Resources, Conservation & Recycling 211 (2024) 107885

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.sciencedirect.com/journal/resources-conservation-and-recycling

Full length article

Life cycle assessment of Al-Cu-Ag-Si recycling process from photovoltaic waste

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ARTICLE INFO

Keywords:
Environmental impact assessment
Upcycling
C-Si photovoltaic panel
Gravity analysis
Sensitivity analysis
Pilot plant

ABSTRACT

As raw materials become increasingly scarce, it is important to efficiently recycle PV panels to recover the highest quantity and quality of secondary raw materials. This study evaluates the environmental impact and the related benefits of an innovative process for c-Si PV panels recycling, which permits to recover most of the raw materials contained in them. Life Cycle Assessment analysis was carried out with "grave-to-cradle" perspective. Inventory was supported by data from a pilot plant located in Venice (Italy). ReCiPe 2016 method was used for the impact assessment. The results showed that environmental benefits are due to the recovery of aluminium, copper, silicon, silver and glass. Normalization of impact assessment results demonstrates main relevant impact categories of this process, and gravity analysis underlines what steps in the recycling process mainly contribute to the environmental benefits. Sensitivity analysis showed that quality of recovered materials influences the environmental profile of recycling process.

1. Introduction

In terms of enhancing energy security and reducing climate change, photovoltaic (PV) technology is one of the most promising and greenest. Aside from the benefits listed before, PV technology is also one of the most ecologically friendly of all energy and power producing technologies (Majewski et al., 2021). Since 2010, capacity of grid-connected solar PV systems in the EU has increased from 34.2 GWp (Chatzipanagi and Jäger-Waldau, 2023) to about 225 GWp at the end of 2022 (IRENA, 2023) and this value predicted to increase over years because it is considered necessary for the transition to a low-carbon energy future (European Commission, 2019). However, this rapid expansion introduces new problems primarily linked to the economic and environmental sustainability of the whole PV chain, from the supply of raw materials to the end-of-life management. Given an average panel lifetime of 27 years, from 2027 to 2050 15.3 million tons of waste from crystalline silicon (c-Si) modules will be generated in the EU. To ensure that this large quantity of waste does not become a problem for the environment, it must be treated appropriately (Bošnjaković et al., 2023)

In addition, the European Commission has identified silicon, a key component in PV modules, as a Critical Raw Material due to its vital role in the electronics and solar industries, its potential to enhance lithium-ion battery manufacturing for increased energy storage, and the risk associated with its supply, largely controlled by China. Moreover, considering that 15% of the world's silver is used in the manufacturing of photovoltaics (Singh et al., 2023), and the production of crystalline silicon panels is a highly energy intensive process, silver and silicon recovery becomes critical. Furthermore, the reintroduction into the economy of that secondary raw materials, gives the opportunity to manufacture new PV panels strengthening the security of future supply of raw materials used in the production of it.

Therefore, considering the rapid increase of the PV waste generation and resource depletion, proper management of end-of-life PV panels with recovery of precious materials is an urgent issue that requires both cost-effective and environmentally sustainable solutions but also offers exceptional chances to generate small-town enterprises and jobs.

To survive for a long time, PV panels are made of different layers, each of which has a specific function. A soda lime glass is placed on top of the module to ensure mechanical stability and transparency to the incident light. It is characterized by a low iron content since the latter

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https://doi.org/10.1016/j.resconrec.2024.107885
Received 22 April 2024; Received in revised form 29 July 2024; Accepted 25 August 2024

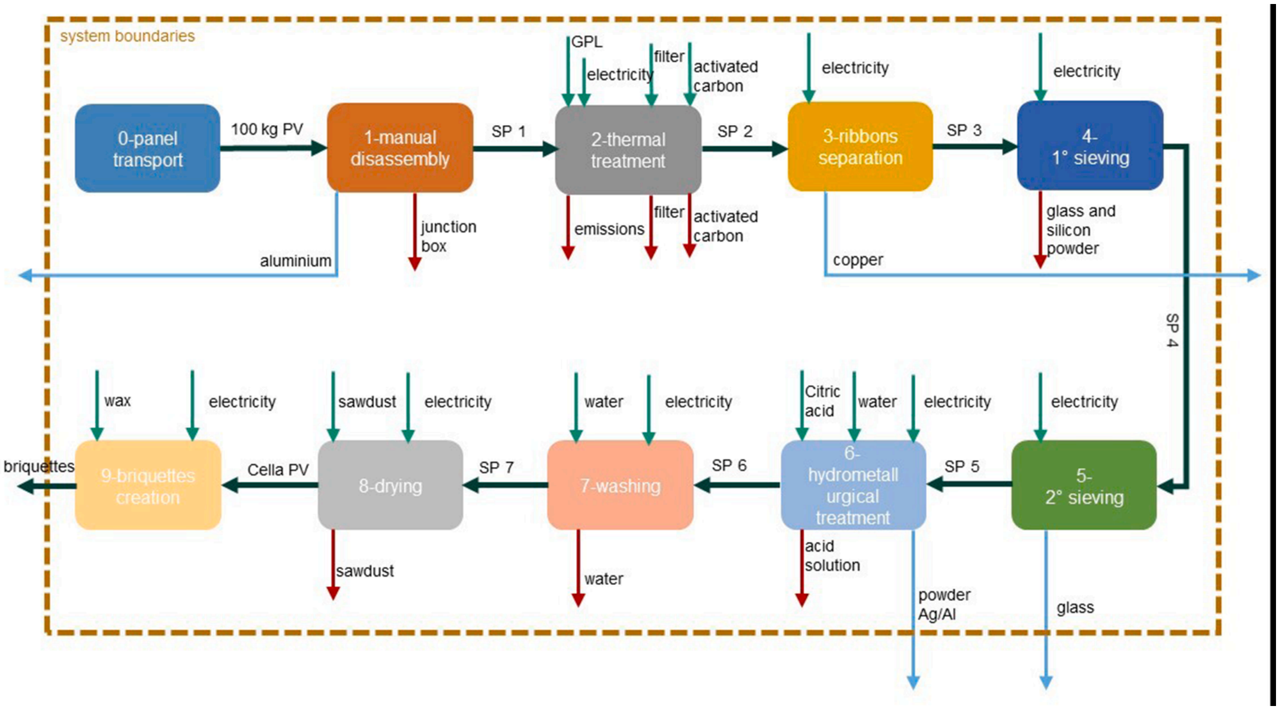

Fig. 1. System boundaries of the LCA of the c-Si PV waste recycling process.

