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Life Cycle Analysis of a Geothermal Power Plant: Comparison of the Environmental Performance with Other Renewable Energy Systems

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Abstract: A life cycle analysis was performed for the assessment of the environmental performances of three existing Italian power plants of comparable nominal power operating with different sources of renewable energy: Geothermal, solar, and wind. Primary data were used for building the life cycle inventories. The results are characterized by employing a wide portfolio of environmental indicators employing the ReCiPe 2016 and the ILCD 2011 Midpoint+ methods; normalization and weighting are also applied using the ReCiPe 2016 method at the endpoint level. The midpoint results demonstrate a good eco-profile of the geothermal power plant compared to other renewable energy systems and a definite step forward over the performance of the national energy mix. The Eco-Point single score calculation showed that wind energy is the best technology with a value of 0.0012 Eco-points/kWh, a result in line with previously documented life cycle analysis studies. Nevertheless, the geothermal power plant achieved a value of 0.0177 Eco-points/kWh which is close to that calculated for the photovoltaic plant (0.0087 Eco-points/kWh) and much lower than the national energy mix one (0.1240 Eco-points/kWh). Also, a scenario analysis allowed for a critical discussion about potential improvements to the environmental performance of the geothermal power plant.

Keywords: geothermal energy; life cycle analysis; solar energy; photovoltaics; renewable energy power plant; wind energy

1. Introduction

Geothermal energy is an important energy resource, largely contributing to limiting the use of fossil fuels, for both electricity and direct uses (mainly heat for district heating). The world installed electrical capacity is over 12×10^3 MWe [1–4], with the provision of direct heat of the order of 165×10^3 GWh/yr [5]. The geothermal resource is well distributed around the world [6,7], and several locations are favored by the presence of hot fluid resources (hydrothermal systems). Recently, the feasibility of enhanced geothermal systems (EGS) has been demonstrated and this technology will allow even more widespread use of the earth's inner heat [8,9]. Experience has demonstrated that geothermal energy can be considered renewable if the resource is correctly managed [10,11], if the sizing of the conversion/utilization plants is compatible with that of the hydrothermal reservoir, and if reinjection of the fluids is practiced.

Italy has a long tradition of geothermal energy utilization [12], with nearly 1×10^3 MWe installed in two areas of the Tuscany region (Larderello/Travale and Monte Amiata) operated by Enel Green Power. Specifically, the plants of the Larderello/Travale region (about 700 MWe) have been in industrial operation for more than 60 years, and this activity has considerably contributed to the local economic growth. An extensive grid exists for the management of fluids, including primary supply to local district heating as well as resource and reinjection fluid distribution. All power plants are equipped with effective emissions treatment equipment, which removes the greatest part of hydrogen sulfide (H_2S) and mercury (Hg) though the application of proprietary technology (AMIS® process [13,14]). The geothermal power plants located in Tuscany have demonstrated high reliability, with equivalent operation time exceeding 7.5×10^3 hrs/yr and with a productivity of more than 6.2×10^3 GWh/yr [15].

Solar electricity is mainly produced by photovoltaic (PV) power plants. Over the world, the power installed exceeds 500 GWe [16]. Italy represents one of the main players in Europe with more than 20 GWe installed and productivity exceeding 24×10^3 GWh/yr [15]. Most of the PV plants in Italy are small (<50 kWe); however, a significant share of production is done by 6% of the power plants with size >50 kWe. The productivity data show that the utilization factor of solar PV is much smaller than for geothermal, with an equivalent full-load operability of about 1.2×10^3 hrs/yr. This is due to the periodic cycle of solar radiation (daily and seasonal).

Wind energy has experienced a strong increase with specific reference to Europe (180 GWe installed with a productivity of about 362×10^3 GWh/yr [16]). In Italy more than 10 GWe are installed (mainly in the south), with productivity exceeding 17×10^3 GWh/yr [15]. The equivalent full-load operability is typically 2000 hrs/yr, as the wind resource is highly stochastic.

The lower operability identifies solar PV and wind as variable renewable energy (VREs), raising strong challenges to the grid infrastructure (solar being today more predictable and favored in this sense). Higher market penetration of renewable energy sources (RES) will entail optimized strategies for production/load matching, and the development of extensive energy storage infrastructures supporting VREs. These latter will entail additional costs and environmental impacts, as well documented by the scientific literature about storage systems. Geothermal energy, which is typically employed as a baseload energy resource, is highly complementary to VREs and can represent very valuable support, both in countries with limited electric grid infrastructure and in developed countries committed to ever-higher market penetration of electricity compared to other energy vectors [17,18].

This work arises from the recognition that completely clean energy does not exist: The only clean energy is the one we do not need to use, namely that saved with efficiency actions. However, in an environmentally sustainable perspective RES are better than fossil fuels, but even in this case choices should be based on a rigorous comparison of the environmental advantages and drawbacks. The life cycle analysis (LCA) approach is an optimum tool to make this comparison.

The goal of this study is to compare the environmental performances of three power plants based respectively on geothermal, solar, and wind energy through the LCA methodology and grounding on robust and reliable primary data.

2. Materials and Method

2.1. Life Cycle Analysis (LCA)

LCA is a method to evaluate the environmental load associated with a product, process, or activity. LCA allows quantifying the used amount of energy and materials and of emissions and waste released in the environment, allowing for the evaluation of the associated potential impacts. The assessment is performed over the entire life cycle of the product, process, or activity covering extraction and processing of raw materials; manufacturing, transportation, and distribution; use, re-use, maintenance; recycling, and final disposal. The results of LCA can be expressed via a large number of environmental indicators and, generally, several impact categories are used to circumspectly detect the full range of ecological burdens associated with the investigated process or activity over the three environmental

compartments (atmosphere, soil, and water), thus aiming at avoiding burden shifting. The LCA methodology is regulated according to the general guidelines described in the International Standard Organization (ISO) series 14040 [19,20] and consists of four phases:

1. Goal and scope definition: In this phase, the goal of the study, the system boundaries, the quality requisites of the data sources are described, and the functional unit of the analysis is specified.
2. Life cycle inventory analysis (LCI): The purpose of this phase is to collect the input/output data pertinent to the system studied; generally robust and reliable LCIs are built on primary data, that is to say specific data that highly characterize the system under study.
3. Life cycle impact assessment (LCIA): This phase evaluates the significant potential environmental impacts using the LCI results; the process involves associating inventory data with specific environmental impact categories and the calculation of indicator values using accepted characterization factors.
4. Life cycle interpretation: It is the final phase of an LCA study in which the results of the LCI and LCIA steps are presented and discussed; interpretation includes conclusions and recommendations adapted to the goal and scope of the study.

LCA was born as a detailed and quantitative approach for the evaluation of environmental sustainability [21]. The regulatory approach described in the ISO standards and the more completely elaborated ILCD Handbook guidelines [22] claims for the development of an LCA study until the characterization of the environmental impacts at a midpoint level. With this approach, the LCIA method looks at the impact earlier along the cause–effect chain of the environmental mechanism, and can refer to a relevant number of impact categories characterized by a low uncertainty but, on the other hand, is difficult to interpret. In principle, it represents a good approach for the characterization of the eco-profile of the product or activity under exam to use several wide-scope LCIA methods and check if findings are consistent in all of them. If so, it is possible to claim that findings appear robust. But when this is not the case, the LCA practitioner might have to delve into the particularities of the LCIA methods and find out why the results are dissimilar, which can be a good learning experience about the characteristics of the applied LCIA methods.

The environmental evaluation at the endpoint level is a non-mandatory part of LCA, which includes normalization and weighting steps that allow expressing the results referring to a limited number of damage categories, typically resources availability, human health, and ecosystem quality. Endpoint results provide insight on the environmental impact at the end of this cause–effect chain of the environmental mechanism, thus with larger uncertainty. If interpretation at this level provides a more limited amount of details, it is recognized that it is more suitable for the presentation of results to non-technical audiences. The various LCIA methods apply different impact category grouping, normalization, and weighting factors, thus it is necessarily recommended to refer to the same methodology when comparing different technologies dealing with the same product or process.

Energy conversion and utilization is one of the most famous and important fields of application of LCA calculations. LCA indeed offers a powerful approach to analyze systems overarching the complete life cycle of a system (from cradle to grave) which is necessary when considering the substitution of fossil fuels with renewables. When applying LCA to energy conversion systems, for fossil fuel-based technologies it is common to find high impacts connected to the use of fossil resources in the operational phase [23–25]; on the other hand, RES, which minimizes the use of consumables such as fossil fuel, entail a consistent use of materials because of the diffuse nature of renewable energy, some of which are rare, or whose extraction and/or production entails direct or indirect negative effects on the environment. In general, RES scores better environmental performance than fossil fuel systems in most impact categories. However, these outcomes should be evaluated, validated, and compared among different RES.

Several LCA studies are available on solar PV energy conversion systems [26–35]; in general, the results indicate that a significant impact is coming from the manufacture of the PV modules,

with the current silicon technology performing better than cadmium telluride, notwithstanding substantial advantages for thin-film manufacturing [36]. A significant fraction contribution to the overall eco-profile (20–30%) comes from the structural materials and glazing. The environmental footprint is lower than the best fossil fuel-based technologies in most categories, with a weighted score typically 4–8 times smaller. The relatively standard production process has led to the development of accepted guidelines [37], which have determined an improved homogeneity in the results and better comparability of the studies. Wind energy has also attracted several LCA studies [38–41]: In comparison with fossil fuel-based systems, the environmental footprint is very limited, and only a restricted number of categories is usually involved (global warming potential, GWP; acidification potential, AP; eutrophication potential, EP; cumulative energy demand, CED). In the field of wind energy, no specific LCA guidelines are available; however, significant studies have been published by leading manufacturers such as Vestas [42]; the results have been cross-checked by researchers and substantial agreement is documented [43–46].

