA guidelines provided by ISO 14040 and 14044 [18,19], a LCA analysis is carried out by iterating four phases: goal and scope definition of the study, life cycle inventory, life cycle impact assessment and interpretation.

The goal and scope definition phase specifies the overall aim of the study, the system boundaries, the sources of data, and the functional unit to which refer all input and output flows. The Life Cycle Inventory (LCI) phase includes a detailed description of all the environmental inputs (material and energy flows) and outputs (air, water, solid emissions), while the Life Cycle Impact Assessment (LCIA) phase quantifies the relative magnitude of all the environmental impacts by using several environmental indicators. Finally, the results from the LCI and LCIA phases are interpreted to identify critical aspects, to evaluate alternative options, and to implement optimizations.

There are many evaluation methods used in LCA analyses and various different commercial codes for the implementation. Among the most used, the following are: the IPCC method, which expresses the impact in terms of CO_2 equivalent emissions, the CED method, which evaluates the energy used during the entire life cycle of the product or service, and the scoring method Ecoindicator 99 that considers a total of eleven impact categories regarding human health, ecosystem quality and resources depletion.

Regarding energy technologies, LCA provides a clearly defined and comprehensive framework to facilitate comparative studies and allows to evaluate the environmental consequences “from cradle to grave”. Furthermore, LCA is recognized to be an effective tool to evaluate the sustainability of various renewable energy sources and to help policy makers to choose the best energy source for a specific purpose [22].

3. Literature data collection

3.1. Screening approach

In order to obtain a high quality research and to select only relevant and high quality information, the definition of screening criteria to filter literature studies and to include data was the first, crucial step of the study. According to previous similar literature studies [23], a preliminary screening based on several rough discriminators was set to eliminate a part of references. All the documents listed below were excluded from the data collection:

- documents published before 1980;
- posters and abstracts;
- journal articles with a number of pages less than or equal to three;
- conference papers with a number of pages less than or equal to five;
- documents regarding technologies that do not produce electricity as a final product; if electricity is a co-product, the document was considered only if the LCA results were clearly separable;
- documents regarding not full LCA studies (less than two life cycle phases evaluated).

A subsequent screening was then set to further narrow the group of references by defining the quality of the studies. Specifically, this screening step assessed the parameters described as follows [24]:

- quality: the study had to follow currently accepted LCA methodologies, such as ISO 14040 series standards. The study had also to consider impacts from materials extraction and component manufacturing stages, since they contribute significantly to the life cycle impact of renewable energies;
- transparency and completeness of reporting: the study had to present an adequate description of the inputs and methods, thus, the results could be traced and trusted. In particular, it was requested:
  - a reasonably description of the study (goal and scope, system boundaries and other assumptions, such as system lifetime and end of life scenario characteristics);
  - a description, numerical where possible, of the power system studied (capacity, site description or location);
  - the citation of primary or secondary data sources used for the analysis;
  - the specification of the software and database used (SimaPro, Ecoinvent, etc.);
- the modern or future relevance of the technology: existing and future technologies were included.

3.2. Data collected

Our data collection focused on six environmental impact categories usually included into LCAs of power plants: Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential (GWP), Photochemical Ozone Creation Potential (POCP), Land Use (LU) and Water Consumption (WC). In addition, two other significant parameters were taken into account: Cumulative Energy Demand (CED) and Energy Pay-Back Time (EPBT). Most of data used in this study were gathered directly from summary life cycle impact tables, but some assumptions were necessary to obtain uniform data. Firstly, when only the outputs of the LCI of the system in terms of emissions were available, equivalent factor tables were used to refer each emission to its impact category. Table 1, in particular, shows the factors used to convert common pollutants emissions in SO_2 equivalent emissions into the AP category, while Table 2 summarize the PO_4^{3-} equivalent factor for the EP category. Table 3, instead, shows the well known GWP values of different GHG and Table 4 reports the factors used to convert pollutants emissions in Ethylene equivalent emissions into the POCP category. Secondly, regarding the water consumption in hydropower plants, the evaporation of water from the reservoir was not taken into account. Therefore, according to literature data [25], we considered an evaporation of 25 kg/kWh to be subtracted from the data that included it. A similar assumption was made for the CED data of hydropower plants. In fact, some studies included both the energy used during the plant

Table 1
Acidification potential equivalent factors [29].