Table 1
. Input-output of primary data of the recycling process related to the treatment of 100 kg of c-Si PV waste panels.

Step	Input	Output
1-manual disassembly	PV waste, 100 kg	Aluminium, 19.10 kg Junction box, 1.80 kg SP1, 79.10 kg
2-thermal treatment	SP1, 79.10 kg Electricity, 9.80 kWh GPL, 1.20 Nm^3	Filters, 10.70 kg Activated carbon, 0.10 kg Emissions, 3500 m^3 SP2, 68.87 kg
3-ribbons separation	SP2, 68.87 kg Electricicty, 0.28 kWh	Copper, 1.02 kg SP3, 67.85 kg
4–1°sieving	SP3, 67.85 kg Electricity, 0.14 kWh	Glass and silicon powder, 1.75 kg SP4, 66.10 kg
5–2°sieving	SP4, 66.10 kg Electricity, 0.18 kWh	Glass, 62.95 kg SP5, 3.15 kg
6-hydrometallurgical treatment	SP5, 3.15 kg Citric acid, 0.45 kg Water, 8.55 kg Electricity, 0.60 kWh	Ag/Al powder, 0.32 kg Acid solution, 9.00 kg SP6, 2.83 kg
7-washing	SP6, 2.83 kg Water, 4.00 kg Electricity, 0.20 KWh	Water, 4,00 kg SP7 2.83 kg
8-drying	SP7, 2.83 kg Sawdust, 0.36 kg Electricity, 1.12 kWh	PV cells, 2.83 kg Sawdust, 0.36 kg
9-briquettes creation	PV cells, 2.83 kg Wax, 0.28 kg Electricity, 0.26 kWh	Pellets, 3.11 kg

causes light absorption in the glass, which can result in losses. Moreover, the glass is tempered to boost its impact resistance. Two encapsulant layers incorporate the solar cells, the most often used material is ethylene vinyl acetate (EVA). Finally, the back layer or back sheet; typically, it is a combination material of polyvinyl fluoride, also known as tedlar, and polyethylene terephthalate. The main function of this layer is to protect the panel from humidity and other stresses. These layers are sandwiched inside of an aluminium frame and a junction box is attached to the rear side (Padoan et al., 2019).

PV modules are produced to last 30 years outdoors but are not designed to be recycled. In fact, the disassembly of the module sandwich for the recovery of the different materials embedded is a great challenge, due to the use of strong encapsulation materials used to glue and protect solar cells. For this reason, the only commercial solution currently available to meet the mandatory recovery rate (80% by weight) set by the Directive 2012/19/EU on waste electrical and electronic equipment (WEEE) (European Parliament, 2012) is mechanical shredding.

Despite this, several alternatives based on thermal and/or chemical processes, have been developed to increase the process efficiency, recovery and recycling rates, cost effectiveness, and environmental performance capabilities of mechanical shredding.

PV module delamination techniques that have been proven to be effective and are currently used or studied include thermal decomposition (pyrolysis or combustion), nitric acid dissolution, solvent dissolution, and irradiation-based treatments (Tao and Yu, 2015; Wang et al., 2022). The mechanical treatment has the benefit of being able to handle mixed PV waste (e.g., broken modules, coated substrates, and entire laminated modules) and requiring no chemicals process. However, the elimination of EVA can be successfully accomplished by the thermal decomposition, nitric acid dissolution, and solvent dissolution procedures; in particular, thermal decomposition is relatively straightforward and cost-effective. The major environmental concerns for industrial application of these types of delamination methods are the high energy demands of thermal treatments, the emission of harmful gases such as NOx during thermal and nitric acid dissolution treatments, and the waste solutions of nitric and solvent dissolution procedures.

