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Life Cycle Analysis of a Geothermal Power Plant: comparison of the environmental performance with other renewable energy systems

Riccardo Basosi[1,4], Roberto Bonciani[2], Dario Frosali[3], Giampaolo Manfrida[3,4], Maria Laura Parisi[1,4] and Franco Sansone[2]

[1] RES Lab, Department of Biotechnology, Chemistry and Pharmacy, University of Siena, 53100 Siena, Italy;riccardo.basosi@unisi.it; marialaura.parisi@unisi.it
[2] Enel Green Power; roberto.bonciani2@enel.com; francosansone1959@gmail.com
[3] Department of Industrial Engineering, University of Florence, 50135 Florence, Italy; dario.frosali@stud.unifi.it; giampaolo.manfrida@unifi.it
[4] Center for Colloid and Surface Science (CSGI), 50019 Firenze, Italy

* Correspondence: giampaolo.manfrida@unifi.it

Abstract: A Life Cycle Analysis was performed considering three existing power plants of comparable size operating with different sources of renewable energy: geothermal, solar and wind. Primary data were used for building the life cycle inventories. The geothermal power plant includes emissions treatment for removal of hydrogen sulfide and mercury. The scenario about the substitution of natural emissions from geothermal energy, with specific reference to the greenhouse effect, is also investigated performing a sensitivity analysis. The results are characterized 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 endpoint level. The results demonstrate a good eco-profile of geothermal power plant with respect to other renewable energy systems and allow for a critical analysis to support potential improvements of the environmental performances.

Keywords: Geothermal Energy; Life Cycle Analysis; Solar Photovoltaic Energy; 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 12,000 MWe [1–4], with provision of direct heat of the order of 165,000GWh/yr[5]. The geothermal resource is well distributed around the world[6,7], and several locations are favoured 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 an even more widespread use of the earth 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 practiced.

Italy has a long tradition of geothermal energy utilization[12], with nearly 1,000 MWe installed in two areas of the Tuscany region (Larderello/Travale and Monte Amiata) operated by Enel GreenPower. 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

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equipped with effective emissions treatment equipment, which removes the greatest part of hydrogen sulphyde (H2S) and mercury (Hg) though the application of proprietary technology (AMIS® process [13,14]). The geothermal power plants located in Tuscany have demonstrated a high reliability, with equivalent operation time exceeding 7,500 hrs/yr and with a productivity of more than 6,200GWh/yr [15].

Solar electricity is mainly produced by photovoltaic (PV) power plants. Over the world, the power installed exceeds 500 GWe. Italy represents one of the main players in Europe with more than 20GWe installed and a productivity exceeding 24,000 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 1,200 hrs/yr. This is due to the periodic cycle of solar radiation (daily and seasonal).

Wind energy has had a strong increase with specific reference to Europe (180 GWe installed with a productivity of about 362,000 GWh/yr). In Italy more than10GWeare installed (mainly in the South), with a productivity exceeding 17,000 GWh/yr [15]. The equivalent full-load operability is typically 2,000 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 favoured in this sense). A 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 a very valuable support, both in countries with limited electric grid infrastructure and in developed countries committed to an ever higher market penetration of electricity with respect to other energy vectors.

This work raises from the consideration that the clean energy does not exist: the only clean energy is the one we do not need to use, namely the saved one with efficiency actions. However, in an environmental sustainable perspective RES are better than fossil ones, but even in the use of RES the only rationale to make a choice should be based on benefit/cost ratio and a rigorous comparison of their environmental advantages and drawbacks. LCA analysis is a optimum tool to make this comparison.

In this study the comparison of the environmental performances of three power plants based respectively on geothermal, solar and wind energy is performed through the life cycle assessment (LCA) methodology grounding on robust and reliable primary data.

2. Life Cycle Assessment

LCA is a method to evaluate the environmental load associated with a product, process, or activity. LCA allows to quantify 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, processor 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 series 14040 [16,17] 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.

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2. Life Cycle Inventory Analysis (LCI): the purpose of this phase is to collect the input/ output data with regard to the system studied; generally robust and reliable LCI are built on primary data, that's 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 indicators 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 in accordance with the goal and scope of the study.

LCA was born as a detailed and quantitative approach for the evaluation of environmental sustainability [18]. The regulatory approach described in the ISO standards and in the more completely elaborated ILCD Handbook Guidelines [19] claims for the development of an LCA study till 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, difficult to interpret. In principle, it represents a good approach for the characterization of the eco-profile of the product or activity under study 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 to express 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 less 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 analyse 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 [20–22]; 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 with respect to the use of fossil

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resources. However, these outcomes should be evaluated, validated and compared among different RES.

Several LCA studies are available on solar PV energy conversion systems [23–32]; in general, the results indicate that a significant impact is coming from the manufacture of the PV modules, with the current silicon technology performing definitely better than CdTe, notwithstanding substantial advantages for thin-film manufacturing [33]. 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 [34], which have determined an improved homogeneity in the results and better comparability of the studies. Wind energy has also attracted several LCA studies[35–37]: 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 [38]; the results have been cross-checked by researchers and substantial agreement is documented [39–42].

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[43–48]; 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 [50-53]; 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 are definitely 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 of commitment of construction work 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 primary motivation behind the present study.

The case studies described in the following were analysed using the OpenLCA 1.10 software package [49]; for secondary data, the Ecoinvent database 3.6 was adopted [50, 51]. The interpretation was performed comparing the Recipe 2016 [52] and the ILCD 2011 Midpoint+ [53] LCIA methods both employed for the characterization of potential impact at midpoint level. Normalization and weighting applying an Hyerarchist (H) cultural perspective were applied to the Recipe 2016 results in order to determine the systems eco-profiles at the endpoint level (with weighted results expressed in Ecopoints). 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. Operation and maintenance (including replacement of major equipment) were included following the experience of Enel Green Power as power plant manager.

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

3. Case Studies

The case studies examined represent three power plants of similar nominal capacity (about 20 MWe): the geothermal power plant Chiusdino 1, the solar photovoltaic power plant SerrePersano (SP) and the wind farm in Pietragalla (P).

3.1. Chiusdino Geothermal Power Plant

Chiusdino 1 (Location: 43°09'37.0"N; 11°03'49.9"E) is a standard Enel Green Power geothermal power plant, with a nominal size of 20 MWe. The live steam (139 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 the capability of providing 7 MWth of heat.