Emission	SO_2 equivalent factor
1 kg SO_x as SO_2	1 kg eq SO_2
1 kg NO_x as NO_2	0.7 kg eq SO_2
1 kg NH_3	1.88 kg eq SO_2
1 kg H_2S	1.88 kg eq SO_2
1 kg HF	1.6 kg eq SO_2
1 kg HCl	0.88 kg eq SO_2
1 kg SO_3	0.8 kg eq SO_2
1 kg NO	1.07 kg eq SO_2
1 kg H_2SO_4	0.65 kg eq SO_2
1 kg HNO_3	0.51 kg eq SO_2
1 kg H_3PO_4	0.98 kg eq SO_2

Table 2
Eutrophication potential equivalent factors [30].

Emission	PO_4^{3-} equivalent factor
1 kg PO_4^{3-}	1 kg eq PO_4^{3-}
1 kg COD (Chemical O_2 Demand)	0.022 kg eq PO_4^{3-}
1 kg NO_x as NO_2	0.13 kg eq PO_4^{3-}
1 kg NH_3	0.35 kg eq PO_4^{3-}
1 kg NO_3^-	0.1 kg eq PO_4^{3-}
1 kg NH_4^+	0.33 kg eq PO_4^{3-}
1 kg N	0.42 kg eq PO_4^{3-}
1 kg P	3.06 kg eq PO_4^{3-}

Table 3
Global warming potential equivalent factors [31].

Emission	CO_2 equivalent factor
1 kg CO_2	1 kg eq CO_2
1 kg CH_4	25 kg eq CO_2
1 kg N_2O	298 kg eq CO_2
1 kg SF_6	22,800 kg eq CO_2
1 kg CF_4	5,700 kg eq CO_2
1 kg C_2F_6	11,900 kg eq CO_2

Table 4
Photochemical ozone creation potential equivalent factors [32].

Emission	C_2H_4 equivalent factor
Alkane	0.398 kg eq C_2H_4
Alkene	0.906 kg eq C_2H_4
Butane	0.363 kg eq C_2H_4
CH_4	0.007 kg eq C_2H_4
CO	0.036 kg eq C_2H_4
Ethane	0.082 kg eq C_2H_4
Ethylene	1 kg eq C_2H_4
Ethylbenzol	0.593 kg eq C_2H_4
Formaldehyde	0.421 kg eq C_2H_4
Heptane	0.529 kg eq C_2H_4
Hexane	0.421 kg eq C_2H_4
NMVOC	0.416 kg eq C_2H_4
Pentane	0.352 kg eq C_2H_4
Propane	0.42 kg eq C_2H_4
Propene	1.03 kg eq C_2H_4
Toluol	0.563 kg eq C_2H_4
Xyloles	0.849 kg eq C_2H_4
Aromatic CHs	0.761 kg eq C_2H_4

Table 5
Number of data collected and processed.

Environmental indicator	No of data
Acidification potential	57
Eutrophication potential	58
Global warming potential	99
Photochemical ozone creation Potential	41
Land use	39
Water consumption	32
Cumulative energy demand	93
Energy pay-back time	94

construction and the potential energy embodied in water, presenting CED values 10 times higher than those given in other studies. We proceeded considering an embodied energy of 3.79 MJ/kWh [26,27] to calculate the value to be subtracted and to obtain comparable CED data. Finally, with regard to EPBT, we found some studies presenting a value in terms of primary energy and other studies which supply only the ratio between the primary energy consumption during the whole life cycle and the electricity produced by the plant (not accounting the utilization grade of primary energy source to produce electricity, *g*). In our study, we chose to consider the "primary" EPBT and we set a value of *g* equal to 0.365 [28] (average world value) for the data adaptation. The total number of data collected and processed is summarized in Table 5.