Regarding the significant energy consumption of the pyrolysis/

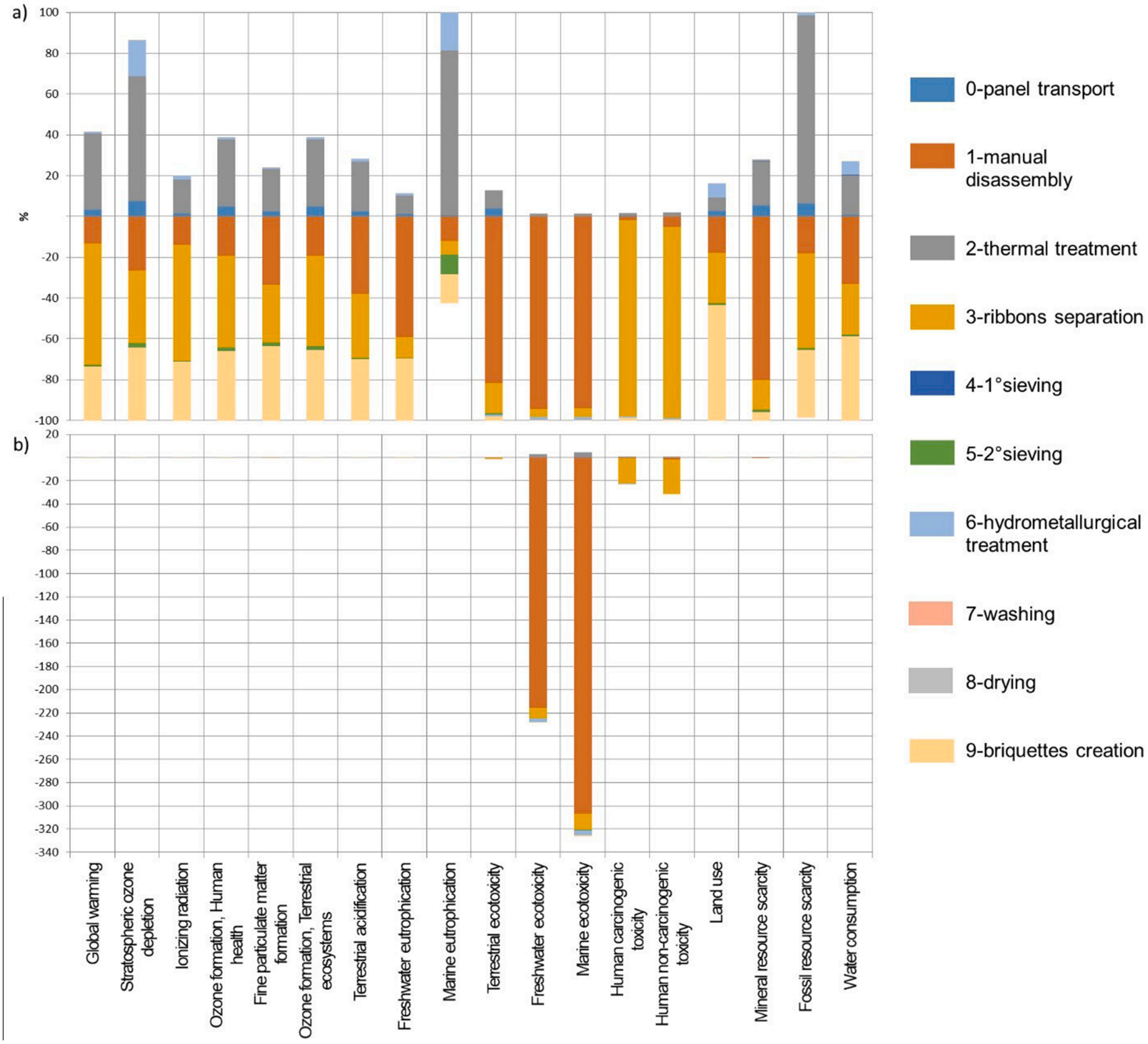

Fig. 2. a) Graphical results of the LCIA of the recycling process related to the treatment of 100 kg of c-Si PV waste panels, b) graphical results of the LCIA of the recycling process in normalised form.

combustion process, energy recovery appears to be a feasible solution (Wang et al., 2022).

To solve the abovementioned challenges, the Italian start-up 9-Tech developed a proprietary process to recover all secondary raw materials (such as glass, Al, and Cu, as well as valuable compounds like Si and Ag) from c-Si end-of-life photovoltaic panels with high purity, so that they can be efficiently re-used in several value chains. The method, comprising a thermal process, mechanical separation, and ultrasound washing treatment, is able to recover approximately 90% by weight of raw material contained in PV waste and over 95% of the economic value of these materials. In fact, most of the value is represented by metals and silicon whereas the plastic fraction is worthless (Peplow, 2022). The process employs controlled combustion of EVA encapsulant for high energy efficiency and incorporates heat recovery, in order to minimize energy costs and material wear typically associated with mechanical grinding. Other advantages of the process, with respect to other delamination techniques under investigations (e.g. hot knife, (Ghahremani et al., 2024)) is that the procedure can handle broken panels and completely avoid the creation of waste, including hazardous wastewater and plastic fractions, which are currently a cost for recycling plants. In the future, this process aims also to produce high-value silicon powder from recovered silicon, suitable for lithium-ion battery anodes, and silver.

This technology was tested in a pilot plant. Before bringing the technology to industrial scale, it is important to refine the plant not only technologically but also environmentally (Heiho et al., 2023). This allows a preliminary understanding of the plant environmental benefits, but also to identify which phases have the greatest impact and therefore understand what the opportunities for improvement may be included. A robust method for assessing environmental impacts and benefits is the Life Cycle Assessment (LCA) (Hauschild et al., 2018). Literature shows that recycling of discarded panels provides the opportunity to recover materials and achieve greater environmental benefits than end-of-life (Lunardi et al., 2018). Previous LCA studies show that influencing the environmental profile are transport (Mao et al., 2024) and material recovery; the last one is crucial to decrease impacts on the whole life of the panel (Rossi et al., 2023). Furthermore, material recovery provides economic benefits (Li et al., 2023), but the quality of the material recovered remains to be investigated.

To contribute to a better understanding of the environmental benefits and drawbacks of PV waste recycling, the environmental performance of the 9-Tech innovative recycling process for end-of-life c-Si PV

Table 2
Gravity analysis results of the process for the impact categories global warming, marine ecotoxicity and freshwater ecotoxicity.

