Comparative scenario-based LCA of renewable energy technologies focused on the end-of-life evaluation

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Abstract

In this article, a comparison was made between the environmental performance of three existing renewable energy systems, namely a photovoltaic, a wind, and a geothermal power plant; particularly, this study is focused on the end-of-life stage. More specifically, a scenario-based Life Cycle Assessment model was developed. It returns a wide range of possible results expressing the eco-profile of the analysed systems; moreover, the interpretation of the results allows pointing out the main priorities to implement in a sustainable end-of-life strategy. According to the results, the photovoltaic system can benefit from recycling most in comparison to the other systems, also because the disposal and decommissioning do not determine a large environmental burden. More specifically, the recovery of secondary metals from the structures of the solar arrays and the materials composing the photovoltaic modules (including the metals contained inside the panels) is particularly effective to improve the environmental performance of the system. Concerning the wind farm, the decommissioning operations of the installation site (i.e. the removal and transportation of asphalt, cement and gravel) turn out to be critical for several environmental indicators, as well as the combustion of waste lubricating oil; however, the recovery of metals and construction materials can compensate such environmental issues. The eco-profile of the geothermal system is slightly affected by the end-of-life operations, whether the disposal and the recycling processes. Indeed, the direct emission of pollutants and the consumption of reactants, which are not recycled, represent the main environmental issues. Based on a single score, if the disposal is selected as an end-of-life scenario, the photovoltaic system results as the most impacting system, followed by geothermal and wind. Differently, in case all materials are recycled, the environmental burden of the photovoltaic system assumes intermediate values compared to the wind and geothermal systems.

1. Introduction

Renewable energy technologies are considered by international and Italian energy policies as strategic solutions to face climate change because they do not imply the combustion of fossil resources. However, all renewable energy technologies are responsible for some greenhouse gases (GHGs) emissions over their life cycle (i.e. the construction, the operation and the dismantling stages). Moreover, GHG emissions are not the only environmental concern attributable to renewable energy technologies. For instance, the consumption of resources, the occupation of land and the emissions of several types of pollutants should be addressed. For these reasons, life cycle analyses are extremely important in sustainable energy research to perform a quantitative evaluation of all the environmental burdens of several technologies (Asdrubali et al., 2015; Góralczyk, 2003; Mälkki and Alanne, 2017; Singh et al., 2013). This paper addresses a comparative Life Cycle Assessment (LCA) of different renewable energy conversion systems considering multiple end-of-life (EoL) scenarios about the disposal and the recycling of the materials employed during the construction, operation, and maintenance of the systems. More specifically, such scenario-based EoL model is applied to a photovoltaic (PV), a wind, and a geothermal power plant (GPP) to perform a novel comparative environmental assessment focused on the evaluation of several waste management solutions.

Valuable LCA studies comparing the environmental burdens of different energy systems are already available in the literature. For instance, Basosi et al., (2020) have published a cradle to gate cross-evaluation of a geothermal, a wind, and a PV power plant operating in Italy; the construction and the operation and maintenance (O&M) are the life cycle stages included inside the system boundaries. The main outcome of this study is that, based on single score results, wind systems turn out as the technological solution which determines the lowest potential damage to the environment. Similar conclusions are drawn by (Asdrubali et al., 2015) who proposed an extensive review and harmonization of several literature papers to compare different renewable energy systems. Indeed, according to (Asdrubali et al., 2015), wind is assessed as the most sustainable renewable energy solution whereas PV and geothermal resulted as the most impacting plants. These conclusions agree with those reported by another recent review (Rahman et al., 2022), where innovative renewable energy technologies (i.e. tidal, ocean, and osmotic systems) are compared to traditional ones. When comparing renewable energy plants, other authors focused their attention on the geographical reference of the renewable energy conversion systems such as Africa (Mukoro et al., 2021), Europe (Luo et al., 2020), North America or Oceania (Mahmud and Farjana, 2022). Differently from the geographical reference, the environmental effects of the EoL stages are scarcely investigated in comparative assessments of renewable energy systems. Indeed, while the EoL stage is commonly considered in the LCA of single technologies, to the best of our knowledge this topic has not been deeply analysed in comparative studies. Such a literature gap represents a critical issue because, as reported in the following paragraph, the EoL phase can have remarkable effects on the LCA results of all energy technologies. However, to propose a consistent comparison among different energy systems, a common approach shall be adopted for their EoL modelling in LCA.

Differently from the above-mentioned comparative assessments addressing the cross-evaluation of renewable energy power plants, the EoL of single technologies is largely analysed in LCA literature. For instance, the environmental performances of PV systems are largely evaluated during their construction (Cromratie Clemons et al., 2021; Krebs-Moberg et al., 2021; Li et al., 2022, 2021; Pu et al., 2021; Santoyo-Castelazo et al., 2021; Zhao et al., 2022) and recycling (Ansanelli et al., 2021; Ganesan and Valderrama, 2022; Lim et al., 2022; Nain and Kumar, 2022) phases. Concerning the recovery of PV modules' materials, the EoL model proposed by Latunussa et al., (2016) is one of the most detailed ones as the authors proposed a reproducible approach that has been already applied in several LCA studies (Rossi et al., 2021, 2020a, 2020b, 2020c). Accordingly, the recycling of PV can significantly modify the eco-profile of the system, especially in case environmental credits from the recovery of secondary resources are considered. Also, numerous cradle to grave LCA studies of wind energy systems are investigated in the literature, including the construction (Garcia-Teruel et al., 2022; May et al., 2021), the O&M (Garcia-Teruel et al., 2022), and the EoL (Andersen et al., 2016; Arvesen and Hertwich, 2012; Chen et al., 2021; Sommer et al., 2020) stages. Particular attention is given to the treatment of the blades of the turbines that are made of composite materials such as glass- and carbon-fibre with epoxy resin (Sommer et al., 2020). According to these studies, in case environmental credits are associated to the recovery of secondary resources, the environmental impact mitigation of recycling can be extremely relevant (Arvesen and Hertwich, 2012). A completely different situation is observed for GPPs: very reduced information is available in the literature concerning the EoL of the plant. The most widely adopted approach is to consider EoL exclusively as decommissioning, in which there is no disposal nor recycling, but geothermal wells are closed. This type of modelling has been reproduced in several works of the literature (Basosi et al., 2020; Menberg et al., 2021; Paulillo et al., 2019; Tomasini-Montenegro et al., 2017; Zuffi et al., 2022). Furthermore, the guidelines proposed by GEOENVI (Geoenvi Project, 2019), which propose LCA modelling of GPPs, also report a simplified EoL model. The EoL is subdivided into two sub-processes: i) the closure of the wells, and ii) the landfilling of wastes from the drilling operations and from the maintenance of the plant. Potential benefits from dismantling the buildings and recycling of machinery material are not taken into account (Parisi et al., 2020).

The literature analysis underlines that, while the EoL of single technologies has been deeply investigated in LCA studies, this life cycle stage is not sufficiently analysed by comparative assessment models. However, in both types of assessments, another critical issue encountered in literature when examining the EoL of energy systems is the definition of the materials recycling rate (Bongers and Casas, 2022), namely the percentage of materials that are recovered compared to the total, and the recycling input rate that is the penetration of secondary materials in the commodities market. The values commonly attributed to the recycling rates by other authors are extremely variable and dispersive because of the uncertainty affecting the market of commodities (Antonopoulos et al., 2021). For instance, the actual values of the recycling input rate depend on the dynamic geopolitical and economical context of resources (Santillán-Saldivar et al., 2021). For this reason, the aim of this study is not to develop a model that defines or collects the most realistic recycling rates for each material, but to assess a range in which the potential environmental impacts of different renewable energy systems may vary. This approach avoids the increase of uncertainty of the input data and results.

According to the previous considerations, the novelty of this paper is performing a consistent cradle to grave LCA comparison among a specific PV, a wind, and a GPP by evaluating an environmental impact range in which the LCA results can vary as function of the EoL scenarios. To achieve such objective, the model proposed in this work is based on a common and reproducible scenario-based model of the EoL stage, not previously applied in comparative LCA of renewable energy systems. Moreover, through the definition of multiple scenarios, the proposed model also provides interesting insights about the recycling priorities which should be considered when decommissioning a renewable energy plant.

2. Methodology

The methodology proposed in this study is based on the ISO 14040 (International Organization for Standardization, 2021) and ISO 14044 (International Organization for Standardization, 2021) standards. Accordingly, the analysis follows 4 steps: i) Goal and scope definition, ii) Life Cycle Inventory (LCI), iii) Life Cycle Impact Assessment (LCIA) and iv) Interpretation.