4. Review results by technology

4.1. Concentrated solar power

Five papers [42,44–48] and two technical documents [41,43] related to 15 case studies (Fig. 1) were included according to the selection criteria for Concentrated Solar Power (CSP). Nine case studies regarded Parabolic Trough (PT) applications, while six case studies were related to Central Tower (CT) plants. All the reviewed documents included data regarding GWP, CED and EPBT; six studies contained data on LU, whereas data on AP, EP, and WC were gathered from four studies and data on POCP from three documents. Results regarding GWP and CED included in [41,42,44,45,48] were presented by life cycle phases and showed that hybrid plants (i.e. plants with gas boiler integration) have an impact during the operation one order of magnitude higher than the impact of the construction. On the contrary, 100% "sun-fired" plants are characterized by an impact of the construction phase comparable with the impact of the operating phase. The minimum and maximum values observed for GWP were respectively equal to 14.2 and 203 g CO_2eq/kWh, while CED values ranged between 0.16 and 2.78 MJ/kWh. The same high variability connected to the plant typology was observed for AP, EP and POCP values. WC vary significantly, with values in the range 294–4,710 g/kWh, and this is essentially due the cooling option used (high water consumption values in water cooled plants and low values in air cooled plants, where the consumption of water is associated only to cleaning activities). LU values were in the range 2.89E-05–7.92E-04 m^2/kWh.

4.2. Wind power

Regarding wind power, fourteen documents (five papers [49–53] and nine technical documents [54–62]) dealing with 20 case studies were included following the selection criteria (Fig. 1). All the applications considered are comparable in terms of size, with a minimum value of 0.25 MW, a maximum value of 6.00 MW and 13 plants in the range 1.50–4.00 MW. All the reviewed studies included data regarding GWP, CED, and EPBT, while data regarding AP and POCP were gathered from 11 of the documents considered. 12 documents contained data on AP, 10 documents data on WC and only one document data on LU. POCP data showed a high variability (values in the range 0.85–16.10 mg C_2H_4eq/kWh), as well as CED data (values in the range 0.01–1.20 MJ/kWh) and EPBT data (values in the range 2.4–27.5 months). This variability is basically due to different operating conditions (Capacity Factor varying between 19% and 53%) and to different assumptions in LCA modeling (e.g. conservative or non-conservative estimates regarding the maintenance activities). A quite low variability was observed for AP, EP, and GWP data: AP values were in the range 28.0–115.2 mg SO_2eq/kWh, EP values in the range 2.7–12.2 mg PO_4^{3-}eq/kWh, while GWP values in the range 6.2–46.0 g CO_2eq/kWh. All studies, with the exception of [51,52,53,56], presented the results by life cycle phases, showing that the construction phase gives the highest contribution to the overall impact (one order of magnitude higher than the operation phase).

4.3. Geothermal power

Three papers [15,71,72] and two technical documents [73,74], related to 20 case studies, were included according to the selection criteria for geothermal power (Fig. 1). All the reviewed studies included data regarding GWP, while data regarding CED and EPBT were gathered from four documents. Only two studies included data on LU and WC and the same applies for POCP, whereas data regarding AP and EP were included in four documents.

AP values were in the range 212–662 mg SO_2eq/kWh, CED values in the range 0.27–1.27 MJ/kWh and EPBT values in the range 8.2–46.5 months. A quite low variability was observed for POCP (values ranging between 13.1 and 43.7 mg C_2H_4eq/kWh) and for EP (values in the range 27.5–88.7 mg PO_4^{3-}eq/kWh), while CO_2 emissions factors showed a high variability (GWP values ranging between 16.9 and 142.0 g CO_2eq/kWh), essentially due to the characteristics of the used technology. Moreover, one paper [72] showed that the environmental impacts result significantly influenced by the geological conditions at a specific site. Only three studies [72–74] allowed to analyze the impact by life cycle phases, and also in this case the construction phase impact resulted one order of magnitude higher than the impact of the other phases.