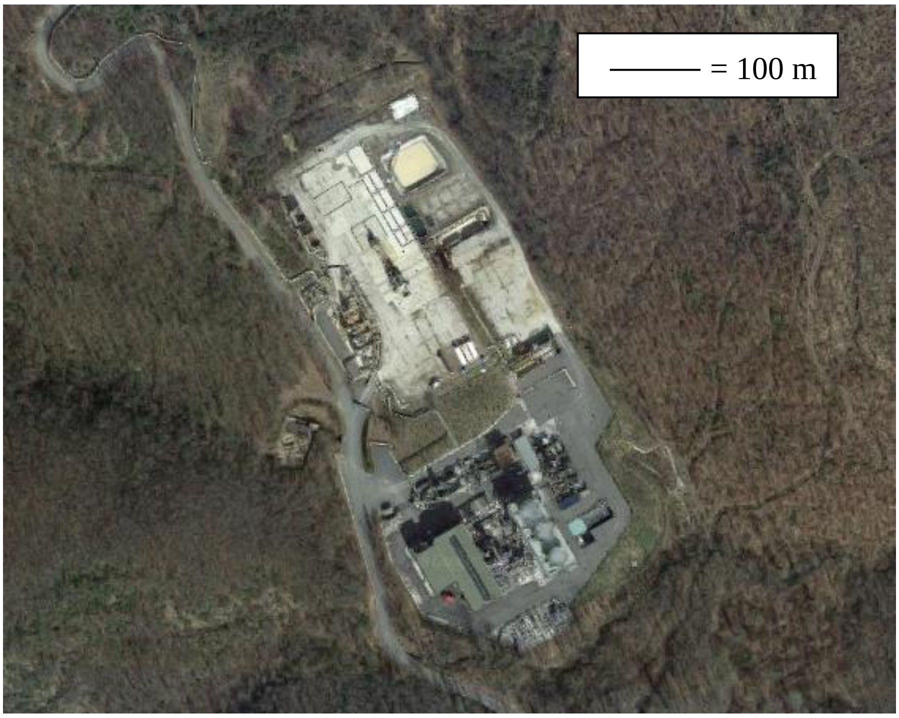

Figure 1. Aerial view of Chiusdino power Plant

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

Name	*Distance[1], m*	*Depth, m*	*Flow rate, t/h*	T, °C	p, bar	NGG, %
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.

The Chiusdino 1 power plant is equipped with an AMIS® emissions treatment system, which removes H_2S and Hg with measured efficiencies of respectively 99,8% and 82,2%. A soda solution is currently used for acid gas treatment, while Hg is captured by a solid adsorption reactor. Details on the pollutant streams emitted, according to measured values certified by the regional authority (ARPAT), are provided in Table 2.

For Chiusdino 1, two scenarios are documented in order to consider the effects of emissions treatment: the real scenario GEO featuring the AMIS® process and the hypothetical scenario GEO_NA representing the power plant as if no AMIS® process were operating. Moreover, a third case was considered (GEO_AS), considering emissions treatment plus the partial substitution of natural emissions (several scenarios were investigated: the GEO_AS assumes that 40% of the power plant emissions would anyway reach the atmosphere as natural emissions).

The whole liquid condensate of Chiusdino 1 is re-injected using a complex network of pipelines connecting to the Larderello reinjection sites, with an overall estimated length of about 20 km.

Table 2. Emissions of the Chiusdino 1 power plant.

Emission	Flow Rate, kg/h
CO_2	5100
CO	0.4
H_2S	18.4
CH_4	79.3
NH3	1.5
Hg	0.0011
As	0.0000028
Se	0.0004

The Chiusdino1 power plant is operated at full load, with a demonstrated operability of 7560 h/yr. This leads to a very high productivity, that's to say about 151,200 MWh/yr. Appendix A collects the Life Cycle Inventory data for the Chiusdino 1 power plant.

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3.2. Pietragalla Wind Farm

The Pietragalla wind farm (Location: 40°43’31.63” N; 15°49’41.85” E) is composed of 9 horizontal axis wind turbines MM92 Repower, each having a nominal rating of 2 MWe. The wind farm is operational since 2011. The wind turbine has a rotor diameter of 92,5 m and is installed on top of a pre-assembled tower (3 pieces) with an overall height of 100 m. The tower, nacelle and rotor require substantial construction work for the foundations; moreover, erection (and maintenance) of the machine requires 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) allowed to evaluate the productivity at 42,069 MWh/yr, equivalent to a full-load operability of 2,337 hrs/yr (a very high value for Italian typical wind energy installations). Appendix B collects the Life Cycle Inventory data for the Pietragalla wind farm.

Figure 2. Aerial view of Pietragalla wind power plant (3 of the 9 turbines).

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3.3. Serre Persano Photovoltaic Solar plant

The Serre Persano DS photovoltaic solar plant (Location: 40°34'08.5"N 15°06'10.5"E) was the largest PV plant in Europe at the initial time of the installation (3,3 MWe, 1994). The current plant (having a peak power level of 21 MWe) is owned by the Italian Ministry of Defense and was built by Enel Green Power in 2011-2013 using PV modules built in the Italian factory 3Sun (Catania), originally a joint venture among ENEL, Sharp and STMicroelectronics. The area covered is 770,000 m^2, 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 (Santerno SUNWAY TG760 1000VTE). Table 3 resumes the features of the two PV fields.