Impact category	Life cycle step	Input-output data	Value	Unit
Global warming	0–panel transport	Transport	3.58	Kg CO2eq
		Other input–output data	0	Kg CO2eq
	1–manual disassembly	Aluminium, wrought alloy, post–consumer	−14.90	Kg CO2eq
		Other input–output data	0.074	Kg CO2eq
	2–thermal treatment	Polystyrene granulate	17.30	Kg CO2eq
		Waste polystyrene	11.40	Kg CO2eq
		Glass fibre	7.96	Kg CO2eq
		Other input–output data	5.60	Kg CO2eq
	3–ribbons separation	Precious metal from electronics scrap, in blister–copper	−66.90	Kg CO2eq
		Other input–output data	0.02	Kg CO2eq
	4–1° sieving	Ag/Al powder transport	0.03	Kg CO2eq
		Other input–output data	0.01	Kg CO2eq
	5–2° sieving	Glass cullet	−1.37	Kg CO2eq
		Other input-output data	0.04	Kg CO2eq
	6-hydrometallurgical treatment	Citric acid	1.29	Kg CO2eq
		Other input-output data	−0.63	Kg CO2eq
	7-washing	Electricity, low voltage	0.01	Kg CO2eq
		Other input-output data	0	Kg CO2eq
	8-drying	Electricity, low voltage	0.06	Kg CO2eq
		Other input-output data	0.02	Kg CO2eq
	9-briquettes creation	Silicon, metallurgical grade	−31.30	Kg CO2eq
		Other input-output data	1.692	Kg CO2eq
Marine ecotoxicity	0–panel transport	Transport	0.20	Kg 1,4–DCB
		Other input–output data	0	Kg 1,4–DCB
	1–manual disassembly	Aluminium, wrought alloy, post–consumer	−317	Kg 1,4–DCB
		Other input–output data	0	Kg 1,4–DCB
	2–thermal treatment	Waste polystyrene	1.51	Kg 1,4–DCB
		Waste glass fibre	1.50	Kg 1,4–DCB
		Other input–output data	0.91	Kg 1,4–DCB
	3–ribbons separation	Precious metal from electronics scrap, in blister–copper	−14.5	Kg 1,4–DCB
		Other input–output data	0.01	Kg 1,4–DCB
	4–1° sieving	Electricity, low voltage	0.01	Kg 1,4–DCB
		Other input–output data	0	Kg 1,4–DCB
	5–2° sieving	Glass cullet	−0.14	Kg 1,4-DCB
		Other input-output data	0.01	Kg 1,4-DCB
	6-hydrometallurgical treatment	Aluminium, wrought alloy, post-consumer	−4.72	Kg 1,4-DCB
		Other input-output data	0.01	Kg 1,4-DCB
	7-washing	Electricity, low voltage	0.01	Kg 1,4-DCB
		Other input-output data	0	Kg 1,4-DCB
	8-drying	Electricity, low voltage	0.05	Kg 1,4-DCB
		Other input-output data	0	Kg 1,4-DCB
	9-briquettes creation	Silicon, metallurgical grade	−0.79	Kg 1,4-DCB
		Other input-output data	0.04	Kg 1,4-DCB
Freshwater ecotoxicity	0–panel transport	Transport	0.133	Kg 1,4–DCB
		Other input–output data	0	Kg 1,4–DCB
	1–manual disassembly	Aluminium, wrought alloy, post–consumer	−256	Kg 1,4–DCB
		Other input–output data	0	Kg 1,4–DCB
	2–thermal treatment	Waste glass fibre	1.15	Kg 1,4–DCB
		Waste polystyrene	1.09	Kg 1,4–DCB
		Other input–output data	0.68	Kg 1,4–DCB
	3–ribbons separation	Precious metal from electronics scrap, in blister–copper	−11.2	Kg 1,4–DCB
		Other input–output data	0.01	Kg 1,4–DCB
	4–1° sieving	Input–output data	0	Kg 1,4–DCB
	5–2° sieving	Glass cullet	−0.1	Kg 1,4-DCB
		Other input-output data	0.01	Kg 1,4-DCB
	6-hydrometallurgical treatment	Aluminium, wrought alloy, post-consumer	−3.95	Kg 1,4-DCB
		Other input-output data	0.01	Kg 1,4-DCB
	7-washing	Electricity, low voltage	0.01	Kg 1,4-DCB
		Other input-output data	0	Kg 1,4-DCB
	8-drying	Electricity, low voltage	0.04	Kg 1,4-DCB
		Other input-output data	0	Kg 1,4-DCB
	9-briquettes creation	Silicon, metallurgical grade	−0.59	Kg 1,4-DCB
		Other input-output data	0.03	Kg 1,4-DCB

panels was thoroughly evaluated using the LCA methodology, based on primary data provided at TRL6 (pilot plant scale). LCA analysis permit to identify the process steps with the highest and lowest environmental impact and then investigate the cause. These highlights and classifies opportunities for improvement of the plant so that targeted action can be taken in the design of the industrialised plant. In addition, the weight of transport and the quality of the materials recovered from the process is to be investigated in terms of environmental benefits. LCA methodology was applied in accordance with ISO 14040 (International Organization for Standardization (ISO), 2020) and ISO 14044 (International Organization for Standardization (ISO), 2021).

The use of primary data provided trustworthy and practical results that might influence best practices for recycling PV waste, aligning with the European circular economy goal. When compared to previous literature research, this work is novel in that it examines the environmental effects of end-of-life c-Si PV panels by utilizing a full life cycle viewpoint, which considers all treatment and recovery procedures carried out at the pilot scale (Ansanelli et al., 2021).

Table 3
Description of changes related to each scenario analysis.

Scenario	Description	Changes	
		From	To
Base scenario	Study results	//	//
Transport scenario	Input data of PV cell transport has been changed	800 km by plane	100 km by euro5 van
Energy mix scenario	Percentage of electricity from the incinerator, from the photovoltaic plant or from the grid has been changed	75% photovoltaic plant 25% incinerator	33% photovoltaic plant 67% grid
Virgin materials scenario	Data selected from databases on materials recovered from the process were changed.	Materials recovered from WEEE	Virgin materials recovered

2. Materials and methods

2.1. Description of the PV waste recycling process

9-Tech developed and patented a thermo-mechanical process (patent n. EP3993067B1; EP3989296B1) to upcycle all the valuable materials present in c-Si end-of-life PV panels. The process showed a recovery rate of approximately 87% of the total module mass and recovery of five distinct material fractions: junction box, aluminium, copper, glass, and PV cells (with silicon and silver). A similar thermo-mechanical, chemical process was initially studied in University of Padova and upscaled during the ReSiELP project “Recovery of Silicon and other materials from End-of-Life Photovoltaic Panels” (Cerchier et al., 2021). After 2020 the process was modified by the start-up and optimized during 2023 in a pilot plant with 30 kg/h capacity that was specifically realized in Porto Marghera (Venice) to test such a treatment and authorized by Veneto region with Decree n.138 of 4/7/2023.

The process consists of a first manual dismantling step, in which the aluminium frame and the junction box (made mainly of plastic and copper) are dismantled. The panels are then cut into strips of 33 cm in order to reduce their size and make them suitable for the following step. The panel strips undergo a thermal treatment to obtain a full combustion of EVA encapsulant. This step is performed in a continuous furnace designed to minimize energy losses and equipped with heat-exchanger, which highly decreases the heat needed for the treatment, and a fume abatement system comprising pocket filter and active carbons.

After this step, the other three fractions (copper ribbons, silicon cells and glass) can be mechanically separated. Firstly, some rollers remove copper wirings and then the material is sieved to eliminate the fine fraction. After that, a specific vibrating screen separates the PV cells from the glass. The silicon cells are recovered in the form of foil pieces with dimensions of 1–20cm^2.