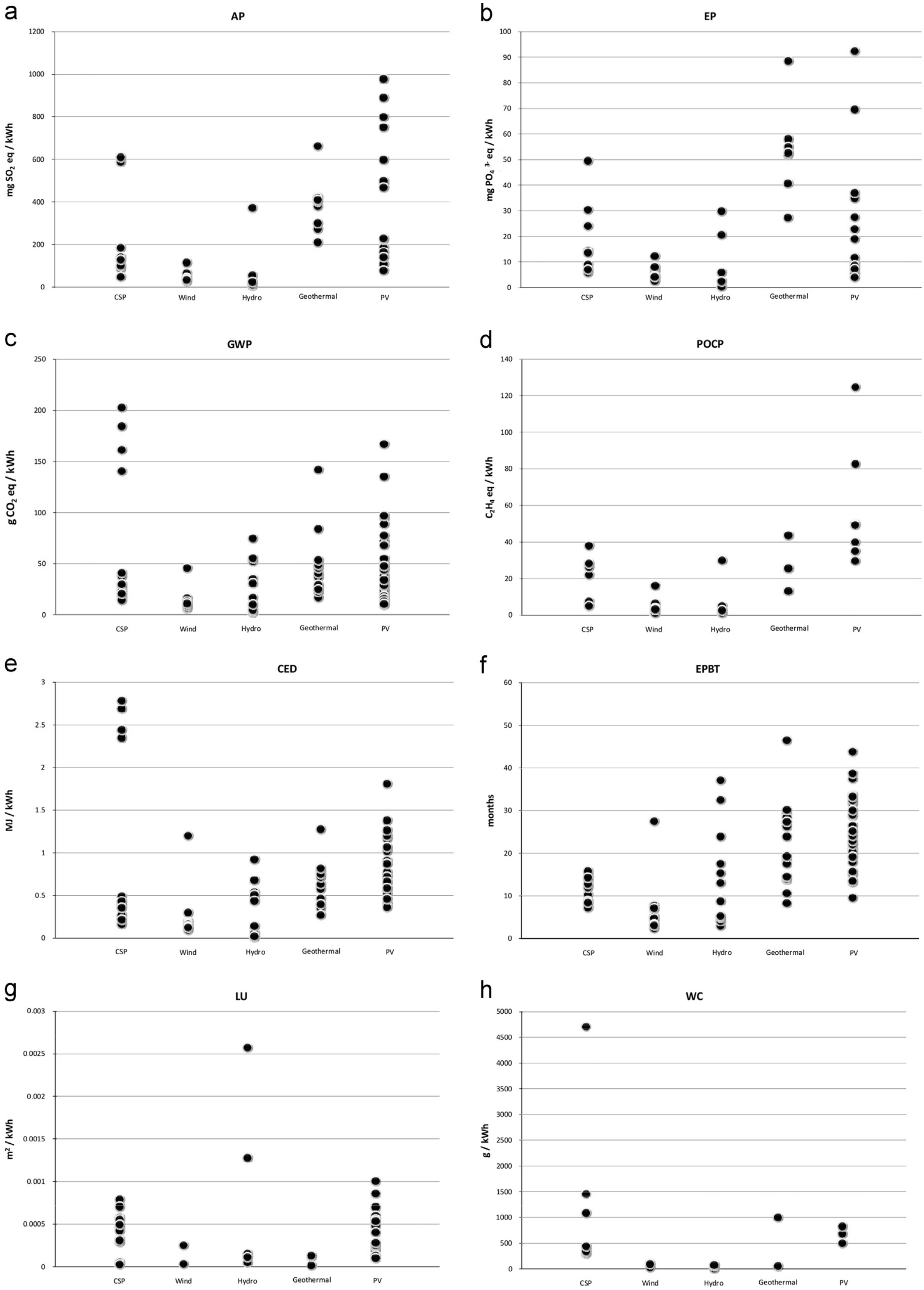

Fig. 1. Data collected from the reviewed studies.