Geothermal power plants have raised the attention of local and national policymakers in terms of their environmental performances and sustainability, and the comparison with other RES has then become necessary. Several studies on the application of LCA to geothermal power systems are available in the literature [47–58]; however, most studies are only focused on GWP, and there is a considerable spread in the results.

Examples of comparison of RES options are documented in the technical literature [59–62]; however, they mostly rely on previously published LCA studies and, in most cases, on the use of literature data. There is a substantial lack of primary data (produced by the plant owner or operator), which stand as more reliable as the source of the information can be completely tracked. Utilities such as Enel Green Power have a good opportunity to access these primary data (often gathered with the purpose of economic analyses, or in case of the commitment of construction works or trusting of maintenance services), and to use them to document the environmental quality of their product (electricity). This represents a key passage in the environmental evaluation, both in terms of company, services, and products (possibly leading to an ECO-Label), and is also a motivation behind the present study.

The case studies described in the following section were analyzed using the OpenLCA 1.10 software package [63]; for secondary data, the Ecoinvent database 3.6 was adopted [64,65]. The system modeling approach employed is cradle to grave. The functional unit was set as 1 kWh of electricity delivered to the grid, assuming a lifetime of 30 years for all the power plant solutions investigated. The system boundaries were defined to include the whole life cycle of the system. Operation and maintenance (including replacement of major equipment) were modeled following the experience of Enel Green Power as power plant manager.

The assessment was performed comparing the ReCiPe 2016 [66] and the ILCD 2011 Midpoint+ [67] LCIA methods both employed for the characterization of potential impact at midpoint level. Normalization and weighting, applying an hierarchist (H) cultural perspective, were applied to the ReCiPe 2016 results to determine the systems eco-profiles at the endpoint level (with weighted results expressed in Eco-points).

All data gathered in the LCI are primary data provided by Enel Green Power resulting from checked information about materials employed for construction. Secondary data were used for common materials (e.g., steel, concrete, copper, plastics, etc.) and upstream processes (e.g., transport). The LCI also reports data for operation and maintenance, including replacement of equipment, consumables, etc.

2.2. Case Studies

The case studies here considered represent three Italian power plants of similar nominal capacity (about 20 MWe): The geothermal power plant Chiusdino 1, the wind farm in Pietragalla, and the solar photovoltaic power plant Serre Persano Difesa Servizi (DS).

2.2.1. Chiusdino Geothermal Power Plant

Chiusdino 1 is a standard Enel Green Power geothermal power plant, with a nominal capacity of 20 MWe (Figure 1). The live steam (130 t/h; 14,5 bar, 196 °C) is provided by five production wells located close to the power plant or in the neighborhood (Table 1). The plant was built in 2011 and has recently been connected to a district heating network, with a planned capacity of 7 MWth of heat.
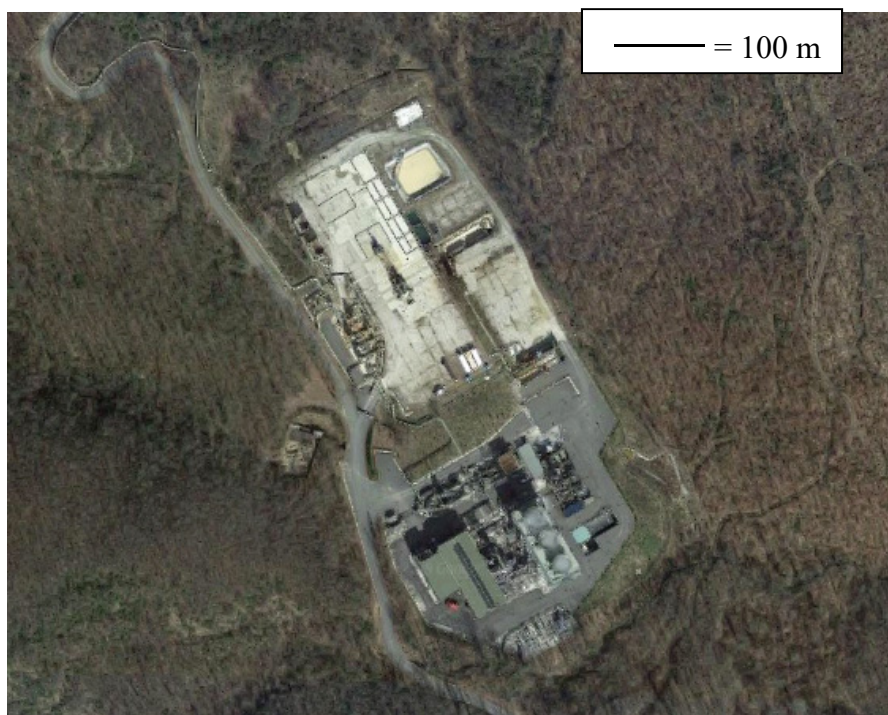

Figure 1. Google Earth aerial view of Chiusdino power Plant (location: 43°09′37.0″ N; 11°03′49.9″ E); bottom: Power plant; upper: Travale wellhead platform.

Table 1. Details of production wells, Chiusdino 1 Power plant.

Name	Distance [1], m	Depth, m	Flow Rate, t/h	T, °C	p, bar	NCG [3], %
Montieri 5 [2]	2630	3447	78.8	200.8	16.2	6.0
Montieri 5A [2]	2630	4137	22.4	200.9	16.1	4.2
TravaleSud 1B	172	3361	26.4	198.6	15.5	6.1
TravaleSud 1C	172	3713	25.2	198.9	15.4	4.5
TravaleSud 1D	172	4432	24.5	198.8	15.4	4.5

[1] Distances are calculated from the two platforms (Montieri and Travale). [2] Only 53,5% of the flow rate from Montieri is used by the Chiusdino power plant. [3] Non-condensable gases (NCG) are commonly found in the geothermal fluid and are mainly composed of carbon dioxide (CO_2), hydrogen sulfide (H_2S), hydrogen (H_2), nitrogen (N_2), methane (CH_4), and ammonia (NH_3).

The Chiusdino 1 power plant is equipped with an AMIS® emissions treatment system, which removes H_2S and Hg with measured efficiencies of 99.8% and 82.2%, respectively. A soda solution is used for acid gas treatment. The whole liquid condensate of Chiusdino 1 is reinjected using a complex network of pipelines connecting to the Larderello reinjection sites, with an overall estimated length of about 20 km. Details on the pollutant streams emitted, according to measured values certified by the regional authority for environmental protection (ARPAT), are provided in Table 2.

For Chiusdino 1, three scenarios were examined to consider the effects of emissions treatment: (i) The real scenario "GEO," featuring the AMIS® process; (ii) the hypothetical scenario "GEO_NA," representing the power plant as if no AMIS® process were operating; and (iii) the "GEO_AS," featuring

the emissions treatment plus a 40% substitution of natural emissions (i.e., 40% of the power plant emissions would anyway reach the atmosphere as natural emissions).

Table 2. Emissions of the Chiusdino 1 Power plant.

Emission [1]	Flow Rate, kg/h	Specific Emission, kg/kWh
CO_2	5100	2.6×10^{-1}
CO	0.4	2.0×10^{-5}
H_2S	18.4	9.2×10^{-4}
CH_4	79.3	4.0×10^{-3}
NH_3	1.5	7.5×10^{-5}
Hg	1.1×10^{-3}	5.5×10^{-8}
As	2.8×10^{-6}	1.4×10^{-10}
Se	4.0×10^{-4}	2.0×10^{-8}

[1] Carbon dioxide (CO_2), carbon monoxide (CO), hydrogen sulfide (H_2S), methane (CH_4), ammonia (NH_3), mercury (Hg), arsenic (As), selenium (Se).

The Chiusdino 1 power plant is operated at full load, with a demonstrated operability of 7560 hrs/yr. This leads to very high productivity of about 151,200 MWh/yr. Appendix A shows the LCI and technical details for the Chiusdino 1 power plant.

2.2.2. Pietragalla Wind Farm

The Pietragalla wind farm is composed of nine horizontal axis Repower MM92 wind turbines, each having a nominal rating of 2 MWe (Figure 2). The wind farm has been operational since 2011. Every wind turbine has a rotor diameter of 92.5 m and is installed on top of a pre-assembled tower (three pieces) with an overall height of 100 m. The tower, nacelle, and rotor require substantial construction work for the foundations; moreover, the erection (and maintenance) of the machine requires the construction of a platform with suitable extension and load-supporting capability. The installation site required only minor works for viability. The operational data over the recent three years period (2016–2018) indicate productivity of 42,069 MWh/yr, equivalent to full-load operability of 2337 hrs/yr (a very high value for typical Italian wind energy installations). Appendix B shows the LCI and technical details for the Pietragalla wind farm.

Figure 2. Google Earth aerial view of Pietragalla wind power plant; three of the nine turbines are visualized (location: 40°43′31.63″ N; 15°49′41.85″ E).