2.1 Goal and scope definition

The LCA methodology is applied to the following real-existing renewable energy plants selected by Basosi et al., (2020) and constructed and owned by ENEL group (Enel Green Power, 2017, 2014, 2011) as a case study. Table 1 summarizes all the most relevant technical characteristics of the analysed power plants, but more details of the system can be found in the paper published by Basosi et al., (2020); the photos of the systems can be found in Figure 1 while a representation on the maps is available in Basosi et al., (2020).

Table 1: Technical characteristics of the power plants analysed in this study according to Basosi et al., (2020).

	Location	**Size**	**Productivity**	**Year**	**Description**
PV	Serre Persano (Salerno, Italy) location: 40◦34’08.5”N; 15◦06’10.5” E.	21 MWe	24768 MWh/yr	Constructed in 1994, extended in 2011 and 2013.	This PV plant includes more than 150000 silicon-based PV modules connected in strings and equipped with 24 inverters; also, the balance of system is considered, such as the electrical connections, the supporting structures of the modules and other additional equipment.
Wind	Pietragalla (Potenza, Italy)	18 MWe	42069 MWh/yr	2011	This wind farm contains 9 turbines made of a horizontal axis glass-fiber reinforced plastics rotor

	location: 40°43?31.63”N; 15°49?41.85”E				(92.5 m diameter) including a gearbox; the rotor grounds on a pre-assembled steel tower (100 m height) and on reinforced concrete foundations. The balance of system is included in the study as well.
GPP	Chiusdino (Siena, Italy) location: 43°09’37.0”N; 11°03’49.9”E	20 MWe	151200 MWh/yr	2011	The GPP is fuelled by steam extracted from the underground with five production wells located in the nearby of power plant. An effective abatement system (AMIS$^{®}$) is also present to treat the direct emissions of the plant.

Figure 1: Photos of a) the PV system in Serre Persano, b) the wind farm in Pietragalla and c) the GPP in Chiusdino.

- ~~A PV plant located in Serre Persano (Salerno, Italy) with a nominal capacity of 21 MWe and a lifetime productivity of 744 GWh, estimated over a 30-years operational life.~~
- ~~A wind farm located in Pietragalla (Potenza, Italy) composed of 9 turbines with a total nominal capacity of 18 MWe and a lifetime productivity of 1262 GWh, estimated over a 30-years operational life~~.
- ~~A GPP located in Chiusdino (Siena, Italy) with a nominal capacity of 20 MWe and a lifetime productivity of 4536 GWh, estimated over a 30-years operational life.~~

Coherently with the introductory remarks of the paper, the goal of the analysis is considering different scenarios to compare the environmental performances of the above-listed renewable energy technologies as a function of the EoL waste management. Moreover, for each analysed power plant, the interpretation of the results also allows to define the effects of different recycling strategies and to select some priorities in the materials to be recovered. Hence, the system boundaries comprise the construction, the O&M and EoL process: the latter was modelled based on three sub-processes for each treatable material. The first one is the decommissioning, after which, depending on the type of waste and recovery potential, a disposal or recycling process is applied. The environmental benefits of recycling are estimated through a system expansion approach: recycled materials replace the corresponding average product in the market, based on Ecoinvent 3.6 (Moreno-Ruiz et al., 2019) thus avoiding its impact as an environmental credit. The function of the analysed system is producing electricity; therefore, the functional unit is set to 1 MWh of electricity. The lifetime productivity of each plant is calculated by multiplying the annual energy throughput (Table 1) and the expected lifetime of the systems. Since all the analysed systems are operational at the current state, the time horizon by which they will be dismantled is unknown. However, according to the primary data gathered by Basosi et al., (2020) from the owners of the plants, it is possible to expect that the lifespan of the power plants will reach 30 years in case of proper maintenance. This value is aligned with the possible lifetime achievable by PV (Lim et al., 2022b) wind turbines (Arvesen and Hertwich, 2012) , and GPP (Hu et al., 2021).

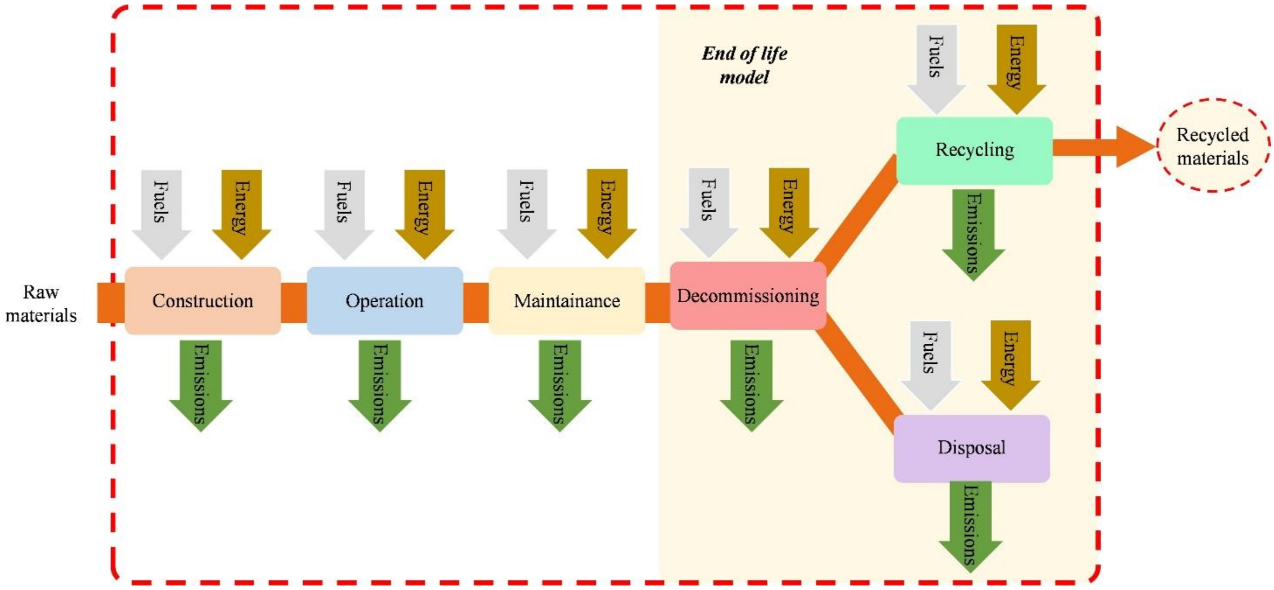

Figure 2: System boundaries definition, the end-of-life model proposed in this study is highlighted in a yellow area; according to the representation of recycled materials in this scheme, the “system expansion” approach is adopted to calculate environmental credits.

2.2 Life Cycle Inventory

The construction of a LCI consists of the definition and the quantification of the materials and energy flows exchanged between the product system and the environment. A complete and reproducible inventory of the construction and operation phases of the analysed power plants is provided by Basosi et al., (2020). The primary data provided by Basosi et al., (2020) are used as a base to construct the LCI grounding on Ecoinvent 3.6 cut-off as background database (Moreno-Ruiz et al., 2019). However, as some processes available in the Ecoinvent library already contain a default EoL model (i.e. the wind turbines), such processes are removed and replaced by the scenario-based EoL model developed in this study to prevent double-counting the waste treatment of the system.

As remarked in Figure 2, the first step of the EoL stage is the decommissioning of the power plants, namely the removal and transport of the wastes from the power plant to the waste treatment centre. To cover a regionally plausible area from the power plant to the treatment plant, 200 km was set as the average transport distance (Latunussa et al., 2016). Accordingly, two processes were used as inputs of the decommissioning model (Corona et al., 2014):

- The energy consumed to remove the components of the systems (*diesel, burned in building machine – GLO*).
- The transportation of the materials (*transport, freight, lorry >32 metric ton, EURO3 – RER*).

The corresponding quantities, calculated grounding on Corona et al., (2014), are assumed to be proportional to the mass of the materials that shall be removed and transported. A specific legislation identifying which parts of the plant shall be decommissioned depends on the country and it is subject to variations. Therefore, in this study it has been considered a complete decommissioning of the systems; this assumption entails that all the equipment is removed, and all the structures and infrastructures are demolished. The only exception is made for geothermal wells, for which the cement-filled well closure procedure is applied (Basosi et al., 2020). The avoided products selected to evaluate environmental credits from recycling are modelled using global market processes, in which the ratio of virgin and recycled material in the market is already considered by the database. A detailed description of the EoL is available in the following list and in the Supporting Information.