4.4. Hydropower

Eleven case studies, contained in four papers [63,64,68,69] and four other documents [65,66,67,70] were included for hydropower (Fig. 1). These studies encompass dams with reservoir plants and run-of-river plants, large and small size installations. Data regarding GWP, CED, and EPBT were included in all the documents considered, while data regarding AP, EP and POCP were gathered from seven of them. Only five studies included data on LU and WC. Due to the consistent differences characterizing the plants considered, and also to the different approaches used (e.g. regarding/disregarding water evaporation from the reservoir and the potential energy embodied in water), a high variability (one order of magnitude) was observed for all the environmental indicator considered. In particular, AP values ranged from 7.6 to 129.4 mg SO_2eq/kWh, EP values from 0.4–30.0 mg PO_4^{3-}eq/kWh and POCP values from 1 to 30 mg C_2H_4eq/kWh; GWP data were in the range 2.2–74.8 g CO_2eq/kWh, CED data in the range 0.01–0.90 MJ/kWh and EPBT in the range 2.9–37.1 months. Data regarding LU varied from 4.87E-05–2.58E-03 m^2/kWh and data on WC from 1 to 75 l/kWh). All studies, except for [67], presented the results by life cycle phases.

4.5. Photovoltaic

The reviewed papers about photovoltaic (PV) applications were 11 [47,48,75–83], regarding 33 case studies; also one technical document [84] concerning three case studies was included according to the selection criteria (Fig. 1). Data regarding GWP and CED were gathered from 11 documents, while data regarding CED were included in 10 documents. Five studies contained data regarding LU, four studies data on AP and EP and only one paper included data on WC. AP, EP, GWP and LU values showed a high variability (the range was respectively 78.7–979.7 mg SO_2eq/kWh, 4.0–92.5 mg PO_4^{3-}eq/kWh, 9.4–167.0 g CO_2eq/kWh and 1.02E-04–1.01E-03 m^2/kWh), while POCP data were in the range 29.8–125.0 mg C_2H_4eq/kWh, CED data in the range 0.36–1.80 MJ/kWh and EPBT values in the range 9.6–43.9 months. The documents include both “upstream” and “downstream” processes (raw materials production, fabrication of system components, transportation and installation) and both ground and roof mounted systems. It is evident that during the life cycle of PV, emissions mainly occur from the use of fossil-fuel-based energy in generating the materials for cells, modules, and systems [81], with the production of the PV modules accounting for more than the 84% of the total primary energy consumption of the whole PV system [79]. It also emerged that a tracking system may increase significantly the impact of the construction phase and that the tracking system itself may account for 65-70% of the overall impact of the PV application [77]. An interesting projection of GWP for some PV technologies in the years 2025 and 2050 is given in [78].

5. Data harmonization

The harmonization process aims at reducing the data variability, aligning methodological inconsistencies in published LCAs, such as not coherent system boundaries, the use of outdated data, variations on similar energy process chains, and even simple differences in reporting of results. Capacity Factor (CF), which is the ratio of average output power to peak power that a plant could deliver, was chosen as harmonization parameter for wind power and hydropower, thus normalizing data to a similar operation scenario. For geothermal power, Conversion Efficiency (CE) was selected in addition to CF, as it represents a characteristic parameter of plant operation. As far as solar energy technologies, Direct Normal Irradiance (DNI), expressing the amount of solar energy available, was chosen as the main harmonization parameter. In addition, for CSP, Solar-to-electric Efficiency (SE) and Solar Fraction (SF) were selected, while for PV the other parameters indicated were Performance Ratio (PR) and Module Efficiency (ME). Regarding some technologies (CSP, wind power, PV), previous harmonization reviews were found and the same values of these literature studies were chosen for the analysis; on the other hand, for all the other technologies (hydropower, geothermal power) the harmonization parameters values were set equal to the median values of data collected.

Finally, since the resulting life cycle impacts of a power plant are closely related to the lifetime period used to carry out its LCA, a reference value of the lifetime for each technology (equal to the median value resulting from published data) was also selected for the data harmonization of all technologies considered. Different technologies are characterized by different lifetimes.

The parameters are listed in Table 6, with the related harmonization formula. With regard to CSP data, it must be stressed that the contribution associated to the gas boiler integration in hybrid plants was excluded in the harmonization procedure.

6. Harmonization procedure results

Looking at the central tendency of the harmonized AP values (Fig. 2a), hydropower seems to be the best technology (median value equal to 12.8 mg SO_2eq/kWh), immediately followed by wind (median value equal to 48.9 mg SO_2eq/kWh). CSP, with a median value of 91.2 mg SO_2eq/kWh, is positioned at a medium level of impact, while PV and geothermal have the highest impact values.