2.2.3. Serre Persano Difesa Servizi (DS) Photovoltaic Solar Plant

The Serre Persano DS PV solar plant, feature a peak power level of 21 MWe and was built by Enel Green Power in the period 2011–2013. The surface covered is 770,000 m², with two fields connected to the same electrical works station (Figure 3). On the whole, the PV plant has 157,556 modules, arranged in 11,254 strings with 24 inverters. Table 3 resumes the features of the two PV fields.
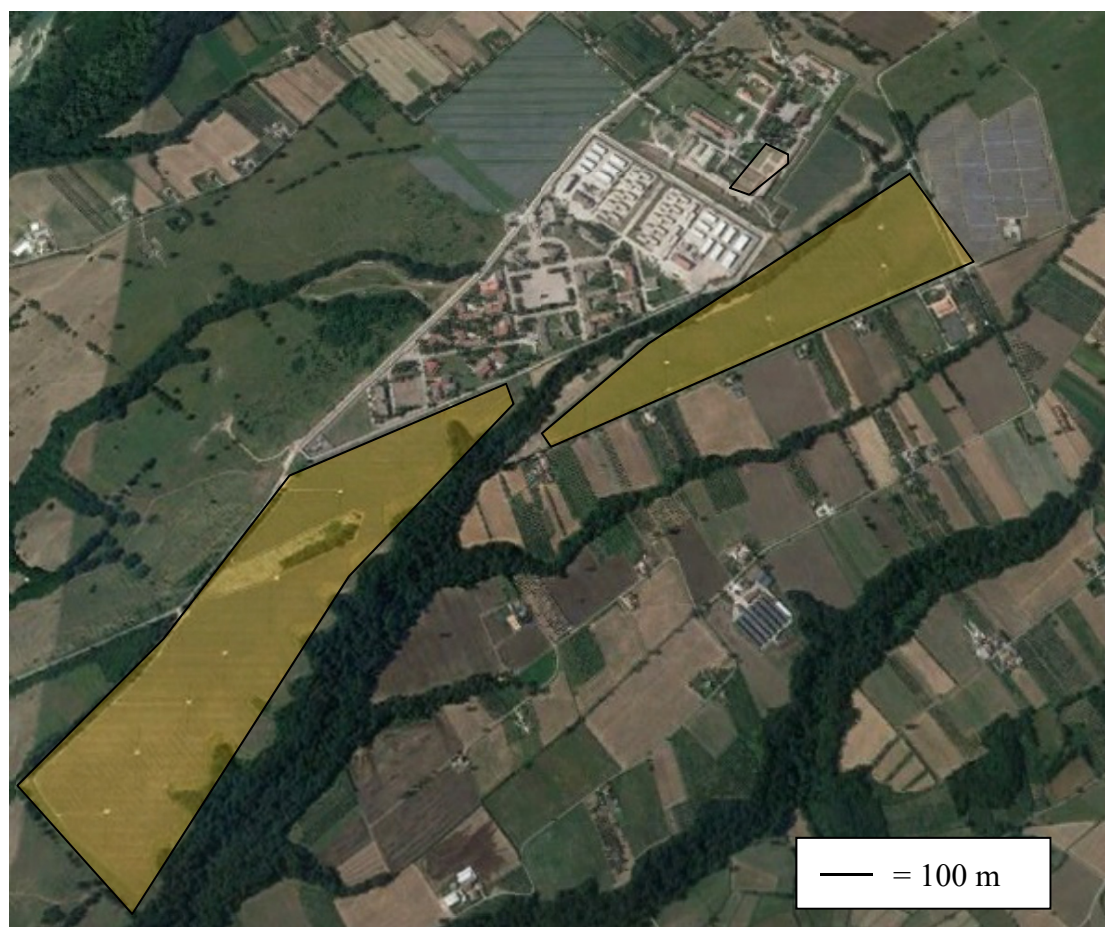
Figure 3. Google Earth aerial view of Serre Persano DS Photovoltaic (PV) plant; shaded areas highlight the PV installations (location: 40°34′08.5″ N 15°06′10.5″ E).

Table 3. Summary specifications of the Serre Persano DS Photovoltaic (PV) fields.

Field Name	Modules NAF 130 G5	Modules NAF 135 G5	Strings NAF 130 G5	Strings NAF 135 G5	Number of Inverters
Spineto	26,880	51,912	1920	3708	12
Borgo San Lazzaro	26,880	51,884	1920	3706	12

Including the evaluation of the decay in productivity with aging, the average productivity of the Serre Persano DS solar PV plant was evaluated at 24,768 MWh/yr, with an equivalent full-load operability of about 1179 hrs/yr (a good performance for a plant built during 2011–2013 in Southern Italy). Appendix C shows the LCI and technical details for the Serre Persano DS solar PV plant.

3. Results and Discussion

3.1. Life Cycle Impact Assessment at Midpoint Level: ILCD 2011 Midpoint+ versus ReCiPe 2016

The purpose of this section is to show the results of the midpoint impact categories and to analyze them so that a consistent choice can be made about the impact assessment methodology (ILCD 2011 Midpoint+ or ReCiPe 2016). The results are shown for the three cases referred to as geothermal (GEO, GEO_AS, GEO_NA) and for the solar photovoltaic (PV) and wind (W) reference cases. Furthermore, the comparison with the national electricity mix (NEM) is performed referring to the ecoinvent process that models the Italian energy mix based on Eurostat data for the year 2014 (renewable energies: 43.1%;

coal: 19.0%; natural gas: 28.9%; oil: 1.0%; nuclear-imported: 4.6%; other sources: 3.7%). The detailed results of the midpoint impact analysis are reported in Appendix D.

A graphical comparison among ILCD 2011 Midpoint+ and ReCiPe 2016 results calculated at midpoint level is shown in Figures 4–8 for the most relevant categories using color-coded bars: The best-performing category is shown with a green bar; a red or a yellow bar identifies the worst or the second-worst technology; grey bars represent intermediate results.

Although ILCD 2011 Midpoint+ and ReCiPe 2016 methods are based on different calculation methodologies for some environmental impact, the ranking between RES technologies is similar (the best and worst technology are, in general, correctly identified for the main categories). An exception is the land use category (Figure 8) for which the ILCD 2011 Midpoint+ method assigns a large impact in the case of PV because of relevant soil preparation and excavation operations. Another relevant case is the high score assigned to W in the mineral resource scarcity category for the ReCiPe 2016 method (Figure 6), which is motivated by the use of rare mineral resources (lanthanides) in the generator for wind turbines. ReCiPe 2016 is also more effective in the assessment of land use because it refers directly to equivalents of squared meters of crops subtracted per year; in this case, the score is largest for the NEM, followed by PV (Figure 8). The ILCD 2011 Midpoint+ (and its more recent development into the Environmental Footprint (EF) method [68,69]) is more sound scientifically and pays strong attention to eco-toxicity and human health, but ReCiPe 2016 seems, at present, more suitable for application to energy conversion (with specific reference to the urge for substituting fossil with renewable resources).
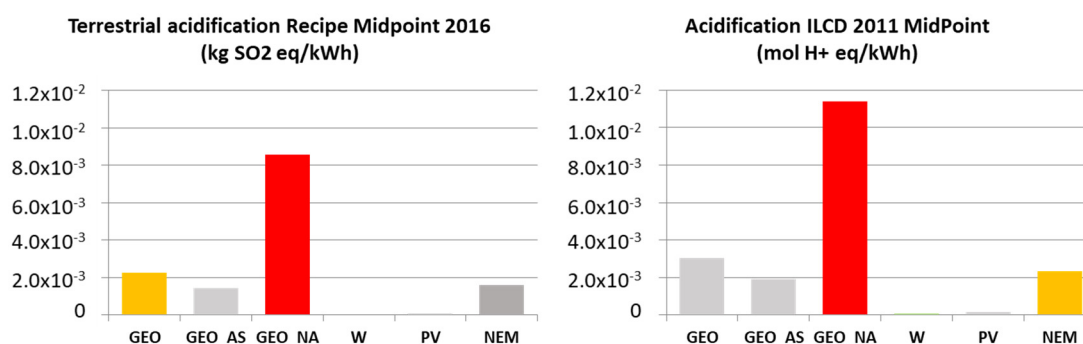
Figure 4. Bar diagrams of ILCD 2011 Midpoint+ and Recipe 2016 impact assessment at midpoint level: Acidification.
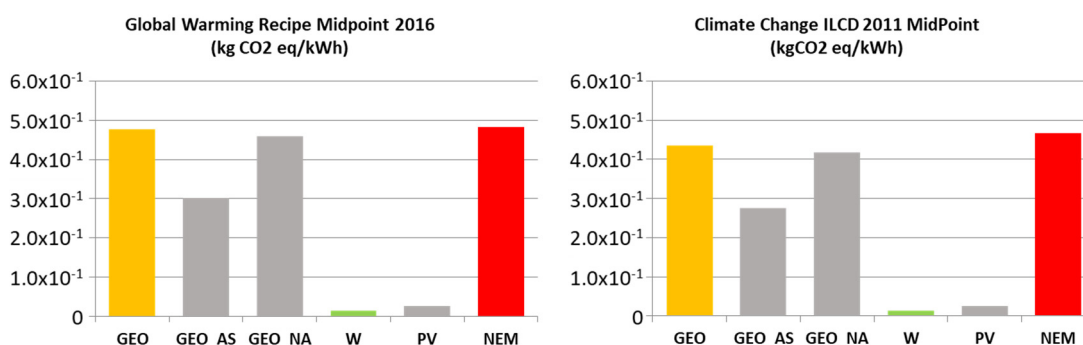
Figure 5. Bar diagrams of ILCD 2011 Midpoint+ and ReCiPe 2016 impact assessment at midpoint level: Climate change.