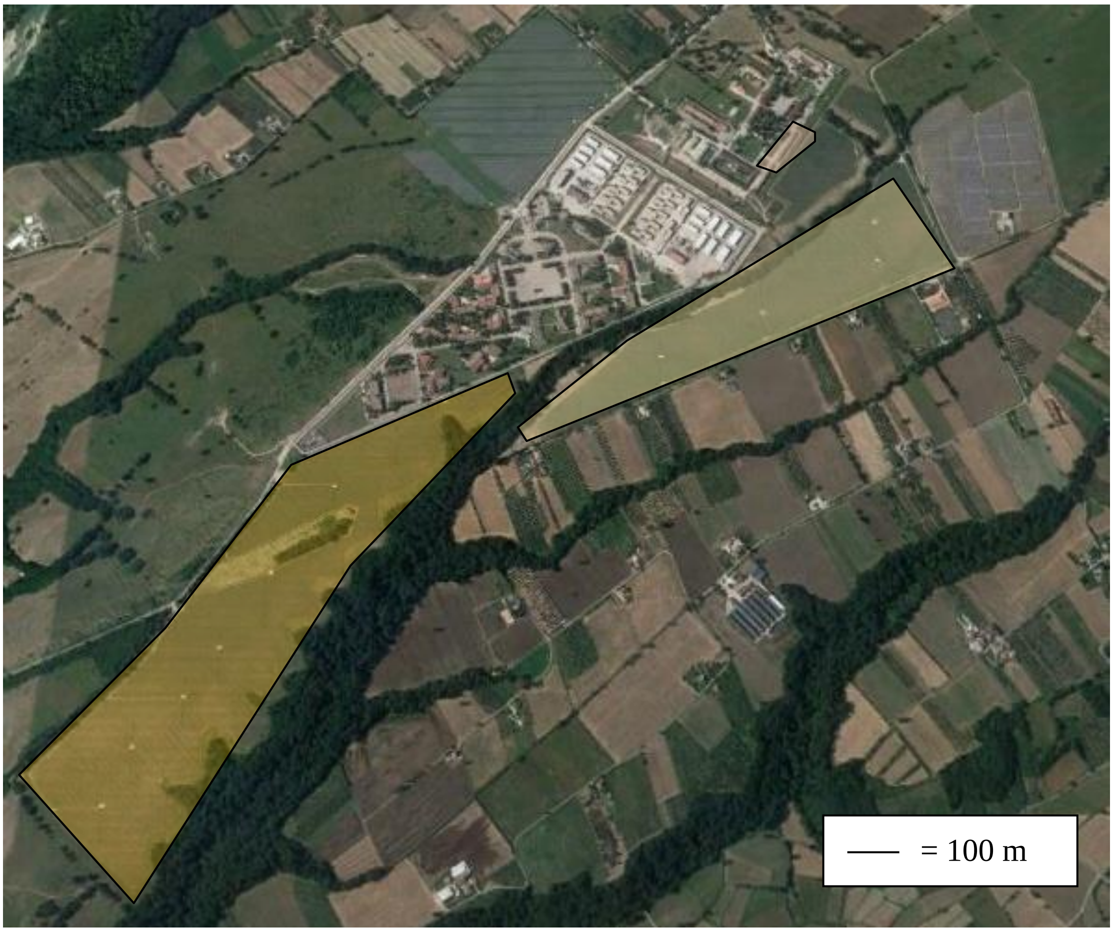

Figure 3. Aerial view of Serre Persano DS PV plant (shaded areas).

Table 3. Summary specifications of the Serre Persano DS 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	1,920	3,708	12
Borgo San Lazzaro	26,880	51,884	1,920	3,706	12

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Including the evaluation of the decay in productivity with aging, the average productivity of the Serre Persano PV plant was evaluated at 24,768 MWh/yr, with an equivalent full-load (21 MWe) operability of about 1,179 hrs/yr (a good performance for a plant built in 2011-2013 in Southern Italy). Appendix C collects the Life Cycle Inventory data for the Serre Persano Solar PV plant.

4. Results of the LCA

4.1 Life Cycle Impact Assessment at midpoint level: ILCD 2011 Midpoint+ vs 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 done about the impact assessment methodology (ILCD 2011 Midpoint+ or Recipe 2016). The results are shown for the three cases referred to geothermal (GEO, GEO-AS, GEO-NA) and for the solar photovoltaic (PV) and for the Wind (W) reference cases. Furthermore, the comparison with the national electricity mix (NEM) is performed referring to the Ecoinvent database 3.6 process that models the Italian electricity mix based on Eurostat data for year 2014. The detailed results of the Midpoint impact analysis are reported in table form in Appendix D.

A graphical comparison among ILCD 2011 Midpoint+ and Recipe 2016 results calculated at midpoint level is shown in the following (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 2011Midpoint+ and Recipe 2016 methods are based on different indicators 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 to 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. With respect to ILCD 2011 Midpoint+ method, Recipe 2016 is more analytical in classifying the resource consumption into mineral and fossil (this last in direct terms of kilogram of oil equivalent). Consequently, due to the large percentage of fossil fuel sources present in the electricity mix, in Recipe 2016 the fossil resource scarcity band is larger for the NEM. 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 years; 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[54,55]) 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).

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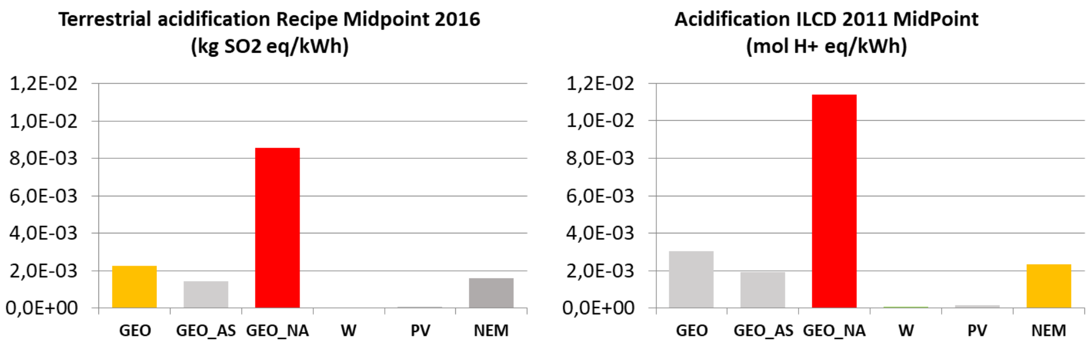

Figure 4. Bar diagrams of ILCD 2011 Midpoint+ and Recipe 2016 impact assessment at midpoint level: Acidification

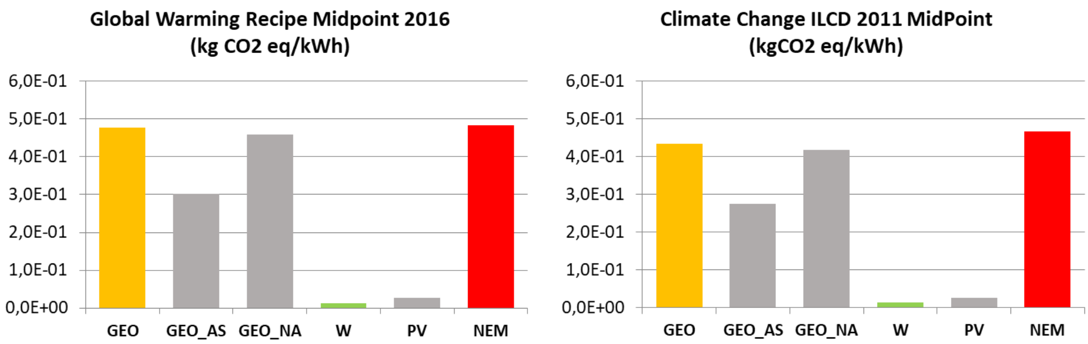

Figure 5. Bar diagrams of ILCD 2011 Midpoint+ and Recipe 2016 impact assessment at midpoint level: Climate Change.