- Waste steel, iron, zinc, aluminium, and copper can be remelted to recover the original material, or they can be disposed of (i.e. by landfilling).
- Waste polyethylene can be recycled to recover secondary plastic or it can be disposed of according to the average Italian waste plastic mixture (1% of open burning, 55% of sanitary landfill, 44% of municipal incineration).
- Waste cement, concrete, gravel, and sand can be crushed and recovered as new gravel (downcycling), or they can be disposed of in landfills.
- Rockwool can be disposed of in inert material landfills, or it can be recovered through a specific process available in the Ecoinvent library.
- Waste asphalt can be regenerated after decommissioning to produce new asphalt, or it can be disposed of in landfills.
- Waste glass can be disposed of by landfilling, or it can be recycled by producing glass cullets employed for the production of packaging glass (downcycling) (Latunussa et al., 2016).
- The waste of epoxy resin and glass-fibre composite material can be landfilled like other inert substances, but three pathways (mechanical, chemical and thermal) are available to recycle this composite material (Karuppannan Gopalraj and Kärki, 2020). In this study, it is assumed that all the above-mentioned recycling processes determine some environmental credits and that all recovery routes are equally employed in the treatment of glass-fibre reinforced plastic (1/3 mechanical, 1/3 chemical and 1/3 thermal). Mechanical treatment entails cutting this composite material and scraps can be re-used as filler; therefore *market for inert filler – GLO* is set as avoided product (downcycling). On the other hand, secondary glass-fibre can be separated from epoxy resin that can be dissolved by acetic acid (chemical route) or by heat (thermal treatment). Therefore, *market for glass fibre – GLO* is set as avoided product by the chemical and thermal treatments of glass-fibre reinforced plastic.

- PV modules can be landfilled as electric or electronic wastes, or they can be subject to the recycling process proposed by Latunussa et al., (2016).
- The inverter can be landfilled as electric or electronic waste or it can be disassembled to recover the materials contained inside the device (Moreno-Ruiz et al., 2019).
- Exhausted lubricating oil can be incinerated as hazardous waste, or it can be regenerated according to the process explained by Abdalla et al. (Abdalla et al., 2018) to recover light fuel oil (downcycling).
- According to Basosi et al., (2020), the AMIS® reactants are dissolved in water after reacting with sodium dioxide, the output solution is injected inside the well. An activated silica filter is also installed in the AMIS® system; this device shall be disposed of as a hazardous waste using a dedicated Ecoinvent process.

2.3 Life Cycle Impact Assessment

With respect to the study of Basosi et al., (2020), which considered other calculation methods, the LCIA method selected for this study is Environmental Footprint 3.0 (EF3.0), namely the most updated method recommended by the European Commission. Using this LCIA method, a complete eco-profile of the analysed product systems is assessed. However, to synthetically describe the comparison among EoL scenarios, two key indicators are selected:

- *Climate Change,* namely the GHGs emissions occurring over the life cycle of the system (kg CO_2 eq / MWh). This indicator is selected as it is largely used in LCA analyses of energy systems.

  Resource use, minerals and metals, namely the depletion of mineral materials occurring over the life cycle of the system (kg Sb eq / MWh). This indicator is selected because the net consumption of minerals and metals is directly correlated with the recycling of materials.

3. Scenarios definition

This section addresses the definition of multiple scenarios that are designed to evaluate the effects of the EoL on the eco-profile of the system. Considering the large quantity of different materials employed in the construction of the analysed energy systems, they are classified in the following groups (detailed in the SI):

- The group “metals” includes steel, iron, aluminium, copper, zinc.
- The group “construction materials” includes all the materials that are commonly employed in civil constructions, such as concrete, gravel, sand, fireclay, asphalt and rockwool.
- The group “miscellaneous” includes all the recyclable materials that do not belong to the group of metals nor to the group of construction materials. A few examples are plastics, glass, glass-fibre, synthetic oil, and PV modules.

- The group “not recycled” collects all the materials for which recycling processes are not available or not implemented in this case study. For instance, the AMIS® reactants employed during the operation of GPPs are also included in this category since they are not recovered.

The bill of materials, namely the composition of the analysed systems, is based on the LCI published by Basosi et al., (2020), which grounds on primary data provided by the owner of the power plants (ENEL Spa). However, in case the material composition of certain components is not explicit in Basosi et al., (2020) appendixes because Ecoinvent aggregated processes are used in the LCI, this information is obtained by screening all the inputs of the above-mentioned processes. For instance, this is the case of wind turbines that are modelled as “*wind turbine construction, 2MW, onshore– GLO*”: the materials composing the turbines are therefore identified by checking all inputs of this process.

Figure 3 illustrates with pie-charts the mass percentage of each group of materials that is important to adequately interpret and discuss the results in Section 4. It is possible to observe that most of the materials employed for the construction of the PV plant in Serre Persano are metals, but also construction materials and miscellaneous (mostly composed of PV modules) represent a relevant mass contribution. On the other hand, most of the materials used for the construction of the wind turbine located in Potenza Pietragalla are inert construction materials. Differently, most of the materials consumed in the analysed GPP are not recyclable, such as the chemicals consumed by the AMIS® reactant, which are reinjected inside the wells.

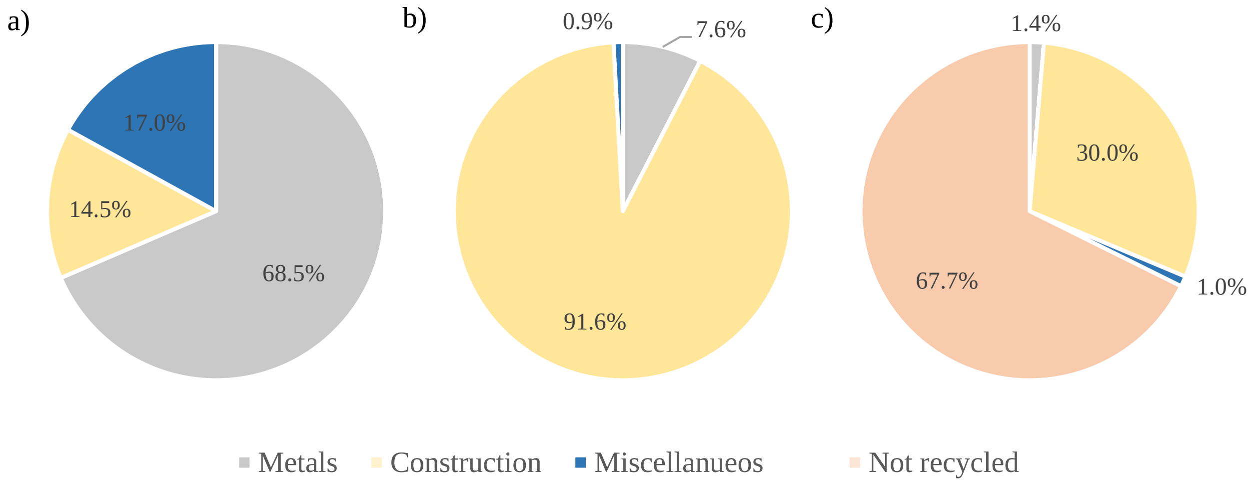

Figure 3: Amount of materials recycled for all the scenarios in a) Serre Persano PV, b) Potenza Piteragalla Wind, c) Chiusdino Geo.

According to the classification of the materials, the environmental effects of the EoL phase on the eco-profile of the system are quantified. More specifically, a range is given in which the environmental impact of energy systems could vary. In order to determine the extremes of such interval, it has been assumed two opposite cases:

- In the worst case, all materials are disposed of.
- In the best case, all materials are recycled, and the recovered resources are set as avoided products.

Based on these assumptions and on the above-mentioned materials classification, the following scenarios are drawn:

- Cradle to gate: this is a baseline scenario where the EoL is excluded from the system boundaries.
- Scenario A: all the materials are disposed of according to the EoL model described in Section 2.
- Scenario B: all the metals are recycled according to the EoL model described in Section 2 whereas all the other materials are disposed of.
- Scenario C: all the construction materials are recycled according to the EoL model described in Section 2 whereas all the other materials are disposed of.
- Scenario D: all the materials belonging to the miscellaneous group are recycled according to the EoL model described in Section 2 whereas all the other materials are disposed of.
- Scenario E: all the recyclable materials are recycled according to the EoL model described in Section 2.

These scenarios are designed to highlight the environmental contribution of recovering and disposing of each class of material; for this purpose, the comparison with the cradle to gate scenario, where the EoL stage is not included in the system boundaries, is particularly significant. It is necessary to remark that the cradle to gate results reported in this manuscript ~~are~~ can be substantially different from those published by Basosi et al., (2020) in some cases, depending on the energy generation system and the impact category under consideration. Indeed, although this study is based on Basosi et al., (2020), the selected environmental impact assessment methods are different (Section 2.3) and a few changes have been applied to exclude the EoL from Ecoinvent processes used to model the construction phase (Section 2.2).

4. Results and discussion

This section summarizes the results of the analysis, and is structured as follows: in Subsections 4.1, 4.2, and 4.3 the results of the analysed systems are discussed separately to assess the environmental hotspots of all the proposed scenarios.

