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
equipped with effective emissions treatment equipment, which removes the greatest part of hydrogen sulphide (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 6,200 GWh/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 20 GWe 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 than 10 GWe are 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.
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
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.
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
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 | 2630             | 3447    | 78,8           | 200,8| 16,2  | 6,0   |
| Montieri 5A| 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 H₂S 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 |
|----------|-----------------|
| CO₂      | 5100            |
| CO       | 0.4             |
| H₂S      | 18.4            |
| CH₄      | 79.3            |
| NH₃      | 1.5             |
| Hg       | 0.0011          |
| As       | 0.0000028       |
| Se       | 0.0004          |

The Chiusdino 1 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.
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).
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 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 (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).](image)

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 |
|------------------|-------------------|-------------------|-------------------|-------------------|---------------------|
| Spinoeto         | 26,880            | 51,912            | 1,920             | 3,708             | 12                  |
| Borgo San Lazzaro| 26,880            | 51,884            | 1,920             | 3,706             | 12                  |
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).
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)
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 10. Spider net diagram of Recipe 2016 Midpoint impact assessment results (log scales)
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 |
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.

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
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](image)

**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 definitively 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
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
Author Contributions: D. Frosali was responsible for LCI building 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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Conflicts of Interest: The authors declare no conflict of interest.
### Appendix A

#### Life 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 m² |
| **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% |
| | CO₂ | 5100 kg/h |
| | CO | 0,4 kg/h |
| | CH₄ | 79 kg/h |
| | H₂S | 90 kg/h |
| | NH₃ | 11,6 kg/h |
### Trace elements

| Element | Value  
|---------|--------|
| Hg      | 5.6 g/h |
| As      | 0.042 mg/l |
| B       | - mg/l  |
| Sb      | - mg/l  |
| Se      | - mg/l  |
| Rn      | - Bq/m³ |

### NCG emissions treatment system (AMIS)

| Component       | Efficiency  
|-----------------|-------------|
| H₂S removal  | 99.80%      |
| Hg removal   | 82.20%      |
| NH₃ removal   | 87%         |
| CO₂ removal   | 0%          |
| B removal     | 99%         |
| As removal    | 99%         |

### Table A.2 - CONSTRUCTION

#### DRILLING

| Category                          | Value            |
|-----------------------------------|------------------|
| 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

| Component   | Value   |
|-------------|---------|
| 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 m³  |
| Drilling mud| 2103718 kg |
Reinjection wells (equivalent)

| Material                  | Quantity   |
|---------------------------|------------|
| 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 m³ |
| Drilling mud              | 320351,4 kg |

**DRILLING PLATFORM**

| Material                    | Quantity   |
|-----------------------------|------------|
| 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**

| Material                    | Quantity   |
|-----------------------------|------------|
| Total length                | 2758 m     |
| Steel for supports and fundations | 163736 kg |
| Steel for 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**

| Material | Quantity |
|----------|----------|
| Total length | 5000 m  |
| Plastics   | 36565 kg |
### POWERHOUSE EQUIPMENT

#### Turbine and Alternator

|                          | Value                  |
|--------------------------|------------------------|
| 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              |

| Material                          | Quantity |
|-----------------------------------|----------|
| 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

|                          | Value                  |
|--------------------------|------------------------|
| Number of compressors    | 1                      |
| Capacity                | 5 t/h                  |
| Type                    | Modified Tosi model    |
| Expected Life*           | 25 yrs                 |

| Material                          | Quantity |
|-----------------------------------|----------|
| Aluminum                          | 5680 kg  |
| Cast iron                         | 12120 kg |
| Steel, unalloyed                  | 8080 kg  |
| Copper                            | 16200 kg |

#### Condenser

|                          | Value                  |
|--------------------------|------------------------|
| Number of condensers     | 1                      |
| Rated Power              | 20 MW                  |
| Type                    | Ansaldo/ENEL           |
| Expected Life            | 30 yrs                 |

| Material                          | Quantity |
|-----------------------------------|----------|
| Chromium steel 18/8               | 68250 kg |

#### Intercooler

| Material                          | Quantity |
|-----------------------------------|----------|
| Chromium steel 18/8               | 18000 kg |
### 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
### Table A.3 - OPERATION & MAINTENANCE

#### Emissions-to-Air

| Emission | Value  | Unit |
|----------|--------|------|
| CO₂      | 5100   | kg/h |
| CO       | 0.4    | kg/h |
| H₂S      | 18.4   | kg/h |
| CH₄      | 79.3   | kg/h |
| NH₃      | 1.5    | kg/h |
| Hg       | 1.1    | g/h  |
| As       | 2.8    | mg/h |
| Se       | 0.4    | g/h  |

#### Machinery maintenance

| Item                                | Value  | Unit |
|-------------------------------------|--------|------|
| 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

| Item     | Value  | Unit |
|----------|--------|------|
| NaOH     | 250000 | kg/yr|

### Table A.4 - END OF LIFE

#### Wells Abandonment (per well)

| Item                  | Value | Unit |
|-----------------------|-------|------|
| Expected time         | 10    | days |
| Diesel fuel consumption | 25000 | l    |
| Portland cement       | 25000 | kg   |
| Inert                 | 5000  | kg   |
| Steel                 | 0     | kg   |
| Water                 | 0     | l    |
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 m²          |
| Production technology               | HAWT Repower MM92   |
| Electrical generation technology     | • Generator at summit.  
                                        • MV at ground .  
                                        • HV at substation |
| End use of energy                   | Electricity         |
| Installed capacity                  | Electrical 18 MWe   |
| Operating capacity                  | Electrical 18 MWe   |
| Expected annual decay rate for the   | 0 % per yr          |
| electrical power supplied           |                     |
| 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/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 length                        | 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 |
| Occupied surface                    | 2620 m2 |
### Table B.3 - OPERATION & MAINTENANCE

| Description                  | Quantity     |
|------------------------------|--------------|
| Lubricating oil              | 202500 kg    |
| Waste mineral oil            | 202500 kg    |
| Steel, chromium 18/8         | 999000 kg    |
| Steel, lowalloyed            | 540000 kg    |
| Iron Scrap                   | 1539000 kg   |
| Diesel for O&M               | 54000 l      |

### Table B.4 - END OF LIFE

| Description                           | Quantity     |
|---------------------------------------|--------------|
| Machinery disassembly 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    |

### Appendix C 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 m²     |
| 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            | 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           |
### 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 |
| 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 CO2 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 |
| Water resource depletion [m² 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 | 4,15E-02 | 9,68E-02 | 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 |
| Category                        | Values               |
|--------------------------------|----------------------|
| Ozone formation, Human health  | 9.10E-05 1.09E-04    |
| Ozone formation, Terrestrial ecosystems | 9.22E-05 1.11E-04    |
| Terrestrial ecotoxicity (kg 1,4-DB eq) | 2.10E-01 1.98E-01    |
| Water consumption (m³)         | 1.60E-01 1.92E-01    |

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