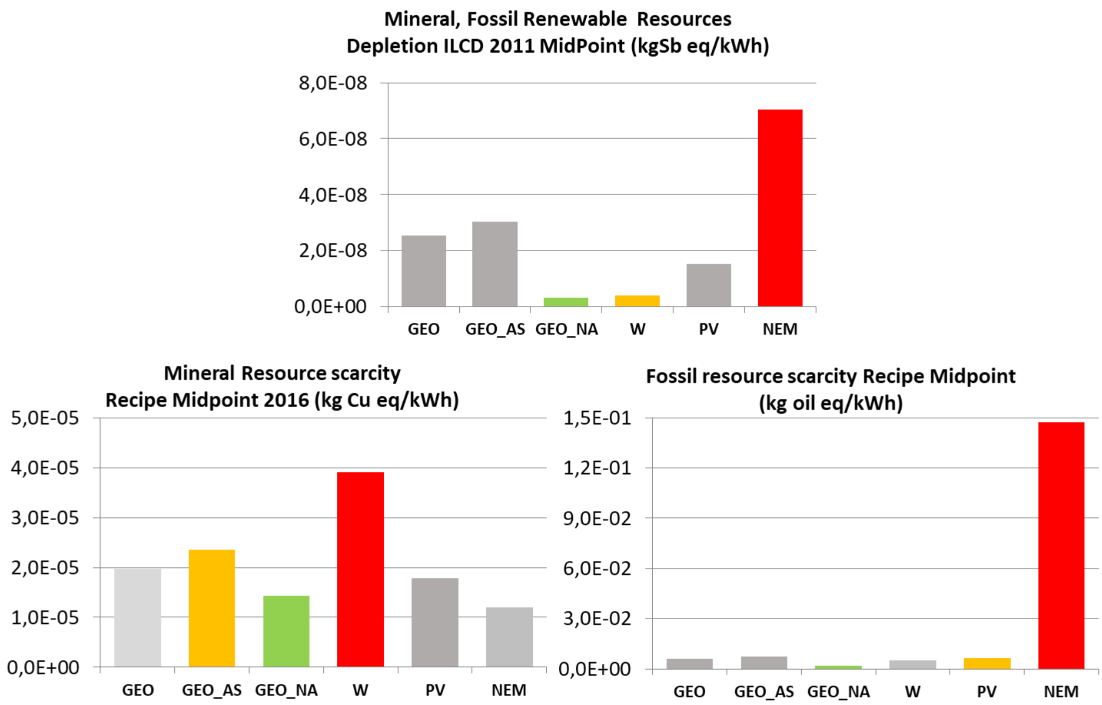

Figure 6. Bar diagrams of ILCD 2011 Midpoint+ and Recipe 2016 impact assessment at midpoint level: Resource Depletion.

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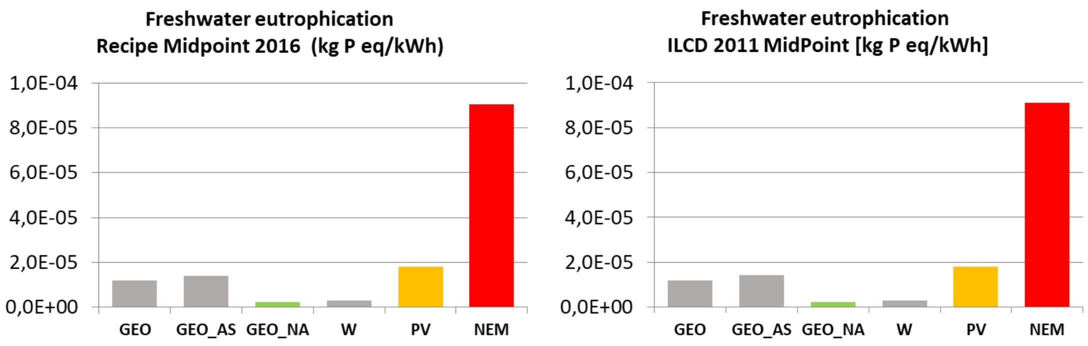

Figure 7. Bar diagrams of ILCD 2011 Midpoint+ and Recipe 2016 impact assessment at midpoint level: Freshwater Eutrophication.

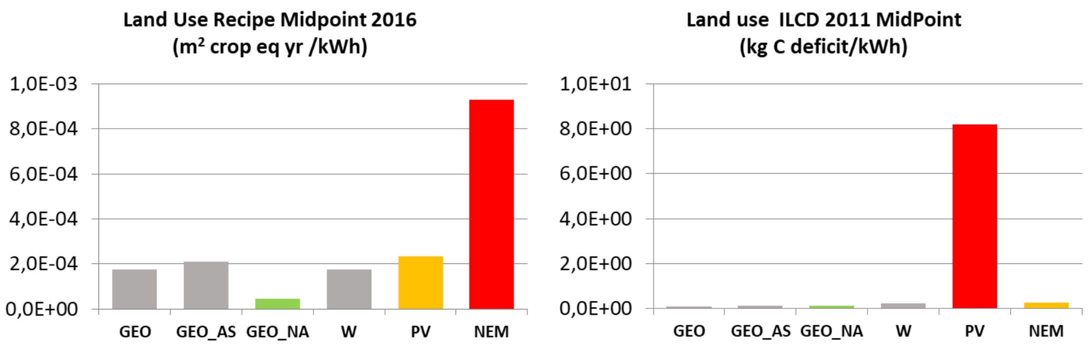

Figure 8. Bar diagrams of ILCD 2011 Midpoint+ and Recipe 2016 impact assessment at midpoint level: Land Use

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).