Then, in Section 4.4 a direct comparison among the analysed power plants is performed: in order to provide a range of possible results, the comparison among the analysed energy systems is screened in the range of two opposite scenarios, where all the materials are disposed of (Scenario A) or recycled (Scenario E).

Figures 3-5 represent the LCA results of the PV plant installed in Serre Persano, of the wind farm installed in Potenza Pietragalla, and of the GPP installed in Chiusdino, respectively. In each diagram, the red column is representative of the results of a cradle to gate LCA where the EoL is not included, which is used as baseline; the other columns represent the results of the scenario-based cradle to grave analysis. A horizontal bond highlights with different colours the range of variability of the results. For both impact categories, two pie charts are illustrated under the histograms: the one on the left represents the percentage contributions of the decommissioning and the disposal of the materials to the overall EoL burdens (Scenario A); the one on the right illustrates the contribution of recycling each group of materials to the overall benefits (Scenario E).

4.1 Serre Persano PV

According to Figure 3, the group of materials mostly employed in the construction of this system are metals (68.5%), followed by miscellaneous (17.0%) and by construction materials (14.5%). In the analysed PV plant, the miscellaneous category is almost entirely dominated by PV modules and, in a minor percentage, by plastics. Overall, steel represents the metal that is most largely employed in the system, especially to construct the structures of the PV modules. These data are useful for a correct interpretation of the following results.

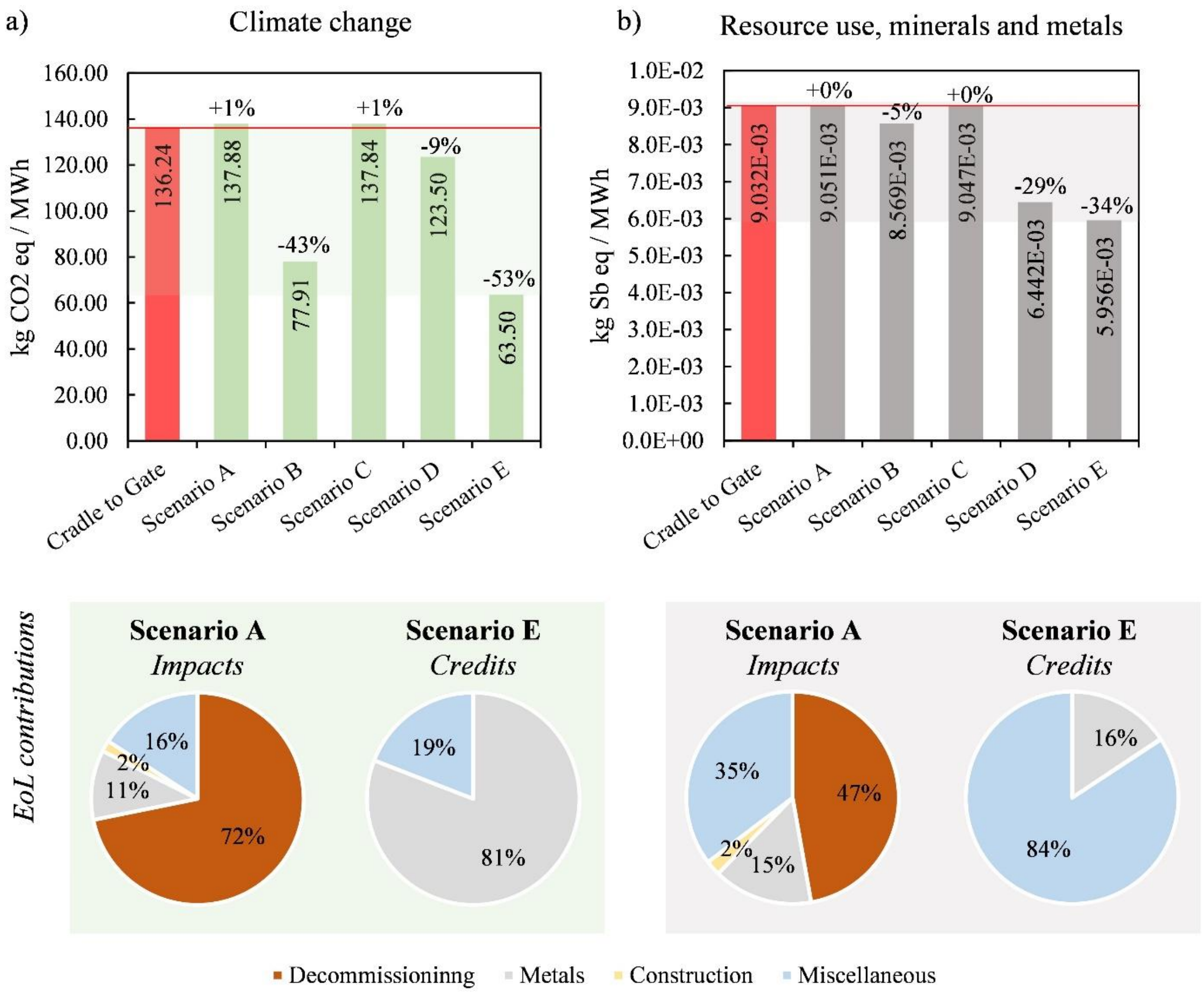

Figure 4: Scenario-dependent environmental impacts of the PV system compared to a baseline cradle to gate scenario for the categories a) Climate Change and b) Resource use, minerals and metals. The environmental impact values of different scenarios are represented with histograms. The pie charts represented below each histogram chart represent the percentage contribution of the EoL processes to the burdens of disposal and the credits of recycling.

Figure 4a represents the *Climate Change* midpoint indicator evaluated for the PV system. A cradle to gate analysis, where the EoL stage is excluded from the system boundaries, is considered as a baseline. During the construction stage, the major environmental burden of this power plant is related to the manufacturing of metals, and particularly of the metallic structures of the PV installation. Such supporting structures are composed of aluminium and steel, which are responsible for 33.9% and 16.3% of the total GHGs emissions respectively. Another relevant contribution is given by the GHGs related to the miscellaneous group, mostly caused by the PV modules' manufacturing (46.1% of the total). Differently, the category of construction materials represents a minor contributor to the *Climate Change* indicator (Table S7 of the SI)..

The second column is correlated to Scenario A, in which all the wastes are disposed of according to the EoL model described in Sections 2 and 3. In this scenario, the disposal operations increase the *Climate Change* of the system by +1.2% compared to the baseline case. According to the pie chart in Figure 3a, the GHGs emitted during the EoL stage can be mainly attributed to the decommissioning operations (around 72%), whereas the GHGs released in landfilling operations are considerably lower (around 29%). Although solar panels do not represent the major mass fraction in the bill of materials (Figure 3), ~~Among the materials disposal, the landfilling~~ ~~of PV~~ their disposal turns out as the most impacting process, followed by that of steel and aluminium. The reason is that in this study, the disposal of PV modules is modelled using an Ecoinvent process for the disposal of electric or electronic wastes (Table S4 of the SI). Accordingly, waste PV panels are subject to pre-treatments (i.e. shredding and magnetic separation) before being landfilled (Moreno-Ruiz et al., 2019), thus increasing the environmental impact of the overall disposal process.

Different considerations can be done when considering the recycling of metals (Scenario B) that allows for a percentage reduction of the *Climate Change* indicator of -43%. Interestingly, the main contribution to this mitigation is given by the environmental credits of secondary aluminium, although its mass contribution to the total is lower than steel. In Scenario C all the construction materials are subject to recovery; however, although the environmental credits from recycling, the *Climate Change* potential of the system increases compared to the baseline (+1.0%). This is due to the GHGs emitted during the decommissioning and the disposal are dominant compared to the emissions avoided by recycling of construction materials, downcycled during the second life. Regarding Scenario D, where all the materials classified as miscellaneous are recycled, a reduction of the *Climate Change* of -9% is achieved. However, such impact mitigation is quite low considering that the manufacturing of PV modules (addressed as miscellaneous) implies 46.1% of the GHGs emitted from cradle to gate. The explanation is that the recycling of PV modules only allows recovering the materials contained in the modules, but the process of Latunussa et al., (2016) does not avoid the GHGs emissions related to the energy spent to transform raw materials to PV modules along with their production chain ~~transformation processes in the supply chain of PV panels~~. In Scenario E, all the groups of materials are recycled; the corresponding results show that it is possible to obtain a strong reduction of the *Climate Change* of the PV system (-53%). Particularly, according to the pie chart related to Scenario E, the recovery of metals is responsible for 81% of the total avoided GHGs emissions. On the other hand, also the recycling of the miscellaneous group (and more specifically of PV modules) allows for a quite significant mitigation of the *Climate Change* potential of the system (19% of the credits). Therefore, when implementing a recycling process aiming to the GHGs minimization, recovering secondary steel and aluminium represents the main priority.