On the photovoltaic cell fraction, containing silicon and silver, it has been tested a washing treatment performed using a blended water solution of citric acid and ultrasound (patent n. US2024229192A1; EP4400617A1; CN118326166A), which is capable of removing silver and most of the aluminium from the PV cells in a short period of time. This treatment was performed at lab scale in special tanks designed to supply high power ultrasound and, from such tests, data were extrapolated for the LCA.

2.2. LCA of the PV waste recycling process

2.2.1. Goal and scope

The aim of the LCA analysis of the recycling process was to assess the environmental profile of the pilot plant based on primary data in order to identify the hotspots of the entire process and investigate the causes through a gravity analysis. Relevance of transport, energy mix and quality of recovered materials was investigated by sensitivity analyses. The functional unit of the study was the recycling of 100 kg of c-Si PV waste panels and it included the treatment of the PV panel with its junction box, not other PV plant components. The function of the process is the recycling of the c-Si PV panels to recover aluminium, copper, silver, glass and silicon through thermal and mechanical treatment. The approach followed for the analysis is a cradle-to-grave approach where the cradle is the decommissioning of the panel and the grave is the use of the material recovered (silicon cells) from the recycling process as a secondary raw material for aluminium production. The system boundaries of this study are defined to include the transport of panels to the recycling site, the transport of recovered and disposed materials as well as the recycling process. For the purpose of LCA, the recycling process was divided into the following steps:

- 0-panel transport; this phase consisted of transporting the panels from the decommissioning site to the recycling process site,
- 1-manual disassembly; the aluminium frame and junction box are manually removed from the panel in this phase. The aluminium is sent for recycling while the junction box is sent to a company that recover recyclable material. During this phase, the panel is cut into strips to facilitate the next phase,
- 2-thermal treatment; the panel passes through a combustion chamber which burns off the EVA layer. This step is a preparatory phase for the separation of the glass and copper, which will take place in the following steps,
- 3-ribbons separation; copper strips present in the panel are separated from the rest of the material and sent for recovery,
- 4–1°sieving & 5–2°sieving; in these two steps the material is sieved. In the first case glass and silicon powder are separated and sent for disposal, while the second sieving involves the recovery of the glass, which is the main fraction of a PV module. The recovered glass is sent for recycling,
- 6-hydrometallurgical treatment; the remaining cells are washed in an ultrasonic tank in an acid solution; silver and aluminium powder is recovered from this phase and sent for refining,
- 7-washing & 8-drying; the cells are washed and dried to be sent for briquette production,
- 9-briquettes creation; the recovered cells are shipped to a company that create silicon pellets to be used as additive for aluminium production.

The production, use and decommissioning phase of panels and refining and treatment processes of materials obtained from the recycling were excluded from the analysis. System boundaries of the LCA are shown in Fig. 1.

In Fig. 1 metals and glass marked with a blue arrow are the materials that are recovered from the process. However, these materials must be properly treated before reused, for this reason they are sent to other plants for processing. The refining and treatment of these materials are not closely related to the treatment of PV panels and therefore these processes are not included in the system boundary. Components that are not directly recovered are marked by the red arrow. The geographical extension of the study was from the place of panel decommissioning to the place of production of silicon cell briquettes and the assessment of impacts associated with end-of-life was conducted using the recyclability substitution. This means that benefits are attributed for producing recycled material, due to the fact that the production of primary material in the future is avoided (Schrijvers et al., 2016).

2.2.2. Life cycle inventory analysis

The primary data used for the study are data measured in the pilot plant whereas the secondary data were taken from ecoinvent 3 (ecoinvent, 2024). The primary data are shown in Table 1. The consumption and emissions of the process were allocated by mass and therefore relate to the processing 100 kg of c-Si PV waste panels. Since