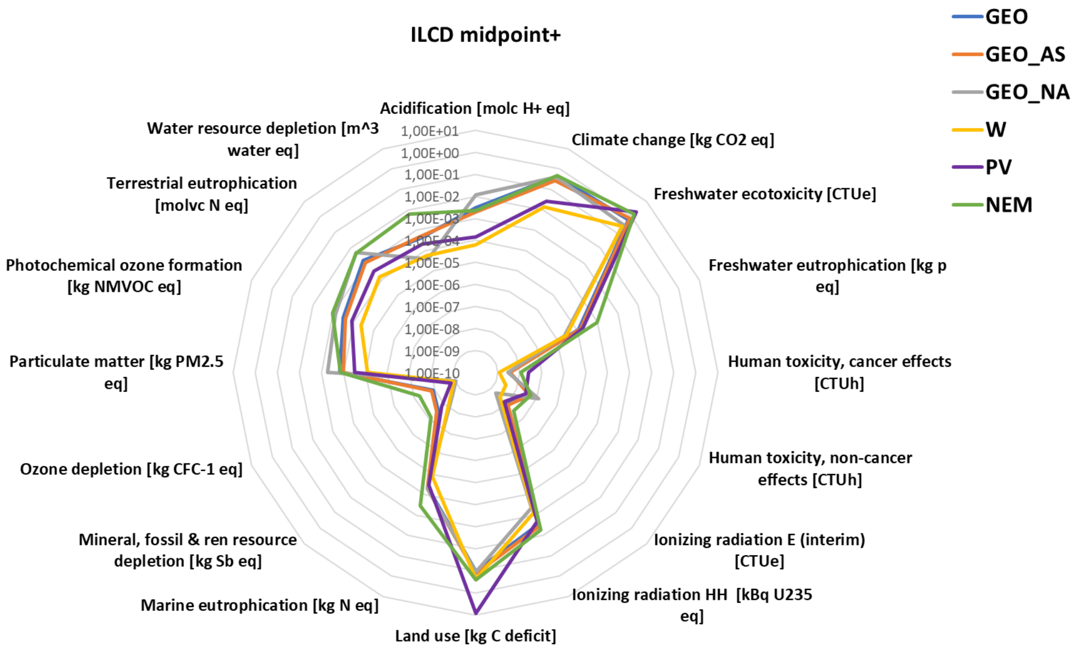

Figure 9. Spider net diagram of ILCD 2011 Midpoint+ impact assessment results (log scales)

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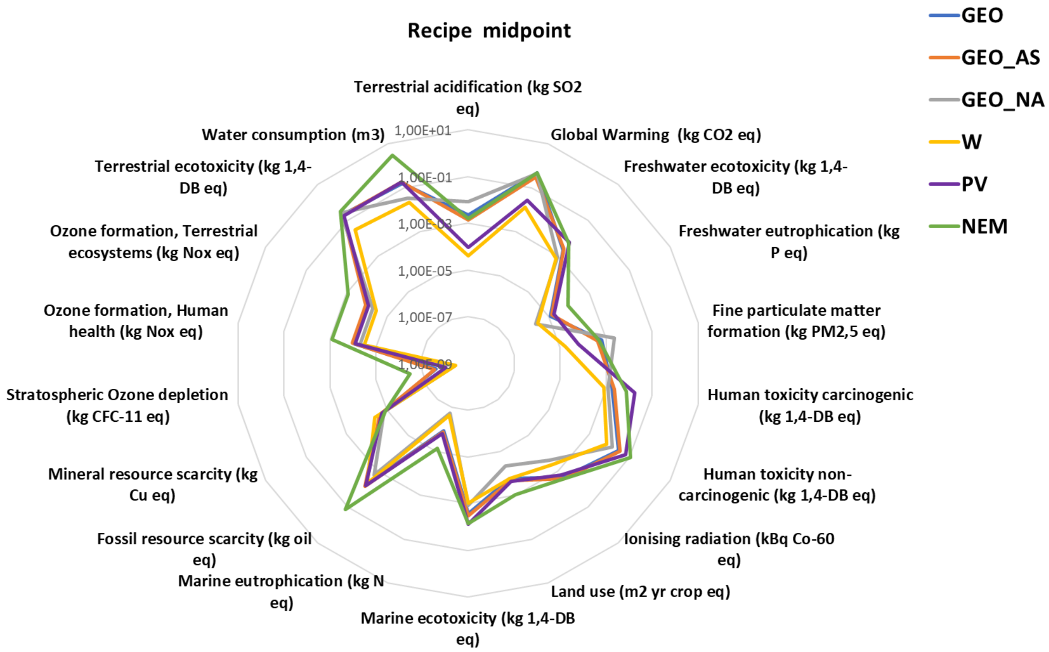

Figure 10. Spider net diagram of Recipe 2016 Midpoint impact assessment results (log scales)

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 evidently 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 in the operation phase on fossil resources. Mineral and fossil resources consumption are separately accounted in Recipe 2016, 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 ecotoxicity. 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.

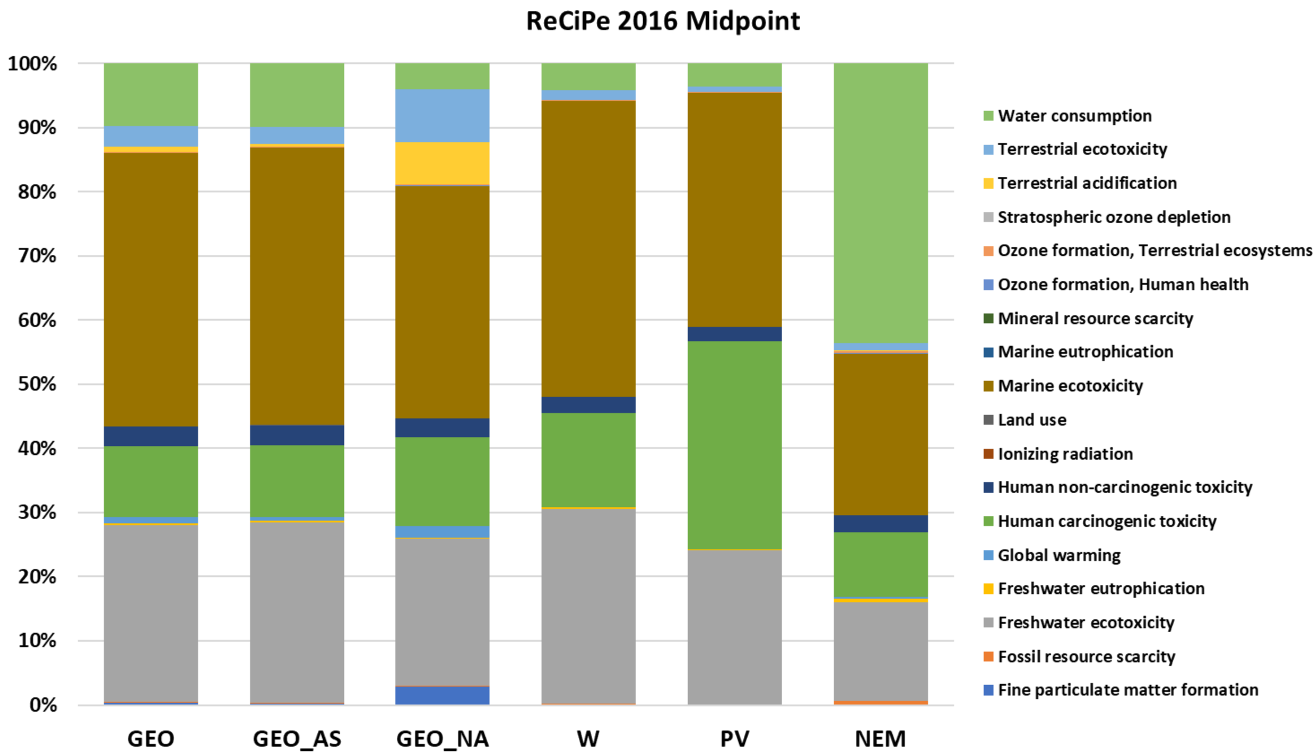

Figure 11. Contribution analysis of the Recipe 2016 method at midpoint level

4.2 Impact assessment at endpoint level: Recipe 2016 normalized and weighted results

In this section results calculated at 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 transition from fossil to renewable resources), Recipe 2016 is applied in the following for normalization and weighting calculations. These operations allow to group 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) DALY unit (disability adjusted life years), 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 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 endpoint level are summarized in Table 4; results are also illustrated graphically in Figure 12.