Figure 6. Bar diagrams of ILCD 2011 Midpoint+ and ReCiPe 2016 impact assessment at midpoint level: Resource depletion.

Figure 7. Bar diagrams of ILCD 2011 Midpoint+ and ReCiPe 2016 impact assessment at midpoint level: Freshwater eutrophication.

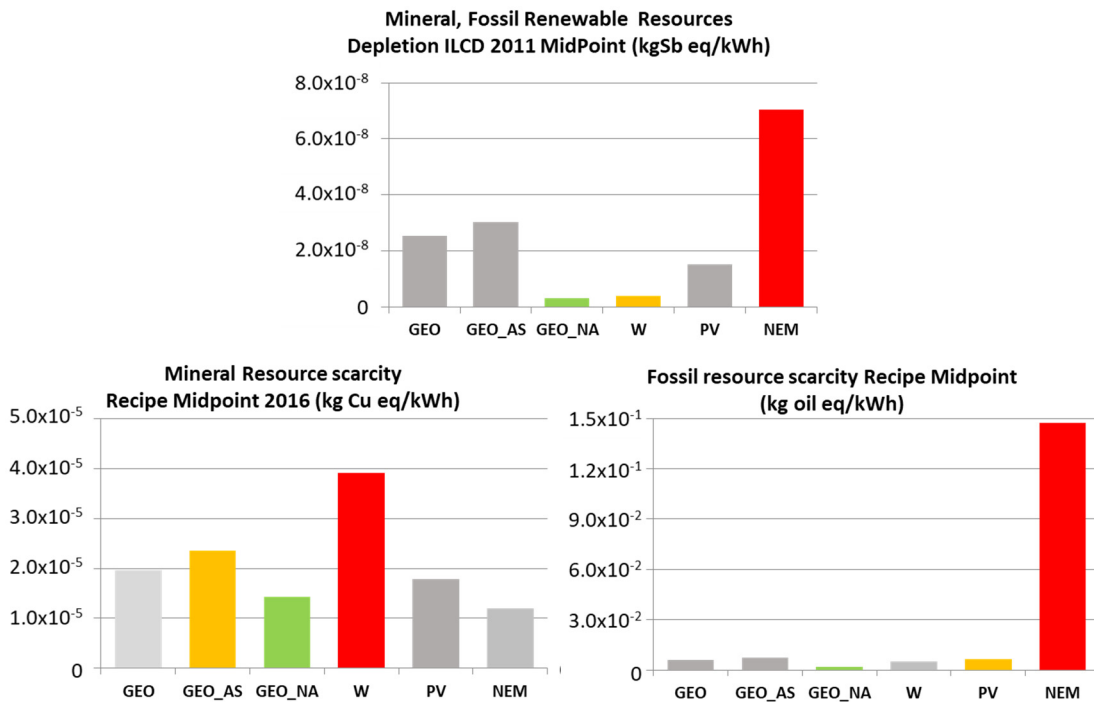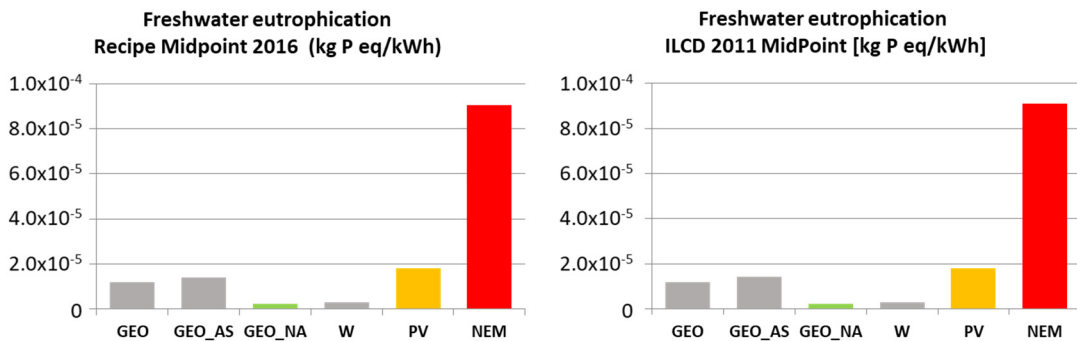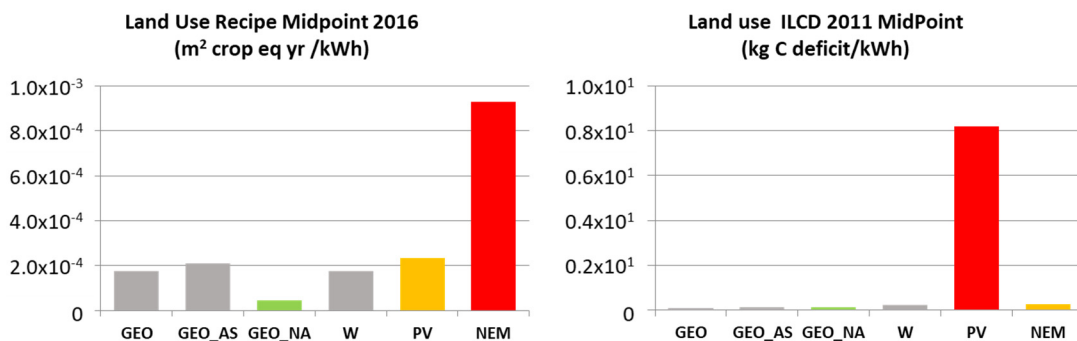**Figure 8.** Bar diagrams of ILCD 2011 Midpoint+ and ReCiPe 2016 impact assessment at midpoint level: Land use.

The results of the comparison are synthesized graphically (impact category indicators) in the spider-net diagrams (Figure 9 for ILCD Midpoint 2011+ and in Figure 10 for ReCiPe 2016).
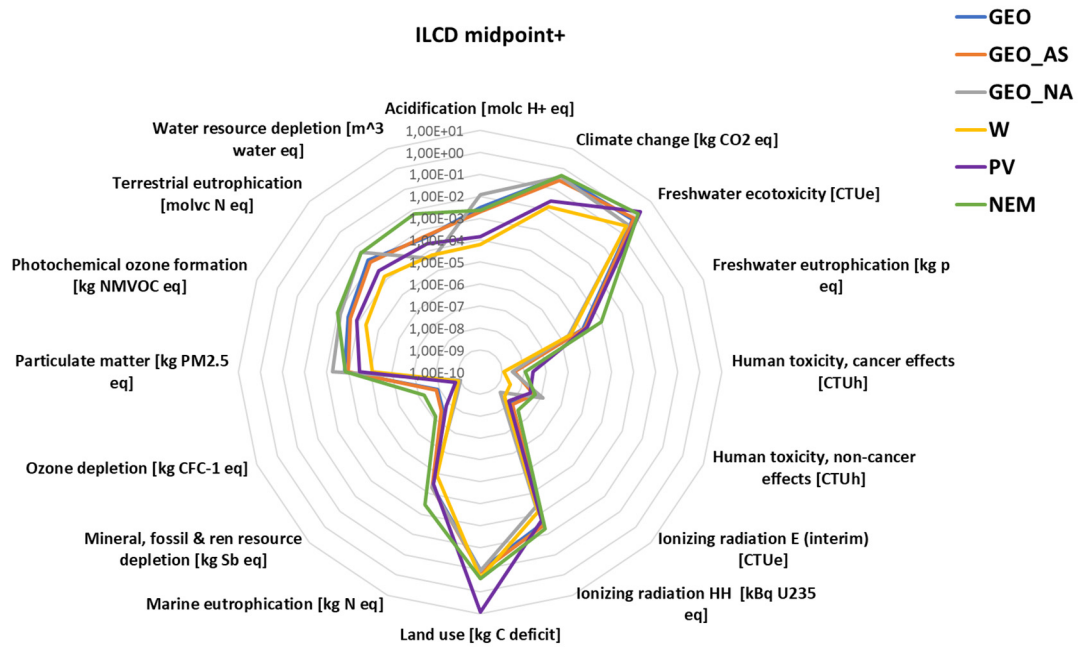
Figure 9. Spider net diagram of ILCD 2011 Midpoint+ impact assessment results (log scales).
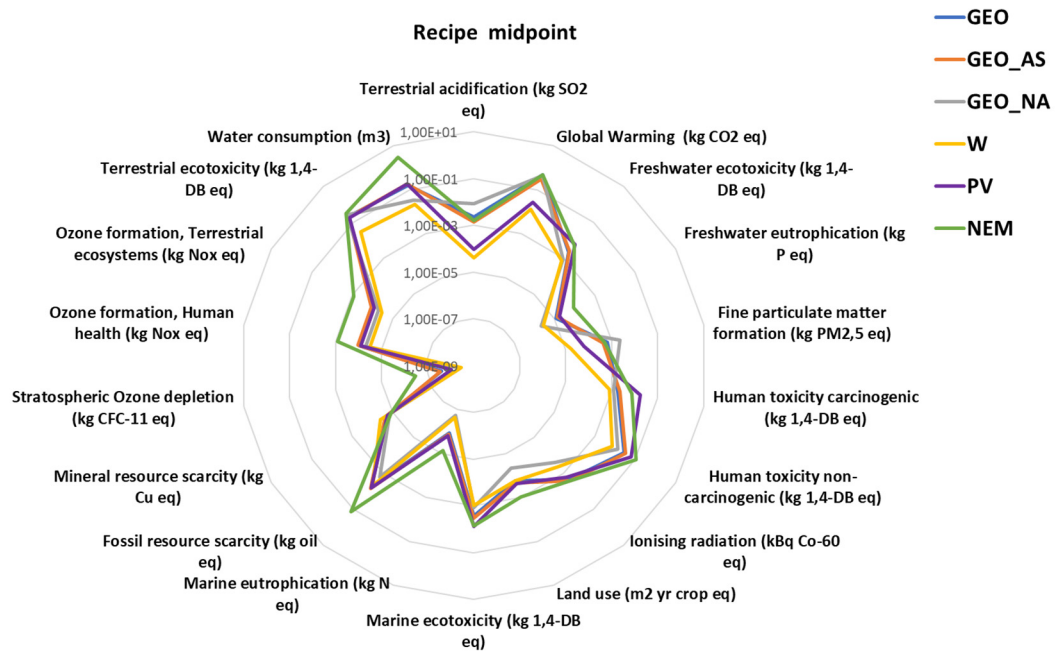
Figure 10. Spider net diagram of ReCiPe 2016 Midpoint+ impact assessment results (log scales).