Another relevant indicator to be considered when evaluating recycling processes is the *Resource use, minerals and metals* category (Figure 4b~~-a~~), expressing the depletion of metal and mineral resources of the planet. A baseline cradle to gate scenario demonstrates that almost the totality of this burden is due to the manufacturing of PV modules (92.1% of the impact) that requires the direct and indirect consumption of precious materials such as gold and silver involved in the production of the metallization paste (Table S8 of the SI).

Concerning Scenario A, the results show that the disposal of the materials of the plant do not affect the *Resource use, minerals and metals* (+0%) since they do not imply a consistent consumption of additional mineral resources. In Scenario B, where all the metals of the system are recycled, the results show a slight mitigation of the *Resource use, minerals and metals* indicator (-5%) due to the recovery of secondary steel and aluminium from the supporting structures of the PV modules. On the other hand, the recycling of construction materials considered in Scenario C does not provide relevant environmental credits in terms of mineral resource avoided use (+0%) ~~due to their low environmental credits~~. More specifically, such low environmental impact mitigation is motivated by the fact that Scenario B and Scenario C do not involve the recycling of PV modules, which largely represent the main contributors for *Resource use, minerals and metals*.

Differently, a strong mitigation of the indicator *Resource use, minerals and metals* can be pointed out when analysing Scenario D (-29%), where the miscellaneous group of materials is subject to recycling; this is due to the possibility of recovering secondary materials from PV arrays, especially silver. The histogram related to Scenario E expresses the maximum impact mitigation potentially obtained by recycling all the recoverable materials in terms of *Resource use, minerals and metals* (-34%). Concerning this impact category, such environmental benefits are almost entirely related to the recycling of PV, which allows to get 84% of the environmental credits of the system, while the burdens avoided by recycling the metallic structures of the panels are only 16% of the total credits obtained during the EoL. Therefore, the priority of a recycling strategy aiming to the reduction of the mineral and metals resources consumption is the recycling of the materials contained inside PV modules.

4.2 Potenza Pietragalla Wind Farm

According to Figure 3, ~~that~~ the wind power plant located in Potenza Pietragalla is almost entirely composed of inert materials (91.6%) whereas the mass of the metals (7.6%) and of miscellaneous (i.e. plastics and glass fibre-epoxy resin) is very low (0.9%). The construction materials that are most largely used in the construction of the system are asphalt, employed to construct new infrastructures to access to the plant, gravel and sand, employed to prepare the areas in which the turbines are erected. On the other hand, steel is the most extensively consumed metallic material as it is used to construct the shaft and the gearbox of the wind turbine. The miscellaneous in this case includes lubricating oil, glass-fibre reinforced plastic, and a waste plastic mixture.

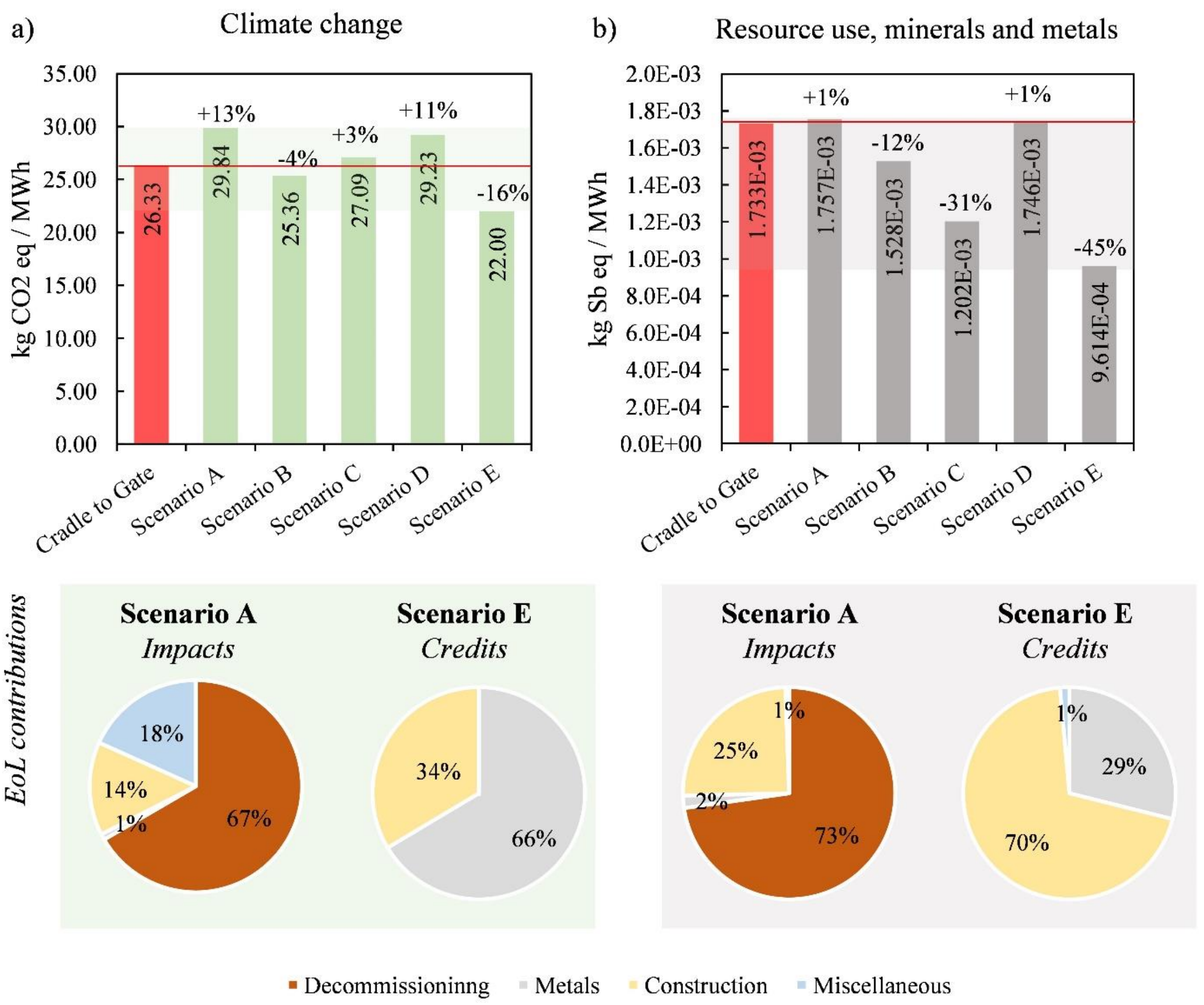

Figure 5: Scenario-dependent environmental impacts of the Wind system compared to a baseline cradle to-gate scenario for the categories a) Climate Change and b) Resource use, minerals and metals. The environmental impact values of different scenarios are represented with histograms. The pie charts represented below each histogram chart represent the percentage contribution of the EoL processes to the burdens of disposal and the credits of recycling.

Figure 5a represents the *Climate Change* midpoint impact category of the wind farm installed in Potenza Pietragalla. Focusing on the cradle to gate baseline scenario, the main environmental burdens of the product system can be attributed to the preparation of the installation area (32.0% of the total GHGs emissions), the turbines (30.2 %), the O&M (21.3%) and to the improvement of the viability (14.5%). More specifically, the huge amount of cement and asphalt employed in the construction phase are very impacting (27.8% and 14.3%). However, also the consumption of steel during the turbines' manufacturing represents a relevant environmental issue since it determines 12.8% of the GHGs emitted from cradle to gate. Moreover, it is important to consider that the turbines require periodic maintenance consisting of the replacement of the gearbox and of the lubricating oil. Overall, 19.5% of the total emissions can be allocated to the steel parts of the gearbox that shall be replaced; therefore, the total contribution of steel amounts to 32.2% (Table S7 of the SI).