Table 4. ReCiPe2016 (H) normalized results at endpoint level

	GEO	GEO_AS	GEO NA	Wind	PV	NEM
Ecosystems, Total species*yr	5,58E-06	5,25E-06	4,99E-06	4,88E-07	3,76E-06	6,20E-05
Human Health, Total DALY	5,15E-05	4,17E-05	8,44E-05	3,20E-06	2,36E-05	3,29E-04
Resources Total USD2013	5,08E-08	6,09E-08	2,02E-08	3,60E-08	4,83E-08	1,56E-06

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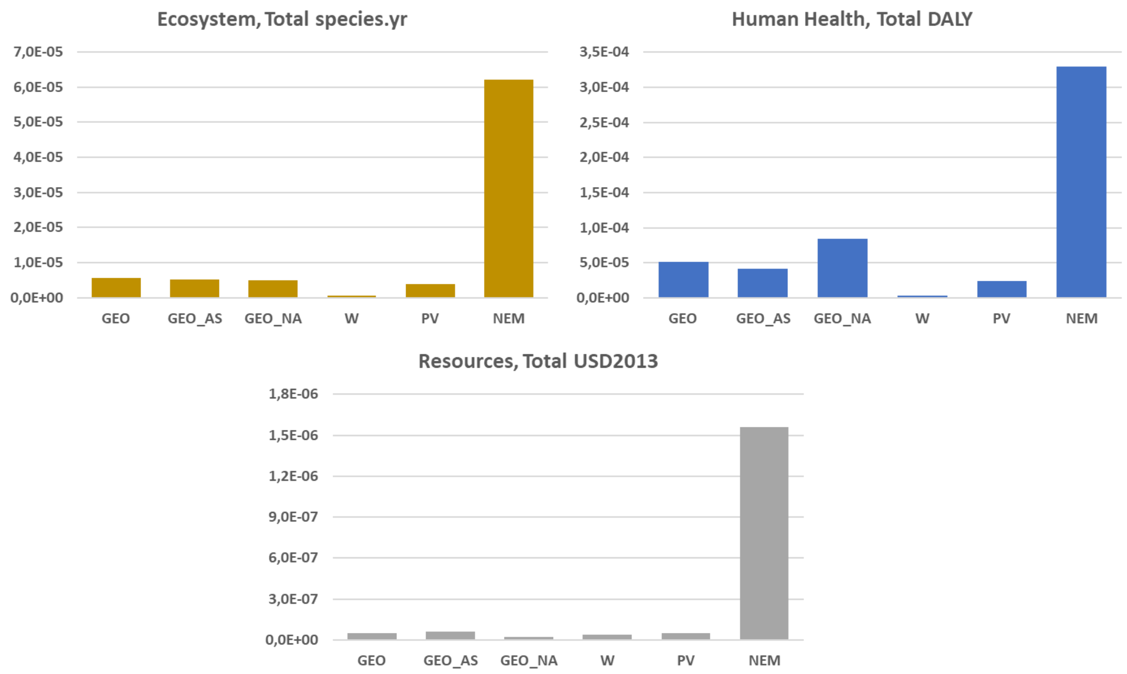

Figure 12. Normalized results of the Recipe 2016 (H) method at endpoint level

In Figure 13 the contribution analysis of the Recipe 2016 normalized results at endpoint level is shown for all the case studies. According to the midpoint-to-endpoint factors values implemented for the method [52], the human health damage category dominate the eco-profiles of all the scenarios with a detectable contribution of the resources damage category that increases going from PV to NEM and to W.

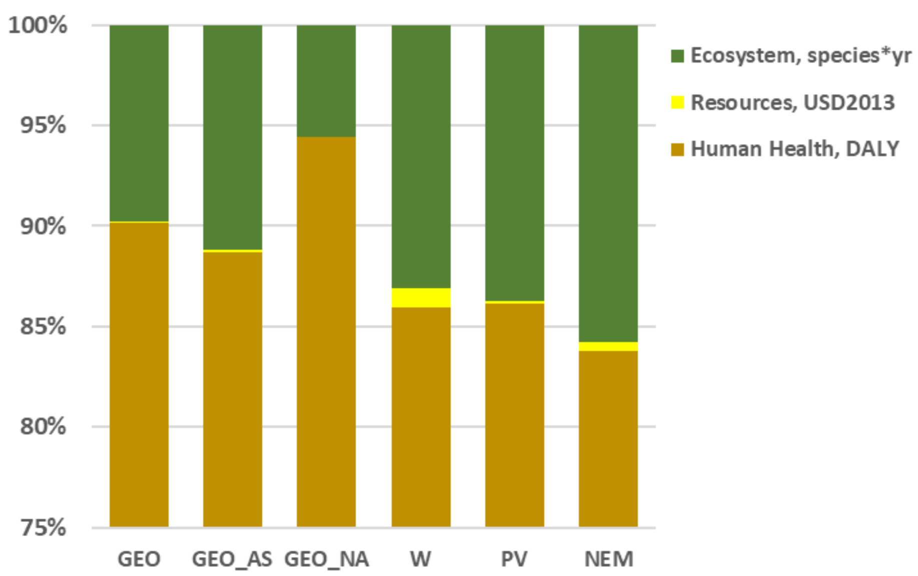

Figure 13. Contribution analysis of Recipe 2016 (H) normalized results at endpoint level

The weighting step in LCA allows to calculate a synthetic indicator (expressed in Ecopoints) in order to express a global environmental performance, which can be used for overall comparison among the different technologies. In this study, in order to weight the normalized results of the Recipe 2016 method at endpoint level, the Hyerarchist cultural perspective was assumed, which involves weighting Ecosystem damages by a factor 400, while Human Health and resources damages are

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weighted by a factor of 300. This perspective is a common assumption in the field of energy conversion system. The Recipe 2016 weighted results are shown in Figure 14 in terms of Ecopoints referred to the functional unit (1 kWh of electricity).