As it emerges from the synthetic representation shown in Figures 9 and 10, the ILCD 2011 Midpoint+ and Recipe 2016 methods—apart from using different reference units for similar categories—are in qualitative agreement. On the whole, the ReCiPe 2016 method appears as a preferable approach for qualitative comparison of RES with the conventional energy mix, as it presents a more balanced representation of the impacts in different categories at the midpoint level. The ILCD 2011 Midpoint+ method pays special attention to toxicity, radiation, and human health effects while, for example, introduces some bias representing the land use impact category in terms of equivalent carbon deficit (which penalizes the PV technology in this analysis). Moreover, the ILCD 2011 Midpoint+ method clusters mineral, fossil, and renewable resources into one category, thereby hindering the direct

comparison with conventional energy conversion systems which relies heavily on the operation phase on fossil resources. ReCiPe 2016 accounts separately mineral and fossil resource consumption, thereby allowing RES to emerge clearly in terms of environmental performances. For the matters above, the ReCiPe 2016 method appears to be a more suitable impact assessment methodology at the midpoint characterization level for the comparison of the environmental performances of RES.

Finally, a contribution analysis of the midpoint impact categories for the ReCiPe 2016 method is presented in Figure 11. The contribution analysis shows that the relative impacts for each of the energy technologies considered take place in different categories: For example, for geothermal the dominant categories are terrestrial acidification and fine particulate matter formation (for the scenario of power plants not equipped with emissions treatment, GEO_NA), water consumption, marine and freshwater eco-toxicity. Wind and solar PV score high, in relative terms, for marine and terrestrial eco-toxicity. The NEM scenario produces large impacts for water consumption, for the marine and freshwater environments, for land use, and fossil resource scarcity.
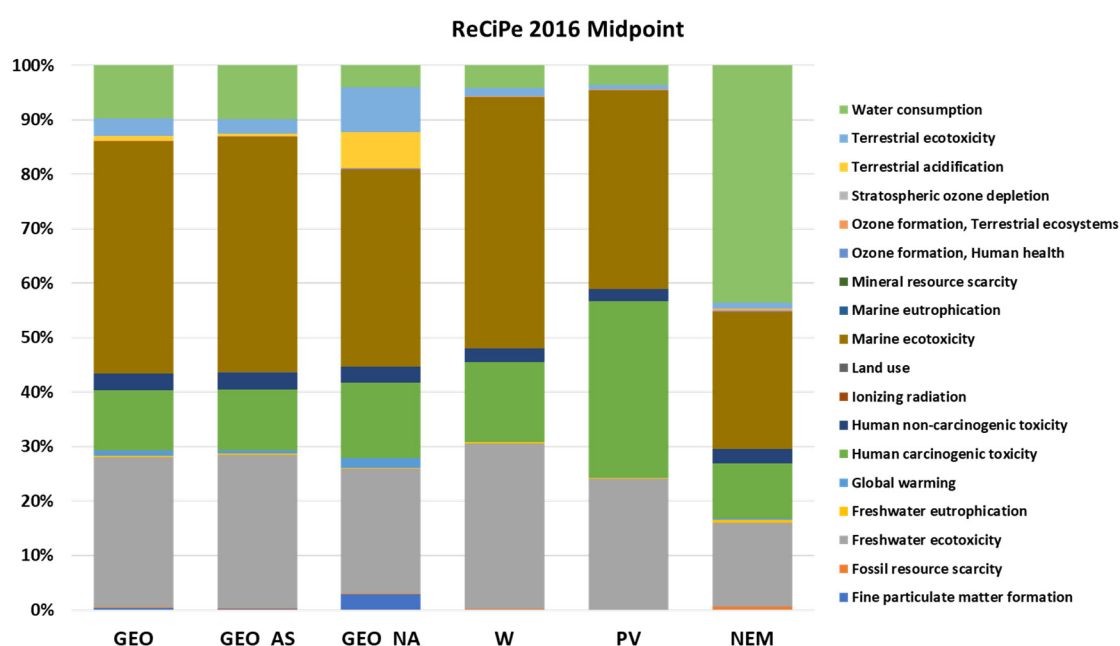
Figure 11. Contribution analysis of the ReCiPe 2016 method at midpoint level.

3.2. Impact Assessment at the Endpoint Level: ReCiPe 2016 Normalized and Weighted Results

In this section results calculated at the endpoint level are presented. For the reasons outlined in Section 3, supported by the better suitability of the method in the field of energy conversion (with specific reference to a transition from fossil to renewable resources), ReCiPe 2016 is applied in the following for normalization and weighting calculations. These operations allow grouping the impact assessment in three areas of protection: Ecosystem quality, human health, and resources. Normalization for ReCiPe is done referring to the European population and leads to the calculation of results in function of (i) disability-adjusted life years (DALY) unit for human health, representing the years that are lost or that a person is disabled due to a disease or accident; (ii) species per year (species*yr) unit for ecosystem quality, representing the local species loss integrated over time; (iii) dollar unit (USD 2013) for resources scarcity, representing the extra costs involved for future mineral and fossil resource extraction. The overall results of the environmental impact evaluation at the endpoint level are summarized in Table 4; results are also illustrated graphically in Figure 12.

Table 4. ReCiPe 2016 (H) normalized results at the endpoint level.

	GEO	GEO_AS	GEO_NA	Wind	PV	NEM
Ecosystems, total species*yr	5.58×10^{-6}	5.25×10^{-6}	4.99×10^{-6}	4.88×10^{-7}	$3.76 \cdot \times 10^{-6}$	6.20×10^{-5}
Human health, total DALY	5.15×10^{-5}	4.17×10^{-5}	8.44×10^{-5}	3.20×10^{-6}	2.36×10^{-5}	3.29×10^{-4}
Resources total USD 2013	5.08×10^{-8}	6.09×10^{-8}	2.02×10^{-8}	3.60×10^{-8}	4.83×10^{-8}	1.56×10^{-8}

species per year (species*yr); disability-adjusted life years unit (DALY).
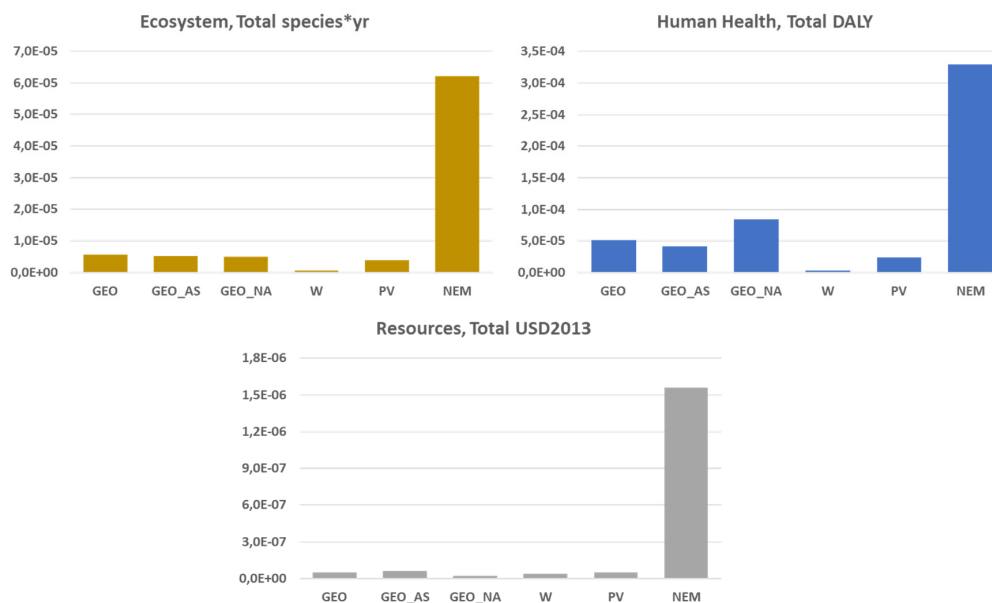
Figure 12. Normalized results of the ReCiPe 2016 (H) method at the endpoint level.