The central tendency of harmonized EP data (Fig. 2b) shows wind and hydropower as the best technologies, with a comparable median value of the impact (4.9 and 4.8 mg PO_4^{3-}eq/kWh respectively). CSP has a median EP impact quite comparable with wind and hydro (6.8 mg PO_4^{3-}eq/kWh), while PV assumes a medium value (22.4 mg PO_4^{3-}eq/kWh for PV). Geothermal is the technology with the highest eutrophication potential.

The harmonized GWP data (Fig. 2c) are characterized by a low variability, due to the larger sample of data found for each technology, and the central tendency of the estimates shows wind and hydropower as the best technologies (median value of the impact equal to 9.4 and 11.6 g CO_2eq/kWh respectively). The other three technologies, instead, present a higher and comparable value of the impact. In particular, PV has a median value equal to 29.2 g CO_2eq/kWh, CSP a median value of 30.9 g CO_2eq/kWh and geothermal is characterized by a median equal to 33.6 g CO_2eq/kWh.

Looking at the central tendency of the harmonized POCP values (Fig. 2d), hydropower and wind seems to be the best technologies, with a median value of 1.5 and 4.6 mg C_2H_4eq/kWh respectively. CSP and geothermal power have a quite similar impact (respectively 16.4 and 22.1 mg C_2H_4eq/kWh), while PV is the technology with the highest Photochemical Ozone Creation Potential.

The harmonized CED data (Fig. 2e) show wind as the best of all the technologies, with a median value of the impact equal to 0.13 MJ/kWh, followed by hydropower (0.16 MJ/kWh), CSP (0.44 MJ/kWh), geothermal power (0.52 MJ/kWh) and PV (0.61 MJ/kWh).

Comparing Fig. 2 with Fig. 1, it is evident that the main effect of the proposed harmonization methodology is a general reduction in the variability of the previously published estimates, increasing the precision and aligning common system parameters to a consistent set of values.

However, some exceptions emerged. In particular, the increase of the variability range of the environmental indicators values observed for Geothermal power is due to two case studies included in [72], with a CE higher than the one set for the harmonization and the same lifetime. The same applies for the raise observed in the variability range of AP values regarding PV: 2 case studies included in [79] were characterized by a lifetime and a ME higher than the ones set to harmonize (in detail, 40 years

Table 6
Harmonization parameters for each technology and related harmonization formulas.

Harmonization parameter	Parameter value used	Notes
CSP technology		
Solar Fraction, SF	1	The harmonization value for SF was chosen to be 100% to better estimate the emissions resulting from a "solar only" CSP plant.
Direct Normal Irradiance, DNI	2,400 kWh/m^2	The value is representative of a high quality solar resource that is incident upon thousands of square kilometers in several global locations. CSP developers typically require about 2000 kWh/m^2/yr to justify construction [33].
Solar-to-electric Efficiency, SE	Parabolic trough plants: 15% Central Tower plants: 20%	These SE values are representative of current state-of-the-art designs for CSP technologies [33].
Lifetime, LT	30 years	Median value resulting from data collection.
Harmonization formula:		
$D_{i,harm} = D_{i,pub} \cdot \frac{SF_{pub} \cdot DNI_{pub} \cdot SE_{pub} \cdot LT_{pub}}{SF_{harm} \cdot DNI_{harm} \cdot SE_{harm} \cdot LT_{harm}}$		
Wind power		
Capacity Factor, CF	On-shore turbines: 35% Off-shore turbines: 45%	Values suggested for modern turbines [34] and also more consistent with the median values obtained from data collection.
Lifetime, LT	20 years	Median value resulting from data collection.
Harmonization formula:		
$D_{i,harm} = D_{i,pub} \cdot \frac{CF_{pub} \cdot LT_{pub}}{CF_{harm} \cdot LT_{harm}}$		
Hydropower		
Capacity Factor, CF	70%	Median value resulting from data collection.
Lifetime, LT	70 years	Median value resulting from data collection.
Harmonization formula:		
$D_{i,harm} = D_{i,pub} \cdot \frac{CF_{pub} \cdot LT_{pub}}{CF_{harm} \cdot LT_{harm}}$		
Geothermal power		
Capacity Factor, CF	70%	Median value resulting from data collection.
Conversion Efficiency, CE	11%	Median value resulting from data collection
Lifetime, LT	30 years	Median value resulting from data collection.
Harmonization formula:		
$D_{i,harm} = D_{i,pub} \cdot \frac{CF_{pub} \cdot CE_{pub} \cdot LT_{pub}}{CF_{harm} \cdot CE_{harm} \cdot LT_{harm}}$		
PV technology		
Direct Normal Irradiance, DNI	1,700 kWh/m^2	Published literature data [35,36], corresponding to the average irradiation in southern Europe.
Performance Ratio, PR	Rooftop and building integrated systems: 0.75 Ground mounted systems: 0.8	Performance ratios recommended in the IEA guidelines [37].
Modules Efficiency, ME	Mono-Si: 20% Multi-Si: 15% a-Si: 6.3% CdTe: 10.9% CIGS: 11.5%	Values representative of current state-of-the-art [35,36,38,39,40].
Lifetime, LT	30 years	Median value resulting from data collection.
Harmonization formula:		
$D_{i,harm} = D_{i,pub} \cdot \frac{DNI_{pub} \cdot PR_{pub} \cdot ME_{pub} \cdot LT_{pub}}{DNI_{harm} \cdot PR_{harm} \cdot ME_{harm} \cdot LT_{harm}}$		