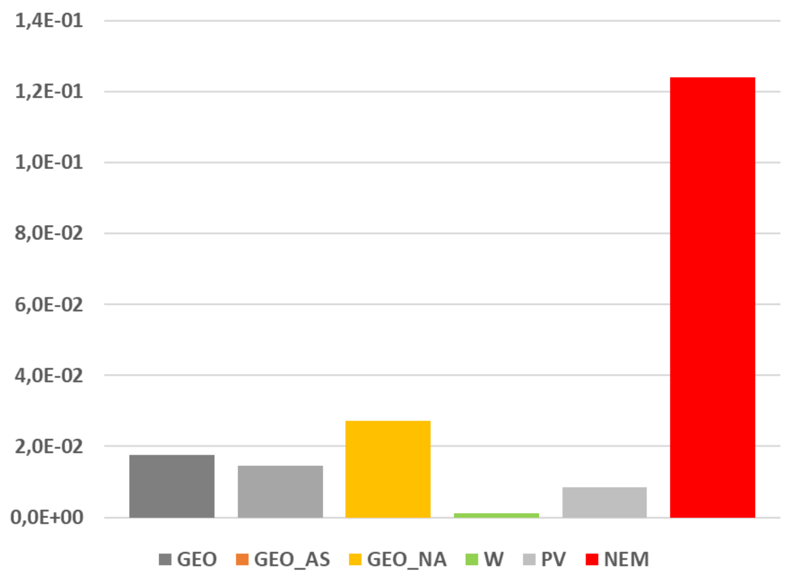

Figure 14. Weighted results calculated with the Recipe 2016 method (Ecopoints/kWh)

5. 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 built on 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 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 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 national energy mix impacts mainly in water consumption and fossil fuel depletion. In absolute term, 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 definitely better than the national energy mix, as this last includes the use of considerable amount of fossil fuel resources (mostly gas and coal). Geothermal scenarios even with emissions treatment (GEO and GEO_AS) resulted to have a lower performance compared with wind and solar PV for ecosystem quality and human health damage categories; however, it represents a definite step forward with respect to the NEM and it compares well with

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respect 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 Hyerarchist cultural perspective was applied to the normalized Recipe 2016 results. Wind resulted to be the best technology with a value of 0,0012 Ecopoints/kWh, a result in line with previous documented LCA studies; however, the geothermal power plants achieved values of about 0,0177 Ecopoints/kWh which were close to solar PV (0,0087 Ecopoints/kWh) and much lower than those of the national energy mix (0,1240 Ecopoints/kWh).

These results, which should also be interpreted in terms of real availability of the RES and of economic profitability, demonstrate that geothermal energy conversion is a good option for sustainable development.

List of symbols/Acronyms

AP	Acidification Potential
CED	Cumulative Energy Demand
EGS	Engineered Geothermal System
EP	Eutrophication Potential
GWh/yr	Giga Watt hour per year
GWP	Greenhouse Warming Potential
Hrs/yr	Hours per year
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MWe	Mega Watt electric
MWth	Mega Watt thermal
PV	Photovoltaic
RES	Renewable Energy Source
VRE	Variable Renewable Energy
W	Wind

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Author Contributions: D.Frosali was responsible for LCIbuilding from primary data. The LCI data was collected using primary data by F. Sansone and D. Frosali. R.Bonciani provided expertise on power plant and emissions treatment processes. G.Manfrida, R. Basosi and M.L. Parisi organized the validation and presentation of the results. All authors contributed to writing and interpreting the results.

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Appendix ALife Cycle Inventory data for the Chiusdino 1 power plant

Table A.1 - 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	11000	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 well head	15,74	bar
Average temperature at well head	199,61	°C
Overall flow rate	36,1	kg/s
Condenser temperature	25	°C
Reinjection		
Temperature	25	°C
Pressure	Atmospheric	
Liquid phase, % of total from 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

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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	99,80%	
Hg removal efficiency	82,20%	
NH_3 removal efficiency	87%	
CO_2 removal efficiency	0%	
B removal efficiency	99%	
As removal efficiency	99%	

Table A.2 - 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)	1970950	l
Diesel fuel consumption - construction works, per well	309734	l
WELLS CASING AN CEMENTING		
Production wells		
Steel	1458476	kg
Portland cement	1737190	kg
Bentonite	832324	kg
Silica sand	503976	kg
Lignosulfonates	11454	kg
Perlite	38180	kg
NaOH	1282848	kg
HCl	328348	l
Oli and lubricants	91632	kg
Excavations	1925	m^3
Drilling mud	2103718	kg

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Reinjection wells (equivalent)		
Steel	228971	kg
Portland cement	272972	kg
Bentonite	130600	kg
Silica sand	79047	kg
Lignosulfonates	0	kg
Perlite	5814	kg
NaOH	188426	kg
HCl	13358	l
Oli and lubricants	14457	kg
Excavations	293,1364589	m^3
Drilling mud	320351,4	kg
DRILLING PLATFORM		
Occupied surface	10000	m2
Portland cement	1230000	kg
Aluminum	9000	kg
Steel	43000	kg
Sand	1937000	kg
Plastic	1250	kg
Excavation	1790	m3
Fills	2150	m3
STEAM ADDUCTION PIPELINE		
Total length	2758	m
Steel for supports and fundations	163736	
Steel fot tubing	313398	kg
Portland cement	493,682	m3
Aluminum	12962,6	kg
Rock whool	130177,6	kg
Excavations	468,86	m3
Fills	468,86	m3
CONDENSATE PIPELINE		
Total length	5000	m
Plastics	36565	kg

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POWERHOUSE EQUIPMENT		
Turbine and Alternator		
Number of turbines	1	
Rated Power	20	MW
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	13400	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	76400	kg
Compressor		
Number of compressors	1	
Capacity	5	t/h
Type	Modified Tosi model	
Expected Life*	25	yrs
Aluminum	5680	kg
Cast iron	12120	kg
Steel, unalloyed	8080	kg
Copper	16200	kg
Condenser		
Number of condensers	1	
Rated Power	20	MW
Type	Ansaldo/ENEL	
Expected Life	30	yrs
Chromium steel 18/8	68250	kg
Intercooler		
Chromium steel 18/8	18000	kg

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Cooling towers		
Number of cells	3	
Type	Hamon cooling tower	
Main material	PSRV	
Expected Life	25	yrs
Steel piping	8190	kg
Plastic piping	81900	kg
Fiberglass	90220	kg
Copper	150	kg
Cast iron	450	kg
Gas treatment system		
Type	AMIS 1 unit	
Main material	Stainless steel 316L	
Size (max flow rate)	5000	kg/h
Expected Life*	25	years
Sorbent (Selenium for Hg)	4000	kg
Catalyst (Titanium for H2S)	9000	kg
Aluminum	500	kg
Chromium steel 18/8	11500	kg
Building		
Portland cement	637500	kg
Diesel fuel for construction works	195500	l
Excavations	8500	m3
Plastic pipes	637500	kg
Fills	17944960	kg
Aluminum	810	kg
Steel, low-alloyed	170000	kg
Accessories		
Copper	30000	kg
Plastic pipes	15000	kg
Chromium steel 18/8	150000	kg
Steel, low-alloyed	220000	kg