In Figure 13 the contribution analysis of the ReCiPe 2016 normalized results at the endpoint level is shown for all the case studies. According to the midpoint-to-endpoint values of the scaling factor implemented for the method [66], the human health damage category dominates the eco-profiles of all the scenarios with a detectable contribution of the resources damage category that increases going from PV to NEM and W.
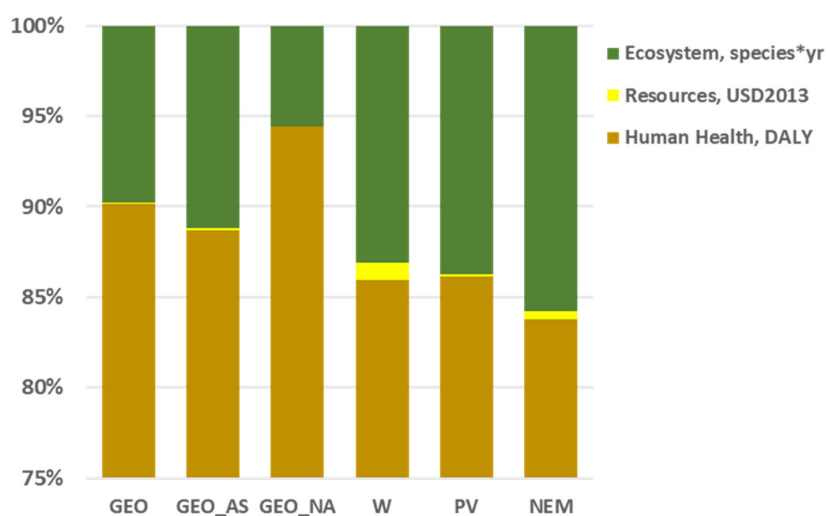
Figure 13. Contribution analysis of ReCiPe 2016 (H) normalized results at the endpoint level.

The weighting step in LCA allows calculating a synthetic indicator (expressed in Eco-points) and, thus, to calculate a global indicator of environmental performance, which can be used for overall comparison among the different technologies. In this study, the hierarchist (H) cultural perspective was assumed to weigh the normalized results of the ReCiPe 2016 method at the endpoint level; this involves weighting ecosystem damages by a factor 400, while human health and resource damages are weighted by a factor of 300. This perspective is a common assumption in the field of energy conversion systems. The ReCiPe 2016 weighted results are shown in Figure 14 in terms of Eco-points referred to the functional unit (1 kWh of electricity).
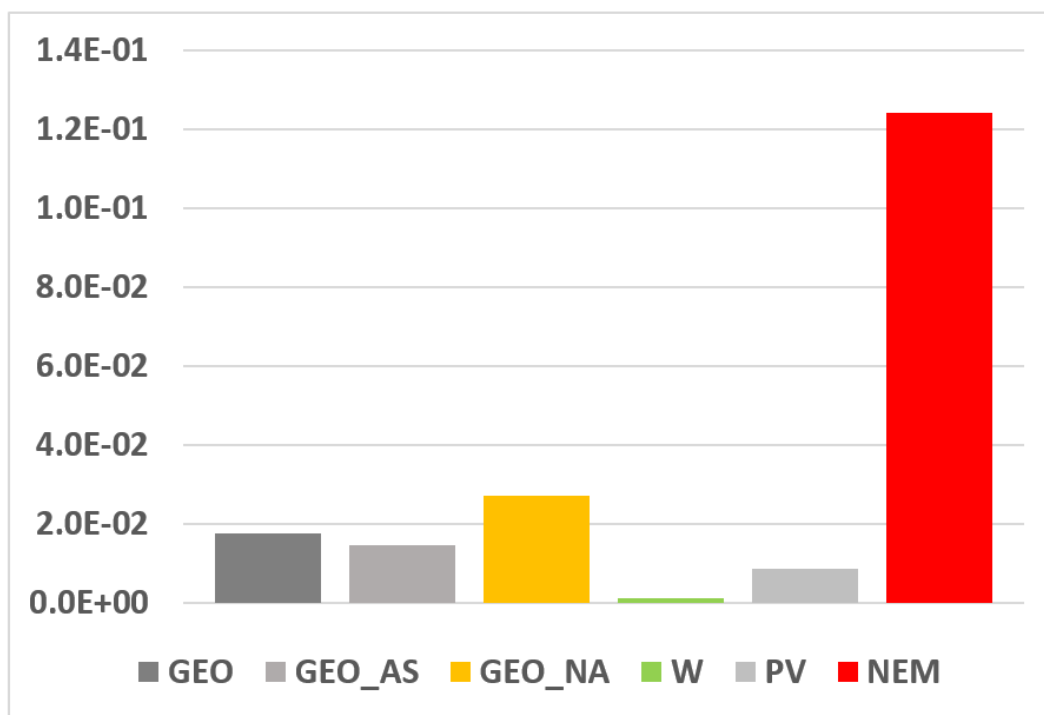
Figure 14. Weighted results calculated with the ReCiPe 2016 method (Eco-points/kWh).

4. Conclusions

Geothermal energy conversion was benchmarked by LCA methodology in comparison with other RES and with the Italian national energy mix. Calculations were performed based on specific power plant info recovered from primary data, taking advantage of life cycle inventories available through the plant operator (Enel Green Power). Three options were considered for geothermal energy: The current power plant with AMIS® emissions treatment (GEO); the same system without emissions treatment (GEO_NA); and a hypothetical case where 40% of the emissions could be considered a substitute of the natural emissions (GEO_AS). The GEO cases were compared with a wind energy farm (W) and with a large solar PV power plant (PV) having a similar capacity.

Midpoint calculations were performed comparing the ILCD 2011 Midpoint+ and ReCiPe 2016 methods. The results were similar in terms of identifying the most impacting categories: Terrestrial acidification, human toxicity, marine and freshwater eco-toxicity for the geothermal power plant (with a notable improvement in the case of emissions treatment); marine and freshwater eco-toxicity for wind and solar PV. The ReCiPe midpoint contribution analysis (Figure 11) shows that several other categories (usually not accounted in the literature [33–35,38–42,55,56,59–62]) should be considered when evaluating RES through LCA (mainly: Human toxicity, marine and freshwater eco-toxicity). The national energy mix impacts mainly on water consumption and fossil fuel depletion. In absolute terms, wind energy emerged as the least impacting technology in most categories. It was evident already for the impact evaluation at midpoint level that the ReCiPe 2016 method can provide a higher

degree of detail, accounting for relevant issues when comparing RES and fossil fuels (for example, mineral and fossil resources depletion).

The impact evaluation at the endpoint level was performed with the ReCiPe 2016 method allowing to cluster the results in three significant damage categories (ecosystem quality, human health, and resources). All RES technologies scored better than the national energy mix, as the latter includes the use of a considerable amount of fossil fuel resources (mostly gas and coal). Geothermal scenarios even with emissions treatment (GEO and GEO_AS) resulted to have lower performance compared with wind and solar PV for ecosystem quality and human health damage categories; however, it represents a definite step forward to the NEM and it compares well to other RES for the resources damage category. This result is a direct consequence of the high productivity of geothermal power plants (over 7500 hrs/yr operation at nominal load, compared to 1300 for solar PV and 2300 for the wind farm). These results were confirmed by the contribution analysis performed on the ReCiPe 2016 normalized results at the endpoint level.

Finally, weighting allowed to calculate a final synthetic indicator that can be used to compare the environmental performances of the different electricity generation systems. To this end, a hierarchist cultural perspective was applied to the normalized ReCiPe 2016 results. Wind resulted to be the best technology with a value of 0.0012 Eco-points/kWh, a result in line with previously documented LCA studies. However, the geothermal power plants achieved values of about 0.0177 Eco-points/kWh which were close to solar PV (0.0087 Eco-points/kWh) and much lower than those of the national energy mix (0.1240 Eco-points/kWh).

The results obtained represent a multi-category LCA comparison of different RES technologies based on primary data for three relevant test cases, and are thus a valuable addition to the available literature which is mostly based on secondary data and/or reworking of published results, often obtained with superseded LCA methodologies. The values are within the ranges for the typical categories considered in the literature (typically: GWP, AP, EP; W: [38–42]; PV: [33–35]; GEO: [55,56]; RES: [59–62]), except for GWP which is substantially higher than average for the operating Italian power plants [50,54] because of the high content of non-condensable gases (NCGs) in the natural resource.

These results, which should be matched with the real local availability of the RES and to an analysis of economic profitability, confirm that geothermal energy conversion is a good option for sustainable development.