Scenario A is representative of a situation where all the materials composing the system are disposed of; as stated by the second column of the system, the *Climate Change* potential of the system shows a considerable increment due to the GHGs emitted during the disposal (+13%). Particularly, the decommissioning operations, which include the removal of the infrastructures necessary to adapt the site and the viability to the installation of a wind farm, are responsible for 67% of the additional GHGs emissions. Among the disposal processes, the incineration of the lubricating oil determines the highest amount of GHGs emissions, followed by the removal of the asphalt and the cement employed during the site preparation. In Scenario B, all materials composing the wind farm are disposed of except for the metals, whose recovery allows to mitigate the overall life cycle GHGs emissions of the system (-4%). Indeed, such environmental benefits are almost entirely related to the recycling of steel, employed for the construction of the turbines' shaft and gearbox. Concerning Scenario C, where only construction materials are recovered, the *Climate Change* impact increases compared to the baseline results (+3%). Such a small increase is calculated by balancing the GHGs avoided by recycling (especially by secondary asphalt recovery) and the GHGs emitted during the decommissioning of the plant and the disposal of the materials such as the incineration of the lubricating oil. Similar considerations apply for Scenario D, where the materials that belong to the miscellaneous are subject to recycling. Like in Scenario C, the balance between the GHGs emitted during the EoL and those avoided by the recovery of the exhausted lubricating oil and plastics is not favourable. For this reason, the *Climate Change* potential of the system increases by +11% compared to the GHGs emitted from cradle to gate. Concerning Scenario E, where all the materials are recycled, the results show that the *Climate Change* indicator decreases by -16% compared to the baseline results. Such environmental credits are mostly related to the recycling of metals which provides 66% of the environmental credits from recycling, especially zinc and steel. The recycling of construction materials, particularly of asphalt, determines 34% of the avoided emissions. Accordingly, the recovery of secondary metals represents the recycling priority when implementing an EoL strategy to cut the GHGs emissions.

Figure 5b represents the *Resource use, minerals and metals* indicator that expresses the potential depletion of mineral resources during the life cycle of the product system. Concerning this impact category, the results of the cradle to gate study show that the construction of wind turbines, especially the use of steel, is the process affecting the category *Resource use, minerals and metals* the most, followed by the adaptation of roads. Particularly, the galvanized steel of the turbine shaft and the asphalt are the most impacting parts of the system followed by steel consumption due to replacements of the gearbox (Table S8 of the SI).

Concerning Scenario A, the *Resource use, minerals and metals* indicator slightly increases compared to the baseline results (+1%). The main contributor to this small increment is the decommissioning, and particularly the transportation of wastes from the installation site; the second major contribution is the disposal of construction materials due to their massive infrastructural content of asphalt, cement and gravel. However, differently from the *Climate Change* potential that is significantly sensitive to the EoL operations, the decommissioning and disposal of the system do not imply a relevant consumption of mineral and metal resources. On the other hand, the results related to Scenario B demonstrate that the recycling of secondary metals allows the reduction of the *Resource use, minerals and metals* indicator sensibly (-12%). Such benefits are due to the recovery of secondary zinc and secondary steel. Similarly, the recycling of the construction materials in Scenario C is particularly effective to mitigate the consumption of mineral and metals resources. Indeed, the *Resource use, minerals and metals* of the Potenza Pietragalla wind farm is reduced by 31% through the recovery of construction materials, particularly to the roads' asphalt. Differently, Scenario D highlights that the recovery of the materials gathered in the miscellaneous group does not guarantee significant advantages in terms of avoided consumption of mineral and metal resources since they are mostly glass fibre, lubricating oil, and mixed plastics. On the other hand, the decommissioning of the system determines a small increase of this indicator (+1%). Concerning Scenario E, it is clear that, according to the proposed model, the maximum impact mitigation achievable by recycling is 45%. The corresponding pie chart shows that the reduction of the *Resource use, minerals and metals* is mostly due to the recycling of construction materials (70%) especially asphalt, while metals recovering represents 29% of the environmental benefits that could be provided by recycling. Therefore, in case the EoL management strategy is oriented to the minimization of mineral and metal resource use, recycling all the construction materials decommissioned represent the main priority.

4.3 Chiusdino Geothermal Power Plant

Figure 3 shows that in the GPP located in Chiusdino, a large quantity of construction materials is employed (30.0%) whereas the metals (1.4%) and the miscellaneous groups (1.0%) represent minor contributions to the total mass of the system. The most largely used construction materials are gravel and cement, employed to construct the central building of the power plant, the drilling platform, and the steam pipeline. Differently from the other energy systems analysed in this work, a large amount of material is generally non-recoverable in geothermal plants (in this case study, 67.7 % of the total weight). In addition, like all flash geothermal systems, the Chiusdino power plant produces direct atmospheric emissions during operation. An effective abatement system (AMIS®) is installed, which removes Hg and H_2S; the removal of acidity requires the consumption of reactants (i.e. sodium hydroxide).

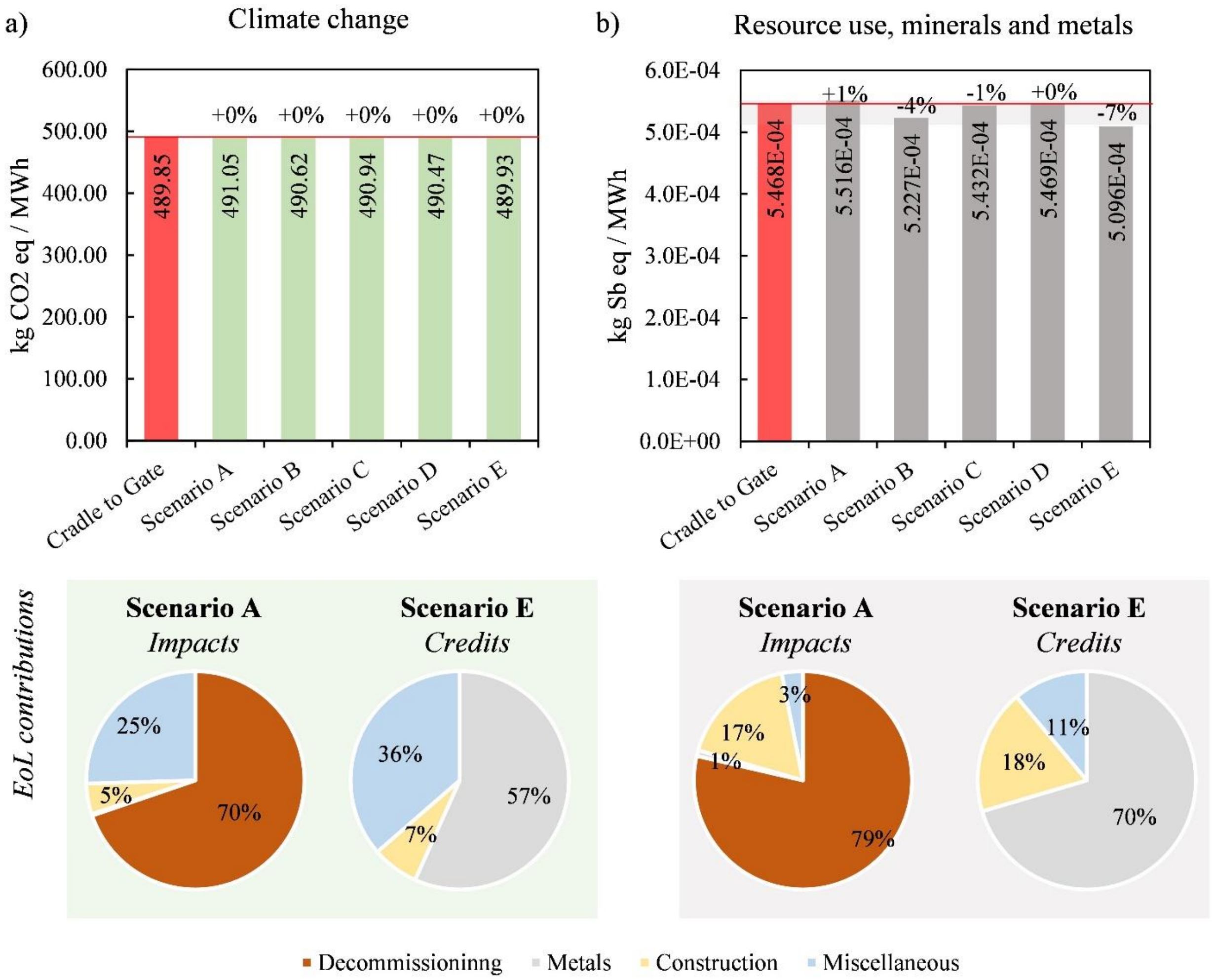

Figure 6: Scenario-dependent environmental impacts of the Geothermal system compared to a baseline cradle to gate scenario for the categories a) Climate Change and b) Resource use, minerals and metals. The environmental impact values of different scenarios are represented with histograms. The pie charts represented below each histogram chart represent the percentage contribution of the EoL processes to the burdens of disposal and the credits of recycling.

The release of non-condensable gases (nearly pure CO_2) takes place at the cooling tower, taking advantage of the buoyant plume, which enhances the diffusion of emissions to air. This determines an impact in the *Climate Change* category (Figure 6a); it is to remark that recent studies (Sbrana et al., 2020) have shown that the largest amount of the Climate Change emissions should be classified as natural, as they would reach the surface considering the structure of the Larderello geothermal region. A more detailed discussion, considering this issue, can be found in the supplementary materials. Following the traditional approach in LCA (that is full accounting of the greenhouse emissions), a cradle to gate evaluation shows that the GHGs emitted are dominated by the direct emissions of carbon dioxide, which represent 94.8% of the total. Another impacting contribution is represented by the consumption of reactants for AMIS® operation, whose embedded emissions represent around 5.0% of the *Climate Change* environmental impact (Table S7 of the SI).