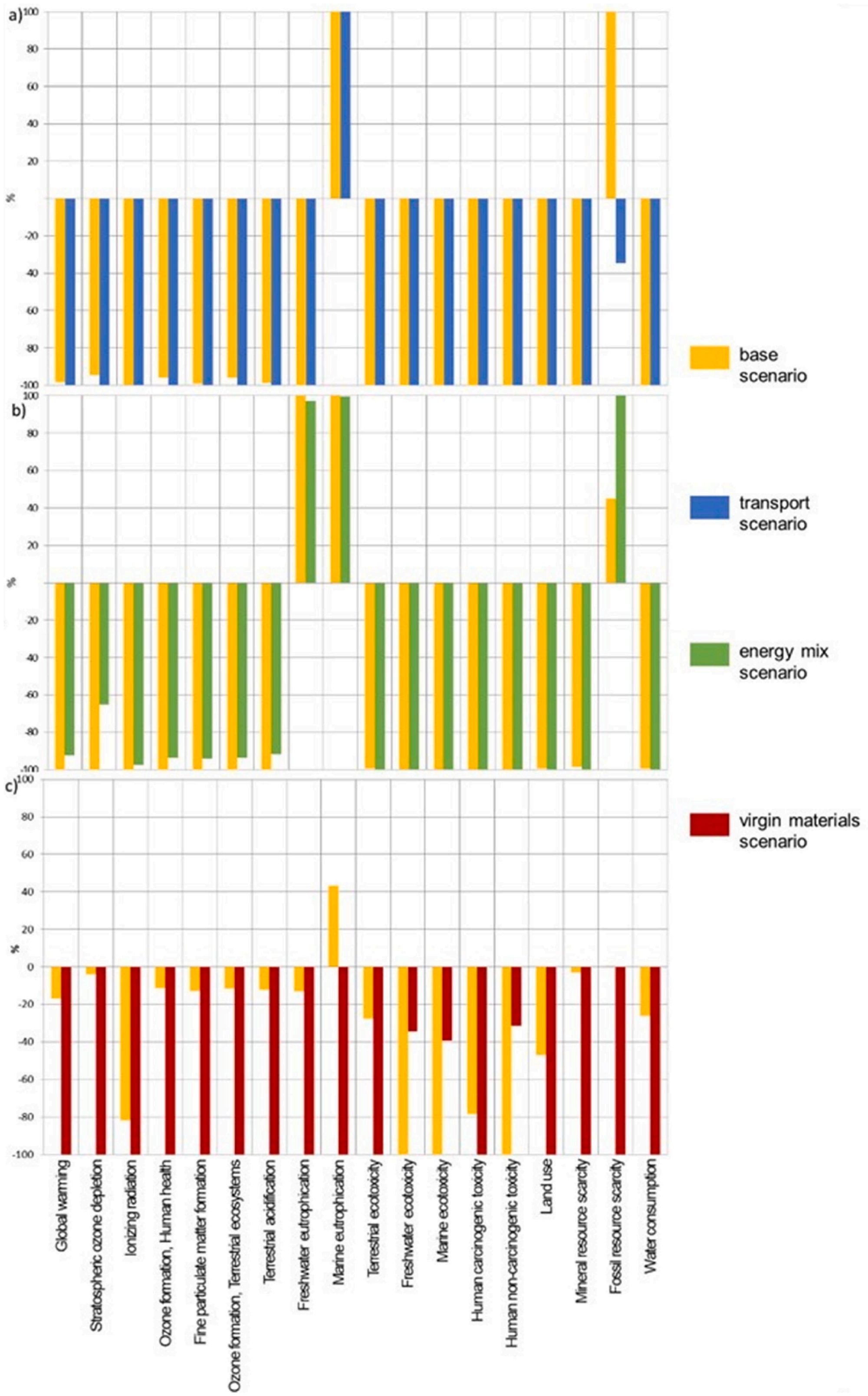

Fig. 3. Sensitivity analysis that compares base scenario with: a) transport scenario, b) energy mix scenario c) virgin materials scenario.

the materials recovered from this process may have more than one use and the type of treatment they will receive is not fixed, the chosen cut-off criterion excludes the preparation phase for the use of the recovered materials.

Based on collected primary data, it was assumed that

- 75% of the electricity used for the process would come from photovoltaic production installed in the research centre, and 25% from nearby waste incineration.

- Transports of input-output materials were carried out using a Euro5 van, except for the transports of the PV cells which are transported to Germany by plane.
- Material recovered from PV was material comparable to recovered material from WEEE and therefore not virgin material ready for reuse.

2.2.3. *Life cycle impact assessment and interpretation*

To convert the data collected during Life Cycle Impact Assessment (LCI) into potential impact it was used the software SimaPro 9.1 (SimaPro; 2024) and ReCiPe 2016 midpoint (H) method was selected for the LCIA. This method was chosen as it was used by many other studies in the literature. Consequently, using the same method made easier the comparison of results. This method is characterised by 18 impact categories which aim to transform the long list of LCI results into a limited number of indicator scores (ReCiPe; 2024). In this study, it was decided to evaluate the plant according to all impact categories proposed by the method. Results have been obtained in absolute and normalised terms. To satisfy the objectives of the study, sensitivity analysis focused on transport, energy mix and recovered materials were performed. A gravity analysis to recognize the most important factors that affect the environmental impact was done in some impact categories of particular interest.

3. Results and discussion

3.1. *Life cycle impact assessment results*

The results obtained from the entire environmental impact assessment for each impact category are summarised in Table A.1 in the Appendix A. The information in this table refers to the functional unit defined in Section 2.2.1, which is 100 kg of c-Si PV panel. The graphs resulting from the environmental impact assessment are shown in Fig. 2: Fig. 2a represents the results in absolute terms while Fig. 2b the results in normalised form.

According to the assessment shown in Fig. 2a, most of the impacts generated by the process can be attributed to two process steps, thermal treatment and hydrometallurgical treatment. Specifically, the impact categories most affected by thermal treatment were fossil resources scarcity (95%) and marine eutrophication (81%) while those most affected by hydrometallurgical treatment were marine eutrophication (19%) and stratospheric ozone depletion (18%). Panel transport was found to have impact higher than 5% in the impact categories stratospheric ozone depletion, mineral resource scarcity and fossil resource scarcity. On the other hand, most of the avoided impacts are attributable to the process steps in which materials are recovered: aluminium from disassembly, copper from ribbons separation, glass from sieving, silver powder and silicon from hydrometallurgical treatment and silicon from the last step. A detailed discussion of these results can be found in Section 3.2. From the graph in Fig. 2b, the impact categories marine ecotoxicity and freshwater ecotoxicity obtained the greatest environmental advantage over the average annual load (Prè sustainability; 2024) due to the manual disassembly phase. Another relevant aspect is the environmental advantage obtained in the impact categories human non-carcinogenic and human carcinogenic toxicity due to the copper ribbons separation step.

3.2. *Gravity analysis results*

A gravity analysis was carried out in order to understand which input and output elements are most responsible for the results of the impact assessment. The analysis was done specifically on processes and some of the 18 impact categories were investigated in priority to the objectives of the study. In particular, global warming category was investigated because of its particular interest in the literature and marine ecotoxicity and freshwater ecotoxicity categories were investigated because they are the categories that most stand out in the normalised results, as can be seen in Fig. 2b. Results are shown in Table 2. According to the findings of the gravity analysis, in all process steps the result is mainly due to only one of the input or output elements of the step. Focusing on the two most impactful phases of the process, thermal and hydrometallurgical treatment, gravity analysis focused in global warming shows that the impact is mainly due to polystyrene and fibreglass in the first case (which are the materials of which the filters are composed) and citric acid in the second case (product used to recover silver from PV cells). Analysing the process steps that provide the greatest amount of avoided impact, which are manual disassembly, separation of the ribbons and creation of the briquettes, the greatest environmental benefit is provided by the material recovered in the steps considered, which respectively are: aluminium, copper and silicon, followed by the glass recovered in the second sieving step. As recently demonstrated by scientists (Daljit Singh et al., 2021; European Commission. Joint Research Centre., 2016), material recovery leads to avoided impacts in more than one impact category. The avoided impact contribution achieved in each impact category through material recovery depends on the types and amount of metal recovered.