Author Contributions: D.F. was responsible for LCI building from primary data. The LCI data was collected using primary data by F.S. and D.F., R.B. (Roberto Bonciani) provided expertise on power plant and emissions treatment processes. G.M., R.B. (Riccardo Basosi), and M.L.P. organized the validation and presentation of the results. All authors contributed to writing and interpreting the results. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Symbols/Acronyms

AP	Acidification Potential
CED	Cumulative Energy Demand
EGS	Engineered Geothermal System
EP	Eutrophication Potential
GEO	Geothermal with AMIS® process
GEO_AS	Geothermal with AMIS® process treatment plus a 40% substitution of natural emissions

GEO_NA　　Geothermal without AMIS® process
GWh/yr　　Giga Watt-hour per year
H　　　　　Hierarchist Cultural Perspective (Endpoint)
GWP　　　Greenhouse Warming Potential
Hrs/yr　　　Hours per year
LCA　　　　Life Cycle Analysis
LCI　　　　Life-Cycle Inventory
LCIA　　　Life Cycle Impact Assessment
MWe　　　MegaWatt electric
MWth　　　MegaWatt thermal
NCG　　　Non-Condensable Gases
PV　　　　Photovoltaic
RES　　　　Renewable Energy Source
VRE　　　　Variable Renewable Energy
W　　　　　Wind

Appendix A　Life Cycle Inventory Data for the Chiusdino 1 Power Plant

Table A1. Description.

Name	Chiusdino 1	
Location	43°09′37.0″ N 11°03′49.9″ E	
Construction start date	Dec-2010	
Expected life	30	yrs
Geothermal reservoir	Metamorphic	
Reservoir depth	3–4.5	km
Land occupation	11,000	m^2
Type of geothermal resource	Steam	
Production technology	Natural draft	
Electrical generation technology	Flash and condensation	
Cooling system	Evaporative towers	
End-use of energy	Electricity	
Installed capacity		
Electrical	20	MWe
Operating capacity		
Electrical	18	MWe
Expected annual decay rate	0	% per year
Net annual production		
Electricity delivered to the grid	151.2	GWh
Capacity factor	8400	h
Out of order	18	h/yr
Average pressure at the wellhead	15.74	bar
Average temperature at the wellhead	199.61	°C
Overall flow rate	36.1	kg/s
Condenser temperature	25	°C

Table A1. *Cont.*

Name	Chiusdino 1	
Reinjection		
Temperature	25	°C
Pressure	Atmospheric	
Liquid phase, % of the total from the wells	30%	
Gas phase	0%	
Composition of the geothermal fluid		
Dissolved gasses (NCG) mass fraction	4.00%	
CO_2	5100	kg/h
CO	0.4	kg/h
CH_4	79	kg/h
H_2S	90	kg/h
NH_3	11.6	kg/h
Hg	5.6	g/h
Trace elements		
As	0.042	mg/L
B	-	mg/L
Sb	-	mg/L
Se	-	mg/L
Rn	-	Bq/m^3
NCG emissions treatment system (AMIS)		
H_2S removal efficiency	99.8%	
Hg removal efficiency	82.2%	
NH_3 removal efficiency	87%	
CO_2 removal efficiency	0%	
B removal efficiency	99%	
As removal efficiency	99%	

Table A2. Construction.

Drilling		
Production wells	5	
Average depth	3818	m
Reinjection wells (equivalent)	2	
Average depth	3000	m
Drilling time	146	days per well
Diesel fuel consumption for generator set (total)	1,970,950	l
Diesel fuel consumption—construction works, per well	309,734	l

Table A2. *Cont.*

Drilling		
Wells casing and cementing		
Production wells		
Steel	1,458,476	kg
Portland cement	1,737,190	kg
Bentonite	832,324	kg
Silica sand	503,976	kg
Lignosulfonates	11,454	kg
Perlite	38,180	kg
NaOH	1,282,848	kg
HCl	328,348	l
Oli and lubricants	91,632	kg
Excavations	1925	m^3
Drilling mud	2,103,718	kg
Reinjection wells (equivalent)		
Steel	228,971	kg
Portland cement	272,972	kg
Bentonite	130,600	kg
Silica sand	79,047	kg
Lignosulfonates	0	kg
Perlite	5814	kg
NaOH	188,426	kg
HCl	13,358	l
Oli and lubricants	14,457	kg
Excavations	2,931,364,589	m^3
Drilling mud	320,351	kg
Drilling Platform		
Occupied surface	10,000	m^2
Portland cement	1,230,000	kg
Aluminum	9000	kg
Steel	43,000	kg
Sand	1,937,000	kg
Plastic	1250	kg
Excavation	1790	m^3
Fills	2150	m^3
Steam adduction pipeline		
Total length	2758	m
Steel for supports and foundations	163,736	
Steel for piping	313,398	kg
Portland cement	493.680	m^3
Aluminum	12,962.6	kg

Table A2. *Cont.*

Drilling		
Steam adduction pipeline		
Rock wool insulation	130,177.6	kg
Excavations	468.86	m^3
Fills	468.86	m^3
Condensate Pipeline		
Total length	5,000	m
Plastics	36,565	kg
Powerhouse Equipment		
Turbine and Alternator		
Number of turbines	1	
Rated Power	20	MWe
Type	Ansaldo TUVA 20 MW 2nd generation	
Expected Life *	25	years
Number of alternators	1	
Rated Power	23	MWA
Type	Ansaldo	
Expected Life *	>25	years
Cast iron	13,400	kg
Copper	4000	kg
Iron-nickel-chromium alloy	1000	kg
Rock wool	4400	kg
Chromium steel 18/8	9800	kg
Steel, low-alloyed	600	kg
Steel, unalloyed	76,400	kg
Compressors		
Number of compressors	1	
Capacity	5	t/h
Type	Modified F. Tosi centrifugal unit	
Expected Life *	25	yrs
Aluminum	5680	kg
Cast iron	12,120	kg
Steel, unalloyed	8080	kg
Copper	16,200	kg
Condenser		
Number of condensers	1	
Rated Power	20	MW
Type	Ansaldo/ENEL	
Expected Life	30	yrs
Chromium steel 18/8	68,250	kg

Table A2. *Cont.*

Drilling		
Intercooler		
Chromium steel 18/8	18,000	kg
Cooling towers		
Number of cells	3	
Type	Hamon cooling tower	
Main material	PSRV	
Expected Life	25	yrs
Steel piping	8190	kg
Plastic piping	81,900	kg
Fiberglass	90,220	kg
Copper	150	kg
Cast iron	450	kg
Gas treatment system		
Type	AMIS 1 unit	
Main material	Stainless steel 316L	
Capacity (max flow rate)	5000	kg/h
Expected Life	30	years
Sorbent (Selenium for Hg)	4000	kg
Catalyst (Titanium for H2S)	9000	kg
Aluminum	500	kg
Chromium steel 18/8	11,500	kg
Building		
Portland cement	637,500	kg
Diesel fuel for construction works	195,500	l
Excavations	8,500	m^3
Plastic pipes	637,500	kg
Fills	17,944,960	kg
Aluminum	810	kg
Steel, low-alloyed	170,000	kg
Accessories		
Copper	30,000	kg
Plastic pipes	15,000	kg
Chromium steel 18/8	150,000	kg
Steel, low-alloyed	220,000	kg

* Major maintenance and refitting every 4 years.

Table A3. Operation and Maintenance.

Emissions-to-Air		
CO_2	5100	kg/h
CO	0.4	kg/h
H_2S	18.4	kg/h
CH_4	79.3	kg/h
NH_3	1.5	kg/h
Hg	1.1	g/h
As	2.8	mg/h
Se	0.4	g/h
Machinery maintenance		
Lubricants	25,000	kg
Waste mineral oil	25,000	kg
Iron-nickel-chromium alloy	5375	kg
Chromium steel 18/8	3500	kg
Waste steel	8875	kg
Fluid treatment		
NaOH	2,500,000	kg/yr

Table A4. End of Life.

Wells Abandonment (per well)		
Expected time	10	days
Diesel fuel consumption	25,000	l
Portland cement	25,000	kg
Inert	5000	kg
Steel	0	kg
Water	0	l

Appendix B Life Cycle Inventory Data for the Pietragalla Wind Farm

Table A5. Description.

Name	Potenza Pietragalla	
Location	40.776954, 15.837555	
Construction start date	2005	
Expected life	30	years
Land occupation	1,500,000	m^2
Production technology	HAWT Repower MM92	
Electrical generation technology	Generator at the summit MV at ground HV at substation	
End-use of energy	Electricity	
Installed capacity		
Electrical	18	MWe

Table A5. *Cont.*

Name	Potenza Pietragalla	
Operating capacity		
Electrical	18	MWe
Expected annual decay rate for the electrical power	0	% per yr
Net annual production		
Electricity delivered to the grid	25.2	GWh
Capacity factor (at 18 MWe)	1400	h
Out of order (per year)	50	h
Resource characteristics		
Mean power density (at 100 m)	1041	W/m^2
Maximum average wind speed (at 100 m)	9.32	m/s

Table A6. Construction.

Pitches and Logistic Surfaces		
Excavations	75,000	m^3
Fills	11,250	m^3
Steel	430,272	kg
Cement	3339	m^3
Occupied surface	20,305	m^2
Wood	324	m^2
Diesel fuel for excavations	37,500	l
Cable-Ducts		
Total length	15,000	m
Aluminum	19,660	kg
Copper	6560	kg
Optical fiber	15,000	m
Excavations	7015	m^3
Fills	1960	m^3
Diesel fuel for excavations	3510	l
Occupied surface	7500	m^2
Horizontal Axis Wind Turbine (HWAT)		
Number of HAWT	9	
Rated power	2	MW
Description	Repower MM92	
Expected life	30	years
Diesel fuel for construction works	14,400	l
Tower		
Steel	146,500	kg
Copper	6480	kg

Table A6. *Cont.*

Pitches and Logistic Surfaces		
Rotor Blades		
Steel	1620	kg
Fiberglass	6480	kg
Nacelle		
Steel	56,520	kg
Copper	5600	kg
Fiberglass	2780	kg
Hub		
Steel	17,000	kg
Viability (Road Constructions)		
Excavations	24,784	m^3
Fills	700,800	kg
Asphalt	8190	m^3
Diesel fuel for construction works	13,000	l
Substation		
Steel	36,800	kg
Fills	1220	m^3
PEAD tubing	1260	kg
Cement	970	m^3
Pre-cast concrete	16.4	m^3
Copper	5000	kg
Aluminum	1500	kg
Diesel	1000	l
Occupied surface	2620	m^2

Table A7. Operation and Maintenance.