and 16% and 50 years and 18%). The increase observed in the variability range of POCP values regarding CSP is the consequence of a case study included in [41] with a DNI higher than the one used for the harmonization.

Regarding LU and WC, only published estimates were analyzed, since, after the screening approach, the number of data available was not sufficient to carry out the harmonization. Data regarding EPBT, on the contrary, were not harmonized because this parameter strongly depends on local economic policies (e.g. feed-in tariff, incentives on capital investments, etc.) and data regarding this aspect were lacking.

7. Conclusions

The evaluation of the environmental impact associated to different energy technologies and, in particular, to renewable energies, is becoming a key issue in policy making. Different evaluation approaches are used in this regard and a LCA approach is considered as one of the most appropriate and comprehensive methods. However, published LCA results vary significantly, creating confusion on the actual environmental consequences of implementing renewable technologies.

In the present article, a selected and critical review of more than 100 different case studies – regarding solar energy (CSP, PV), wind power, hydropower and geothermal power – was performed, which clearly showed this data variability and its causes. Furthermore, a methodological approach to harmonize LCA results was proposed. In fact, even if the energy production from renewable sources is "resource-dependent," a more reliable comparison of the environmental consequences of the different technologies is desirable. A comprehensive set of environmental indicators was selected for the comparison and a set of parameters to harmonize published LCA data was suggested.