* Major maintenance and refitting every 4 years

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Table A.3 - OPERATION & 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	25000	kg
Waste mineral oil	25000	kg
Iron-nickel-chromium alloy	5375	kg
Chromium steel 18/8	3500	kg
Waste steel	8875	kg
Fluid treatment		
NaOH	2500000	kg/yr

Table A.4 - END OF LIFE		
Wells Abandonment (per well)		
Expected time	10	days
Diesel fuel consumption	25000	l
Portland cement	25000	kg
Inert	5000	kg
Steel	0	kg
Water	0	l

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Appendix BLife Cycle Inventory data for the Potenza Pietragalla wind farm

Table B.1 DESCRIPTION		
Name	Potenza Pietragalla	
Location	40.776954, 15.837555	
Construction start date	2005	
Expected life	30	years
Land occupation	1500000	m^2
Production technology	HAWT Repower MM92	
Electrical generation technology	• Generator at summit. • MV a tground . • HV at substation	
End use of energy	Electricity	
Installedcapacity		
Electrical	18	MWe
Operating capacity		
Electrical	18	MWe
Expected annual decay rate for the electrical power supplied	0	% per yr
Net annual production		
Electricity delivered to the grid	25,2	GWh
Capacityfactor(at 18 MWe)	1400	h
Out of order (per year)	50	h
Resource characteristics		
Mean power density (at 100 m)	1041	W/m2
Maximum average wind speed (at 100 m)	9,32	m/s
Table B.2- CONSTRUCTION		
PITCHES AND LOGISTIC SURFACES		
Excavations	75000	m3
Fills	11250	m3
Steel	430272	kg
Cement	3339	m3
Occupied surface	20305	m2
Wood	324	m2
Diesel fuel for excavations	37500	l

CABLE-DUCTS		
Total lenght	15000	m
Aluminum	19660	kg
Copper	6560	kg
Optical fibre	15000	ml
Excavations	7015	m3
Fills	1960	m3
Diesel fuel for excavations	3510	l
Occupied surface	7500	m2
HAWT		
Number of HAWT	9	
Rated power	2	MW
Description	Repower MM92	
Expected life	25	years
Diesel fuel for construction works	14400	l
Tower		
Steel	146500	kg
Copper	6480	kg
Blade		
Steel	1620	kg
Fiberglass	6480	kg
Nacelle		
Steel	56520	kg
Copper	5600	kg
Fiberglass	2780	kg
Hub		
Steel	17000	kg
VIABILITY		
Excavations	24784	m3
Fills	700800	kg
Asphalt	8190	m3
Diesel fuel for construction works	13000	l
SUBSTATION		
Steel	36800	kg
Fills	1220	m3
PEAD tubing	1260	kg
Cement	970	m3
Pre-cast concrete	16,4	m3
Copper	5000	kg
Aluminum	1500	kg
Diesel	1000	l
Occupiedsurface	2620	m2

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Table B.3 - OPERATION & MAINTENANCE		
Lubricatingoil	202500	kg
Waste mineraloil	202500	kg
Steel, chromium 18/8	999000	kg
Steel, lowalloyed	540000	kg
IronScrap	1539000	kg
Diesel for O&M	54000	l

Table B.4 - END OF LIFE		
Machinerydisassemblement		
Time (per HAWT –estimate)	10	days
Diesel for O&M (per HAWT – estimate)	25000	l
Steel (per HAWT - 95% recycled)	221640	kg
Copper (per HAWT - 95% recycled)	12080	kg
Fiberglass (per HAWT - 100% recycled)	22220	kg
Cement (per HAWT - left on site)	371	m3
Iron for foundation works (per HAWT - 95% recycled)	47808	kg

AppendixC Life Cycle Inventory data for the Serre Persano Photovoltaic Power Plant

Table C.1 - DESCRIPTION		
Name	Serre Persano	
Location	40°34'08.5"N 15°06'10.5"E	
Construction start date	2013	
Expected life	30	yrs
Land occupation	770000	m^2
Electrical generation technology	Photovoltaic generator, inverter for subfield, elevation downstream substation	
Module NA F130 G5	53760	
Module NA F135 G6	103796	
Inverter Santerno SUNWAY TG760 1000V TE	24	
End use of energy	Electricity	
Installed capacity		
Electrical	21,00126	MWe
Operating capacity		
Electrical	19,53117	MWe
Expected annual decay rate	0,07	% per year
Net annual production		
Electricity delivered to the grid	29,50407179	GWh
Capacity factor	1281	h
Out of order (per year)	0	h

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Resource characteristics		
Global annual radiation on the normal surface	2131	kWh/m2
Table C.2 - CONSTRUCTION		
PITCHES AND LOGISTIC SURFACES		
Excavations	54000	m3
Fills	1080	m3
Occupied surface	770000	m2
Diesel for excavations	30000	l
METAL CARPENTRY		
Steel	10023790	kg
Aluminum	2594686	kg
Diesel for construction	18135	l
PHOTOVOLTAIC MODULES		
Module NA F130 G5	53760	
Module NA F135 G6	103796	
ELECTRICAL CONNECTIONS		
Copper	63125	kg
Aluminium	1516	kg
Excavations	2954	m3
Sand	29546	kg
Cement	1181	kg
Plastic	18381	kg
Diesel for construction	1477	l
INVERTER		
Inverter Santerno SUNWAY TG760 1000V TE	24	
DELIVERY CABIN		
Precast concrete	41000	kg
Portland cement	272176	kg
Diesel for construction	1176	l
Plastic pipes	1470	kg
Fills	581760	kg
Steel	43052	kg
Aluminum	1743	kg
Copper	5880	kg
Table C.3 - OPERATION & MAINTENANCE		
Diesel for cleaning machine	56270	l
Decarbonised water	16881000	kg
Table C.4 - END OF LIFE		
Diesel for disassembly	341	l
Electricity, medium voltage	159716	kWh
Used cable	29935	kg

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Aluminum scrap for melting	511899	kg
Inert material and fill	2451729	kg

Appendix DSynthesis tables of ILCD and Recipe Impact analysis

Table D.1 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-1 eq]	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

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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 D.2 Recipe 2016 method results at midpoint level

	GEO	GEO-AS	GEO-NA	W	PV	NEM
Terrestrial acidification (kg SO2 eq)	2,27E-03	1,42E-03	8,58E-03	4,15E-05	9,68E-05	1,58E-03
Global Warming (kg CO2 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 (m2 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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