3.3. *Sensitivity analysis results*

Sensitivity analysis was carried out by comparing three different scenarios with the base scenario. Scenarios are described below:

1. Transport scenario: according to the assumptions made, in the base scenario silicon coming out of the drying phase will be shipped by plane to Germany to a plant that use silicon for the production of additives for aluminium foundries. With a view to the development of an industrial plant to recover larger quantities of material, it would be worth considering keeping the silicon within national borders as well. For this reason, the first sensitivity analysis was carried out on the process, to compare the base scenario with the transport scenario
2. Energy mix scenario: energy from photovoltaics and from incinerator, as assumed in the base scenario because reflects the current energy mix, may not always be available, especially since it is not to be excluded that in the future the process will also work during the night and away from the incinerator. With these assumptions, it is interesting to see how the results change by varying the percentage of energy produced by photovoltaics and replacing the remaining energy with energy acquired from the national grid. To answer this doubt, the second sensitivity analysis was conducted.
3. Virgin material scenario: the modelling of the process in the software, aluminium, copper and silver collected after the dismantling of the panels were assumed to be materials recovered from WEEE, not raw materials. While glass was assumed to be waste glass. This highlights the fact that the recovered materials avoid further extraction of raw materials, but also the fact that they must be properly processed before being reused, which leads to further environmental impacts (which are not considered in this case study as specified in Section 2.2.1 Goal and scope). Comparing this study with the literature, it appears that choices made in the database to define the quality of materials recovered from processes are often not well explained (Corcelli et al., 2018; Latunussa et al., 2016). Consequently, the third sensitivity analysis was conducted to understand how the evaluation results change according to the database choices made.

Detailed changes made to the base scenario to perform the sensitivity analyses are shown in Table 3, results in percentage form are given in Appendix A (Table A.2).

The result obtained from this three-sensitivity analysis is shown in Fig. 3. Fig. 3a shows that if the recovered silicon was kept within the territorial boundaries there is a marginally better environmental impact.

Fig. 3b shows that by switching to an energy mix consisting of less photovoltaic production, the process is environmentally worse for most impact categories, with the exception of the eutrophication, mineral resource scarcity, land use and terrestrial ecotoxicity categories. All of these categories refer to damage to the ecosystem. On the other hand, what the Fig. 3c suggest was that by assimilating in databases choices recovered material with virgin material, the environmental benefits obtained from the process were greater in most impact categories. For the impact categories freshwater ecotoxicity, marine ecotoxicity and human non-carcinogenic toxicity the comparison of the two scenarios shows that chose material recovered from WEEE (or second life) in databases is more advantageous than chose virgin material. This is a counterintuitive result and could be further investigated in the future.

4. Conclusions

The study focused on analysing the environmental impact generated by the innovative process developed by 9-Tech for c-Si PV panel recycling. The process comprises thermal, mechanical and hydrometallurgical treatments. The aim of the analysis was to assess the environmental profile of the process and identify which materials and steps mainly contribute to the impact analysis, which can guide the future development of the plant on an industrial scale.

The LCA analysis showed that the steps with the highest amount of material recovery led to the maximum environmental benefits from the process, which is true for all impact categories. This result was confirmed by the gravity analysis, which showed that the environmental benefits are due to the recovery of aluminium, copper, silver, glass and silicon. The sensitivity analysis showed that transport has a small influence on the environmental profile of the pilot plant and that the energy mix consisting of a high proportion of photovoltaic energy is environmentally advantageous. The choice of material recovered from the process has also a significant influence on the impact assessment. Specifically, if the material obtained from the process is assimilated to virgin material, there is a greater environmental benefit for most impact categories. This underline the importance of obtaining raw materials with highest purity possible. However, the advantage is not confirmed by some categories such as freshwater ecotoxicity, marine ecotoxicity and human non-carcinogenic toxicity, which seem to achieve a greater benefit if the recovered material is assimilated with material recovered from e-waste. This aspect needs further investigation in the future as well as the LCA of the industrial plant.

For the development of the plant on an industrial scale, it should be considered that the material that will be processed will be in significantly larger quantities with consequent increase in the recovered metals, glass and silicon. In particular, since the amount of silicon cells recovered will also be greater, keeping them within the national territory will become relevant. In addition, the energy required will be greater, and therefore the amount of energy provided from renewable sources or recovered from the fumes will be important. Moreover, the industrial plant compared to pilot plant will benefit from different fumes treatment system that will not require frequent filters substitution. It is therefore expected that the environmental impact generated by the thermal treatment can be significantly reduced. Finally, the removal of aluminium frame and junction box will be automated, and therefore the disassembly will produce a small impact derived from electricity consumption.

The main limitation encountered during the study is related to the availability of data in the databases. In fact, as far as recycling processes and the materials that can be recovered through recycling are concerned, the available data are very limited.

CRediT authorship contribution statement

Anna Mazzi: Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Caterina Barbiero:** Writing – original draft, Investigation, Formal analysis, Data curation. **Francesco Miserocchi:** Writing – original draft, Validation, Data curation. **Francesco Nisato:** Validation, Funding acquisition. **Graziano Tassinato:** Validation, Funding acquisition. **Pietrogiovanni Cerchier:** Writing – original draft, Validation, Funding acquisition, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

University of Padova was supported in this study by MICS (Made in Italy – Circular and Sustainable) Extended Partnership and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.3 – D.D. 1551.11–10–2022, PE00000004).

9-Tech was supported in this study in the framework of PARSIVAL, a RIS capacity building project supported by EIT RawMaterials, which is supported by the European Institute of Innovation of Technology (EIT), a body of the European Union. Finally, profound thanks goes to Intesa SanPaolo Vita and Fideuram Vita that in 2022 financially supported the construction and test of the pilot plant in Porto Marghera analysed in this work.

This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

Appendix A

Table A.1
Environmental impact assessment of the recycling process related to the treatment of 100 kg of c-Si PV waste panels.