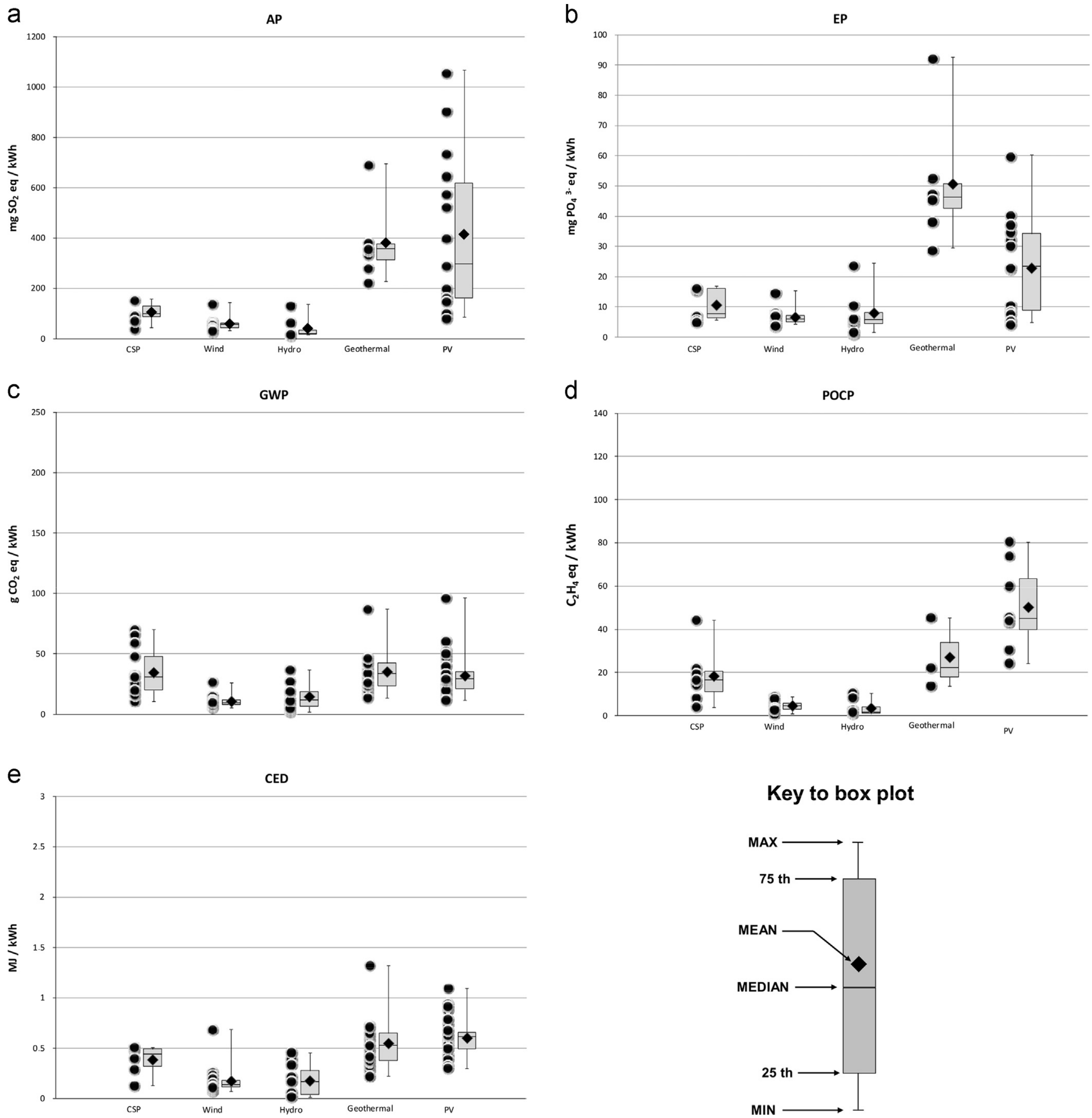

Fig. 2. Main statistics of harmonized data.

Comparing the harmonized results, wind power emerged as the renewable technology with a lower overall environmental impact (it had the lowest impact values and the narrowest ranges of variability). For instance, wind power had the lowest CO_2eq emissions and the lowest embodied energy. Geothermal power and PV power, instead, came out as the renewable technologies with the highest overall environmental impact values and the widest ranges of variability. Within the other technologies considered, CSP was positioned at a medium level of environmental impact, resulting better than PV, geothermal, and hydropower plants in almost all the impact categories considered.

Extending the comparison of the harmonized results to conventional power systems (e.g. hard coal or natural gas power station) the analysis of all impact categories demonstrates that renewable energy technologies show significant environmental advantages. Considering for example GWP values, a combined cycle natural gas plant has a mean emission of 350–400 g CO_2eq/kWh and a hard coal plant with direct combustion has an emission range of 750–1050 g CO_2eq/kWh [8], while all the analyzed technologies are characterized by values lower than 100 g CO_2eq/kWh. Moreover, while an old hard coal plants with direct combustion has an AP range of 2–7 g SO_2/kWh [8], all the analyzed technologies are characterized by values lower than 1 g SO_2/kWh.

As a further example, whereas for conventional fossil fuels-fired power plant it is possible to consider a CED impact in the order of magnitude of 10 MJ/kWh [85], the harmonized CED values of all the considered renewable energy technologies result below 1.3 MJ/kWh.

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