Referring to the GPP, no relevant difference can be observed compared to the outputs of the cradle to gate model regardless of the analysed scenario. Indeed, since materials recycling does not allow mitigating the direct GHGs emissions of the plant, the EoL of the system has a very low effect on the results. However, although the contribution of the EoL is negligible in all the considered scenarios, it is possible to remark that the decommissioning is responsible for 70% of the GHGs emissions related to the EoL; specifically, the filling/sealing of the well represents the most impacting operation. Among the materials, the disposal of gravel, lubricating oil and steel turns out as the most impacting EoL operations. Concerning recycling, the recovery of secondary metals is the process that allows to avoid the largest quantity of emissions of GHGs, followed by that of miscellaneous materials.

Similarly to the *Climate Change*, also the indicator *Resource use, minerals and metals* is slightly influenced by the EoL model. From these baseline results, it is possible to observe that the consumption of reactants in the AMIS® systems turns out as the main responsible for the depletion of mineral and metal resources evaluated from cradle to gate. Indeed, sodium hydroxide determines 80.8% of the environmental impact for the category *Resource use, minerals and metals*, but it is not recovered during the process (Table S8 of the SI). An alternative evaluation considering the replacement of sodium hydroxide with soda ash is proposed in the SI.

Concerning the histograms related to the cradle to grave assessment, no remarkable differences can be highlighted among the different scenarios: since the main contributor to this impact (sodium hydroxide) is not subject neither to disposal nor to recycling, the EoL has a low effect on the results even when included in the system boundaries. Indeed, in case all the materials are disposed of (Scenario A), the increment of the indicator *Resource use, minerals and metals* is very small, and it is mostly due to the transports and the closure of the wells during the decommissioning (79%) while the remaining percentage is mostly related to the disposal of gravel, plastics and steel. On the other hand, when single groups of materials are recycled (Scenarios B-D), very small reductions of the impact indicator *Resource use, minerals and metals* can be observed. Among them, Scenario B is the one which results in the lowest environmental impact because the recycling of steel is the one that allows to reintegrate the largest amount of mineral and metal resources. Concerning Scenario E, Figure 6b shows that the largest environmental impact mitigation effect for the category *Resource use, minerals and metals* corresponds to 7%. Such environmental credits are mostly provided by the avoided burden of secondary metals (70%). Therefore, although the eco-profile of the GPP of Chiusdino is slightly affected by the EoL, recovering the metals turns out as the main priority to cut the environmental indicator *Resource use, minerals and metals*.

The above-mentioned results are calculated by considering the direct emissions of pollutants to the environment from the GPP. However, different results would be evaluated in case such emissions were not accounted for in the impact assessment, as they could be considered natural releases of the geothermal field (Parisi et al., 2020). Another aspect to investigate is the utilization of other reactants for AMIS® instead of sodium hydroxide; for instance, soda ash. See Supporting Information for more details.

4.4 Comparison

The results outlined in the previous subsections allow identifying the environmental advantages and drawbacks of several EoL scenarios, differing for the type of recycled and disposed of materials. This subsection contains the direct comparison among the PV, wind, and GPP analysed in this work. Figure 7 represents the environmental characterization of the three power plants, considering all the impact categories proposed by EF3.0. The histograms in Figure 7 represent relative results as the burdens of the most impacting system is set to 100% for each indicator. More specifically, Figure 7a is representative of Scenario A, where all the materials are disposed of, whereas Figure 7b is related to Scenario E, where all materials are recycled.

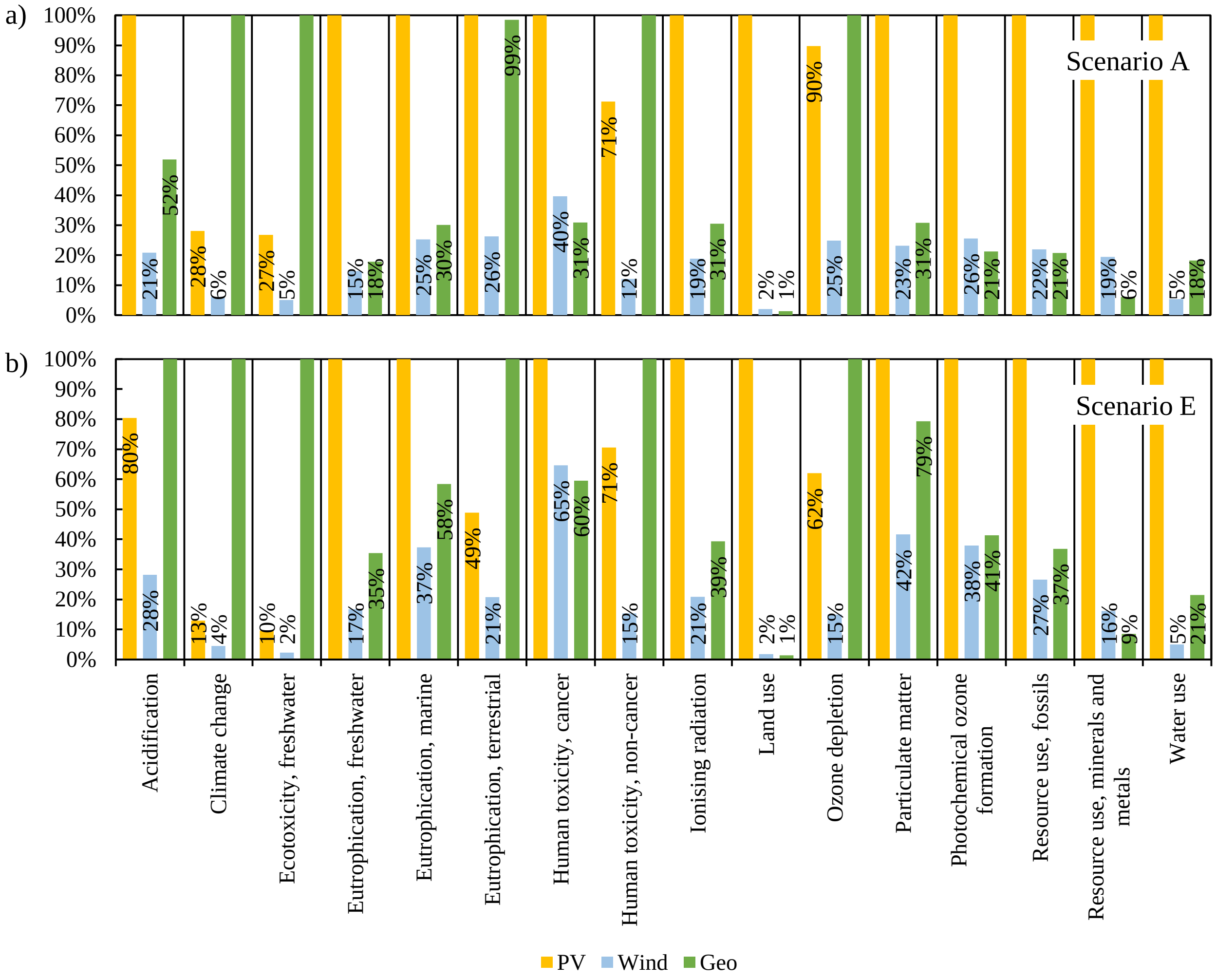

Figure 7: Environmental characterization of the PV, Wind and geothermal systems considering a) Scenario A in which all materials are disposed of and b) Scenario E in which all materials are subject to recycling.

According to Figure 7a, PV largely represents the most impacting system for all impact categories excluding *Climate Change*, *Ecotoxicity, freshwater*, *Human toxicity, non-cancer*, and *Ozone depletion*, for which the GPP located in Chiusdino (with a full accounting of greenhouse emissions) turns out to be the most impacting energy system. However, the environmental impact of the PV and the GPP are very similar also when observing the indicator *Eutrophication, terrestrial*. On the other hand, the environmental burden of the wind system is much lower than the other systems for all the environmental impact indicators.

Compared to the other systems, the eco-profile of the PV plant is particularly critical for several categories such as the *Land use* and the *Water use*, respectively affected by the direct land occupation of the plant and by the virtual water embedded inside the PV modules. Other indicators for which the environmental impact of the PV is considerably higher than the other systems are *Eutrophication, freshwater*, the *Particulate matter* formation, *Photochemical ozone formation*, the *Resource use, fossils* and *Resource use, minerals and metals*. For all these categories, the impact values of PV are roughly equally shared between the metallic structures of the modules and the PV arrays. However, the lower productivity of the PV system is another drawback of the PV system, which is directly reflected on its environmental performance, as the functional unit is set to 1 MWh of output electricity.