Lubricating oil	**202,500**	**kg**
Waste mineral oils	202,500	kg
Steel, chromium 18/8	999,000	kg
Steel, low alloyed	540,000	kg
Iron Scrap	1,539,000	kg
Diesel for O&M	54,000	l

Table A8. End of Life.

Machinery disassemblement		
Time (per HAWT—estimate)	10	days
Diesel for O&M (per HAWT—estimate)	25,000	l
Steel (per HAWT—95% recycled)	221,640	kg
Copper (per HAWT—95% recycled)	12,080	kg
Fiberglass (per HAWT—100% recycled)	22,220	kg
Cement (per HAWT—left on site)	371	m^3
Iron for foundation works (per HAWT—95% recycled)	47,808	kg

Appendix C Life Cycle Inventory data for the Serre Persano DS Photovoltaic Power Plant

Table A9. Description.

Name	Serre Persano DS	
Location	40°34′08.5″ N 15°06′10.5″ E	
Construction start date	2013	
Expected life	30	yrs
Land occupation	770,000	m^2
Electrical generation technology	Photovoltaic generator, inverter for subfield, elevation downstream substation	
Module NA F130 G5	53,760	
Module NA F135 G6	103,796	
Inverter Santerno SUNWAY TG760 1000V TE	24	
End-use of energy	Electricity	
Installed capacity		
Electrical	21.0	MWe
Operating capacity		
Electrical	19.53	MWe
Expected annual decay rate	0.07	% per year
Net annual production		
Electricity delivered to the grid	29.50	GWh
Capacity factor	1281	h
Out of order (per year)	0	h
Resource characteristics		
Global annual radiation on the normal surface	2131	kWh/m^2

Table A10. Construction.

Pitches and Logistic Surfaces		
Excavations	54,000	m^3
Fills	1080	m^3
Occupied surface	770,000	m^2
Diesel for excavations	30,000	l
Metal Carpentry		
Steel	10,023,790	kg
Aluminum	2,594,686	kg
Diesel for construction	18,135	l
Photovoltaic Modules		
Module NA F130 G5	53,760	
Module NA F135 G6	103,796	
Electrical Connections		
Copper	63,125	kg
Aluminum	1516	kg
Excavations	2954	m^3
Sand	29,546	kg
Cement	1181	kg
Plastic	18,381	kg
Diesel for construction	1477	l
Inverter		
Inverter Santerno SUNWAY TG760 1000V TE	24	
Delivery Cabin		
Precast concrete	41,000	kg
Portland cement	272,176	kg
Diesel for construction	1176	l
Plastic pipes	1470	kg
Fills	581,760	kg
Steel	43,052	kg
Aluminum	1743	kg
Copper	5880	kg

Table A11. Operation & Maintenance.

Diesel for cleaning machine	**56,270**	**l**
Decarbonised water	16,881,000	kg

Table A12. End of Life.

Diesel for disassembly	341	l
Electricity, medium voltage	159,716	kWh
Used cable	29,935	kg
Aluminum scrap for melting	511,899	kg
Inert material and fill	2,451,729	kg

Appendix D Synthesis tables of ILCD and ReCiPe Impact Analysis

Table A13. ILCD MidPoint 2011+ method results.

	GEO	GEO_AS	GEO_NA	W	PV	NEM
Acidification (molc H+ eq)	3,04E-03	1,92E-03	1,14E-02	6,30E-05	1,50E-04	2,34E-03
Climate change (kg CO_2 eq)	4,77E-01	3,01E-01	4,59E-01	1,34E-02	2,66E-02	4,84E-01
Freshwater ecotoxicity (CTUe)	2,09E-03	2,50E-03	8,96E-04	7,41E-04	5,85E-03	5,14E-03
Freshwater eutrophication (kg P eq)	1,18E-05	1,41E-05	2,30E-06	2,88E-06	1,81E-05	9,04E-05
Human toxicity, cancer effects (CTUh)	6,58E-04	4,31E-04	2,38E-03	1,72E-05	6,49E-05	5,09E-04
Human toxicity, non-cancer effects (CTUh)	1,89E-03	2,26E-03	1,21E-03	8,09E-04	1,78E-02	7,62E-03
Ionizing radiation E (interim) (CTUe)	2,80E-02	3,26E-02	1,35E-02	7,33E-03	6,22E-02	1,05E-01
Ionizing radiation HH (kBq U235 eq)	2,31E-03	2,77E-03	2,53E-04	4,28E-04	1,64E-03	2,71E-03
Land use (kg C deficit)	1,74E-04	2,08E-04	4,60E-05	1,76E-04	2,33E-04	9,31E-04
Marine eutrophication (kg N eq)	2,71E-03	3,24E-03	1,19E-03	9,41E-04	7,45E-03	7,05E-03
Mineral, fossil & ren resource depletion (kg Sb eq)	1,13E-06	1,36E-06	1,85E-07	2,27E-07	1,50E-06	7,19E-06
Ozone depletion (kg CFC-11 e)	6,15E-03	7,37E-03	1,68E-03	5,17E-03	6,53E-03	1,47E-01
Particulate matter (kg PM2.5 eq)	1,97E-05	2,36E-05	1,42E-05	3,90E-05	1,79E-05	1,21E-05
Photochemical ozone formation (kg NMVOC eq)	2,41E-08	2,89E-08	4,00E-09	3,36E-09	8,91E-09	3,37E-07
Terrestrial eutrophication (molvc N eq)	9,10E-05	1,09E-04	4,92E-05	3,29E-05	8,03E-05	8,33E-04
Water resource depletion (m^3 water eq)	9,22E-05	1,11E-04	5,00E-05	3,39E-05	8,41E-05	8,48E-04

Table A14. ReCiPe 2016 method results at the midpoint level.

	GEO	GEO_AS	GEO_NA	W	PV	NEM
Terrestrial acidification (kg SO_2 eq)	2,27E-03	1,42E-03	8,58E-03	4,15E-05	9,68E-05	1,58E-03
Global Warming (kg CO_2 eq)	4,77E-01	3,01E-01	4,59E-01	1,34E-02	2,66E-02	4,84E-01
Freshwater ecotoxicity (kg 1,4-DB eq)	2,09E-03	2,50E-03	8,96E-04	7,41E-04	5,85E-03	5,14E-03
Freshwater eutrophication (kg P eq)	1,18E-05	1,41E-05	2,30E-06	2,88E-06	1,81E-05	9,04E-05
Fine particulate matter formation (kg PM2,5 eq)	6,58E-04	4,31E-04	2,38E-03	1,72E-05	6,49E-05	5,09E-04
Human toxicity carcinogenic (kg 1,4-DB eq)	1,89E-03	2,26E-03	1,21E-03	8,09E-04	1,78E-02	7,62E-03
Human toxicity non-carcinogenic (kg 1,4-DB eq)	2,80E-02	3,26E-02	1,35E-02	7,33E-03	6,22E-02	1,05E-01
Ionising radiation (kBq Co-60 eq)	2,31E-03	2,77E-03	2,53E-04	4,28E-04	1,64E-03	2,71E-03
Land use (m^2 yr crop eq)	1,74E-04	2,08E-04	4,60E-05	1,76E-04	2,33E-04	9,31E-04
Marine ecotoxicity (kg 1,4-DB eq)	2,71E-03	3,24E-03	1,19E-03	9,41E-04	7,45E-03	7,05E-03
Marine eutrophication (kg N eq)	1,13E-06	1,36E-06	1,85E-07	2,27E-07	1,50E-06	7,19E-06
Fossil resource scarcity (kg oil eq)	6,15E-03	7,37E-03	1,68E-03	5,17E-03	6,53E-03	1,47E-01
Mineral resource scarcity (kg Cu eq)	1,97E-05	2,36E-05	1,42E-05	3,90E-05	1,79E-05	1,21E-05
Stratospheric Ozone depletion (kg CFC-11 eq)	2,41E-08	2,89E-08	4,00E-09	3,36E-09	8,91E-09	3,37E-07
Ozone formation, Human health (kg NOx eq)	9,10E-05	1,09E-04	4,92E-05	3,29E-05	8,03E-05	8,33E-04
Ozone formation, Terrestrial ecosystems (kg NOx eq)	9,22E-05	1,11E-04	5,00E-05	3,39E-05	8,41E-05	8,48E-04
Terrestrial ecotoxicity (kg 1,4-DB eq)	2,10E-01	1,98E-01	2,67E-01	3,09E-02	1,82E-01	3,18E-01
Water consumption (m^3)	1,60E-01	1,92E-01	3,38E-02	2,18E-02	1,90E-01	3,15E+00

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