Impact category	Unit	Total	0-panel transport	1-manual disassembly	2-thermal treatment	3-ribbons separation	4–1° sieving	5–2° sieving	6-hydrometal. treatment	7-washing	8-drying	9-briquettes creation
Global warming	kg CO2eq	−6.6E+01	3.6E+00	−1.5E+01	4.2E+01	−6.7E+01	3.4E-02	−1.3E+00	6.6E-01	1.1E-02	8.5E-02	−3.0E+01
Stratospheric ozone depletion	kg CFC11eq	−4.4E-06	2.5E-06	−8.6E-06	2.0E-05	−1.1E-05	2.2E-08	−6.7E-07	5.6E-06	5.4E-09	4.5E-08	−1.2E-05
Ionizing radiation	kBq Co-60eq	−6.1E+00	1.1E-01	−1.1E+00	1.3E+00	−4.3E+00	1.4E-03	−3.8E-02	1.4E-01	7.8E-04	5.8E-03	−2.2E+00

(*continued on next page*)

Table A.1 (*continued*)

Impact category	Unit	Total	0-panel transport	1-manual disassembly	2-thermal treatment	3-ribbons separation	4–1° sieving	5–2° sieving	6-hydrometal. treatment	7-washing	8-drying	9-briquettes creation
Ozone formation, Human health	kg NOxeq	−1.3E-01	1.0E-02	−4.2E-02	7.1E-02	−9.7E-02	9.7E-05	−3.8E-03	1.6E-03	3.0E-05	2.3E-04	−7.4E-02
Fine particulate matter formation	kg PM2.5eq	−1.3E-01	3.7E-03	−5.5E-02	3.5E-02	−4.7E-02	4.8E-05	−3.1E-03	1.1E-03	2.9E-05	1.9E-04	−6.0E-02
Ozone formation, Terrestrial ecosystems	kg NOxeq	−1.4E-01	1.0E-02	−4.3E-02	7.3E-02	−9.9E-02	1.0E-04	−3.9E-03	1.7E-03	3.2E-05	2.4E-04	−7.7E-02
Terrestrial acidification	kg SO2eq	−2.7E-01	8.8E-03	−1.4E-01	9.3E-02	−1.2E-01	1.1E-04	−2.6E-03	5.1E-03	6.1E-05	4.1E-04	−1.1E-01
Freshwater eutrophication	kg Peq	−3.2E-02	3.8E-04	−2.1E-02	3.3E-03	−3.8E-03	8.9E-06	−1.6E-04	3.2E-04	8.6E-06	5.4E-05	−1.1E-02
Marine eutrophication	kg Neq	3.0E-03	3.3E-05	−6.5E-04	4.3E-03	−3.4E-04	8.1E-07	−5.1E-04	9.9E-04	8.0E-07	4.9E-06	−7.6E-04
Terrestrial ecotoxicity	kg 1,4-DCB	−9.4E+02	4.2E+01	−8.8E+02	9.4E+01	−1.6E+02	5.8E-01	−8.4E+00	−8.4E+00	3.8E-01	2.3E+00	−2.2E+01
Freshwater ecotoxicity	kg 1,4-DCB	−2.8E+02	1.3E-01	−2.6E+02	2.9E+00	−1.1E+01	5.6E-03	−9.4E-02	−3.9E+00	6.5E-03	3.7E-02	−5.6E-01
Marine ecotoxicity	kg 1,4-DCB	−3.3E+02	2.0E-01	−3.2E+02	4.0E+00	−1.4E+01	7.3E-03	−1.3E-01	−4.7E+00	8.3E-03	4.8E-02	−7.5E-01
Human carcinogenic toxicity	kg 1,4-DCB	−6.3E+01	1.1E-01	−1.2E+00	7.3E-01	−6.1E+01	1.7E-03	−8.2E-02	−4.0E-01	1.2E-03	7.3E-03	−8.5E-01
Human non-carcinogenic toxicity	kg 1,4-DCB	−4.6E+03	3.6E+00	−2.4E+02	7.6E+01	−4.4E+03	6.7E-02	−2.5E+00	−3.3E+01	5.8E-02	3.5E-01	−1.7E+01
Land use	m2a cropeq	−3.5E+00	1.1E-01	−7.4E-01	2.8E-01	−1.0E+00	1.0E-03	−3.9E-02	2.7E-01	2.9E-04	2.2E-03	−2.4E+00
Mineral resource scarcity	kg Cueq	−3.0E-01	2.3E-02	−3.4E-01	9.2E-02	−6.1E-02	3.3E-04	−4.3E-03	8.1E-04	2.2E-04	1.4E-03	−1.8E-02
Fossil resource scarcity	kg oileq	2.8E-01	1.2E+00	−3.5E+00	1.8E+01	−8.9E+00	1.1E-02	−2.0E-01	2.3E-01	2.8E-03	2.3E-02	−6.3E+00
Water consumption	m3	−6.4E-01	7.5E-03	−2.9E-01	1.7E-01	−2.2E-01	3.0E-04	−8.8E-03	5.8E-02	3.5E-04	2.0E-03	−3.6E-01

Table A.2
Sensitivity analysis from base scenario to: i. transport scenario, ii. energy mix scenario, iii. virgin material scenario (percentage results).

Impact category	Base scenario	i. Transport scenario	Base scenario	ii. Energy mix scenario	Base scenario	iii. Virgin materials scenario
Global warming	−98	−100	−100	−92	−17	−100
Stratospheric ozone depletion	−95	−100	−100	−65	−4	−100
Ionizing radiation	−100	−100	−100	−98	−82	−100
Ozone formation, Human health	−96	−100	−100	−94	−11	−100
Fine particulate matter formation	−99	−100	−100	−94	−13	−100
Ozone formation, Terrestrial ecosystems	−96	−100	−100	−94	−12	−100
Terrestrial acidification	−99	−100	−100	−92	−12	−100
Freshwater eutrophication	−100	−100	100	97	−13	−100
Marine eutrophication	100	100	100	99	43	−100
Terrestrial ecotoxicity	−100	−100	−100	−100	−28	−100
Freshwater ecotoxicity	−100	−100	−100	−100	−100	−34
Marine ecotoxicity	−100	−100	−100	−100	−100	−40
Human carcinogenic toxicity	−100	−100	−100	−100	−78	−100
Human non-carcinogenic toxicity	−100	−100	−100	−100	−100	−32
Land use	−100	−100	−100	−100	−47	−100
Mineral resource scarcity	−100	−100	−99	−100	−3	−100
Fossil resource scarcity	100	−35	45	100		−100
Water consumption	−100	−100	−100	−100	−26	−100

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