On the other hand, the eco-profile of the GPP is negatively affected by the direct emissions of carbon dioxide (*Climate Change*), hydrogen sulphide (*Ecotoxicity, freshwater*), and mercury (*Human toxicity, non-cancer*). Moreover, the use of sodium hydroxide AMIS® reactant affects the *Ozone depletion* in its production process. In both these systems, the decommissioning and the disposal of materials are not relevant contributors to the analysed midpoint impact indicators, as their burden share is lower than 5%. The decommissioning operations can have a relevant impact on the eco-profile of the wind system since they represent more than 20% of the impact for the categories *Eutrophication, terrestrial*, *Ozone depletion*, *Particulate matter*, and *Photochemical ozone formation*.

Concerning Figure 7b, representing the eco-profile of the analysed systems for all the midpoint impact categories proposed by the method, it is possible to observe that although the PV system is still the most impacting for many indicators, the gap with the other analysed systems is strongly reduced in the scenario, where all recyclables are recycled (Scenario E). This is due to the possibility of recovering a large quantity of materials without heavy decommissioning operations, since the mass of the system is much reduced in comparison to the other powerplants. Differently, GPP contains many not recovered materials, such as the AMIS® reactants; therefore, the possibility to reduce its impacts with recycling is very limited. On the other hand, the wind farm contains many structures, of which decommissioning demands a large amount of energy. For this reason, the relative results of the wind and the GPPs become much more similar to PV compared to Scenario A. A few exceptions can be pointed out, for instance, the PV plant is still much more impacting than the other systems in terms of *Water consumption*, because of water and land use. Indeed, recycling does not change the direct occupation and transformation of land. On the other hand, the water footprint of the PV system is mostly due to the transformation of the materials into PV modules manufacturing. All midpoint LCA results are extensively collected in the Supporting Information.

The previous paragraphs contain a comparison of midpoint impact indicators; nevertheless, a comparison among several product systems can be performed through the discussion of normalized and weighted results, which allows calculating a single score. Figure 8 is representative of a single score indicator for both Scenario A, where all materials are disposed of, and Scenario E, in which all components are subject to a recovery process. The results are expressed using milli-points (mPts) as the reference unit and they are consistent with the midpoint results presented in Figure 7. Indeed, they remark that in case all materials are subject to disposal, the PV system turns out as the most impacting power plant (26.16 mPts), but the total burden of the GPP is very similar (24.10 mPts). Differently, the single score of the wind farm located in Potenza Pietragalla is 5.06 mPts, much lower than PV and GPP. When focusing on Scenario E, where all materials are recycled and as already demonstrated at the midpoint level, the PV is the power plant most advantaged from the recycling. Indeed, while in Scenario A the PV system turns out as the most impacting power plant, in Scenario E its single score burden is intermediate between the geothermal and the wind power system.

Among the most contributing impact categories to the single score, PV and wind show similar results. Indeed, the single score of both these systems is mostly affected by the category *Resource use, minerals and metals*, followed by the indicators *Climate Change*, *Resource use, fossils*, and *Ecotoxicity, freshwater* that overall contribute to around 71% of the single score. On the other hand, the most critical impact category for the GPP is the *Climate Change*, which is responsible for 53% of the single score. However, also the *Ecotoxicity, freshwater* indicator represents a major environmental hotspot for the system since it contributes to 31% of the single score result.

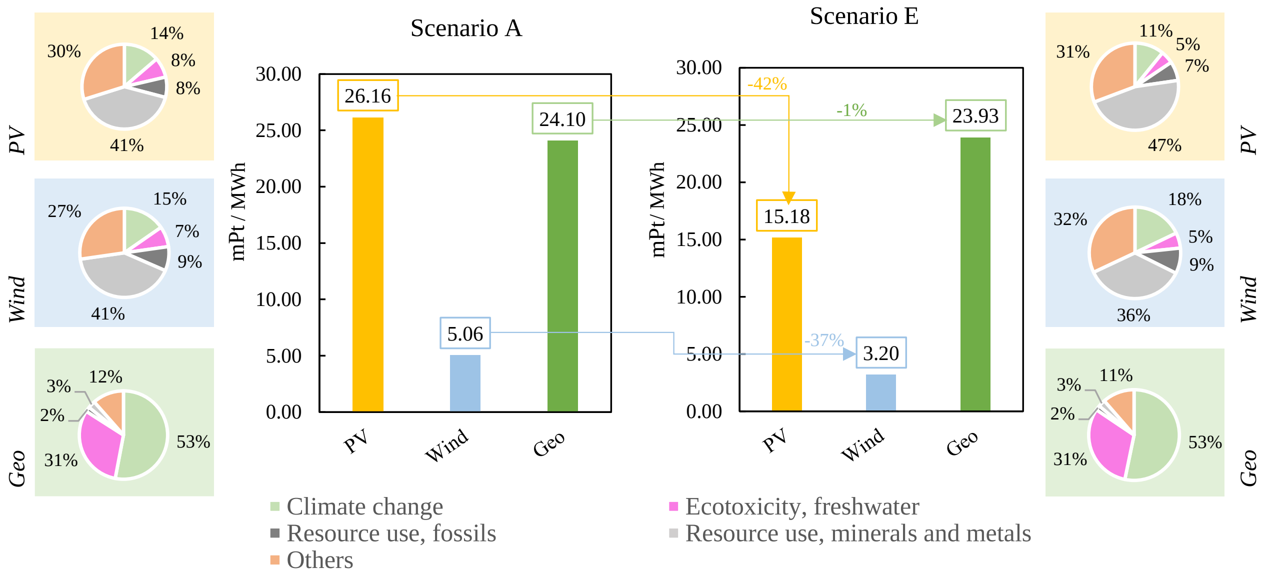

Figure 8: Single score environmental impact of the PV, Wind and geothermal systems considering a) Scenario A in which all materials are disposed of and b) Scenario b in which all materials are subject to recycling. A contribution of all the midpoint impact categories to the single score is represented in the pie charts on the sides of the histogram.

5. Conclusions

This study addresses an LCA aiming at the comparison of environmental performance among a PV, a wind, and a GPP installed in Italy, all having approximately the same nominal size. Differently from previous studies available in the scientific literature, the LCA developed in this work is focused on the role of the EoL phase when comparing renewable energy systems. Particularly, an EoL model suitable to all the analysed systems which provides, as a function of the waste management scenario, a range of possible values for multiple environmental indicators, has been proposed in this study. Firstly, the recyclable materials of the power plants are classified into three groups: i) the metals, ii) the construction materials, and iii) the miscellaneous. Based on this classification, five scenarios are defined. The following outcomes can be derived from this analysis:

- The decommissioning and disposal of the PV system in Serre Persano determine a slight increase of the *Climate change* and the *Resource use, minerals and metals* whereas materials recycling is very effective to mitigate these impact categories. More specifically, the recycling of the metal structures of the system is the main priority to cut the GHGs emissions indicator, whereas the recycling of solar arrays is fundamental to minimize the consumption of mineral and metal resources.
- The decommissioning and disposal of the wind farm in Potenza Pietragalla determine a relevant impact in terms of *Climate change*. In this regard, a critical point is represented by the demolition and the removal of roads and infrastructures necessary to prepare the installation site; the incineration of lubricating oil represents another environmental hotspot. Concerning the impact category *Resource use, minerals and metals*, a slight increase can be observed due to the decommissioning and disposal of the system. On the other hand, recovering the metals employed for the construction and O&M turns out to be a priority to mitigate the *Climate Change*, whereas recovering asphalt, cement and gravel results as the most important strategy to cut *Resource use, minerals and metals*
- The *Climate Change* of the GPP in Chiusdino is not affected by any EoL operation, neither the decommissioning and disposal nor the recycling, because it strictly depends on the direct emission of carbon dioxide. The *Resource use, minerals and metals* is slightly affected by the EoL operation, because this impact can be attributed to the huge consumption of sodium hydroxide, which is reinjected into the ground without the possibility to be recovered.

The direct comparison among the analysed systems based on Single Score shows that if disposal is selected as EoL scenario, the PV system turns out to be the most impacting one, followed by geothermal and wind. In case materials are recycled, the PV plant shows an intermediate impact value between the wind and the GPP.

Concerning the evaluation of direct emissions of pollutants in GPPs, this study evaluates two opposite assumptions: in the manuscript, all the emissions are included inside the system boundaries; the Supporting Information contains an alternative assessment where all emissions are excluded, because they are considered as natural.

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