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A Life Cycle Assessment of a recovery process from End-of-Life Photovoltaic Panels

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HIGHLIGHTS

- A Life Cycle Assessment of a recycling process for photovoltaic panels is performed.
- The recovery of secondary raw materials (Al, Cu, Ag, Si, glass) is achieved.
- The recovered glass is used in the manufacturing of building components.
- The critical steps of the recycling process calling for improvement are identified.
- The benefits of secondary materials recovery are compared to the process burdens.

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ABSTRACT

As a consequence of the photovoltaic (PV) market expansion in the last 20 years, the cumulative global PV waste is expected to exponentially grow. A proper disposal of decommissioned PV panels is crucial for avoiding environmental risks and for recovering value-added materials. In this study, a Life Cycle Assessment (LCA) was performed in order to assess the environmental performance of a new recycling process for crystalline silicon (c-Si) PV panels, at the End of Life (EoL). The process was developed in the framework of the ReSiELP (Recovery of Silicon and other materials from the End-of-Life Photovoltaic Panels) project, aiming at recovering valuable resources from EoL PV c-Si modules and making the recovered materials readily available for different supply chains, in line with the principles of Circular Economy. A "gate to gate" approach was used to investigate two lines of activities: (i) the Recovery line, dedicated to the recovery of secondary raw materials from EoL c-Si PV panels, namely aluminium, copper, glass, silver and silicon, and (ii) the Glass reuse line, for the employment of the recovered glass in prefabricated building components (predalles slabs). The results highlight energy consumption, chemicals and transportation as the main hotspots of the ReSiELP process. For a comprehensive evaluation, the generated loads were compared with the potential environmental benefits gained thanks to the recovery of aluminium, at the largest extent. Overall, the LCA analysis showed that the investigated process is environmentally favorable, also when compared to other EoL PV panels recycling scenarios reported in literature.

1. Introduction

Solar photovoltaic (PV) is becoming an increasingly important alternative energy source. Indeed, it is the third largest renewable electricity technology in terms of generation, after hydropower and onshore wind [1]. At the end of 2019, the global cumulative installed PV capacity reached about 627 GW and its share in electricity generation exceeded 3% worldwide and amounted to about 5% in the European Union [2].

This remarkable growth in PV capacity is associated with an ever larger number of PV plants which, in the coming years, will turn into a huge waste to be disposed of. In 2016, 45,000 tonnes of PV waste were generated globally and, according to the International Renewable Energy Agency (IRENA), the amount of PV wastes will reach 1.7–8 million tonnes by 2030 and 60–78 million tonnes by 2050 [3,4].

PV panels at the end of life (EoL), if not correctly handled during disposal, may pose a threat to human health and the environment [5,6,7]. In fact, they contain dangerous substances such as lead,

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cadmium, chromium and nickel [8,9]. Therefore, hazardous substances can be emitted into the air, if PV waste is incinerated, and can contaminate water and soil, under the action of rain on EoL panels without the protection layer [10,11,12,13]. In addition, since the PV waste is not biodegradable, its volume will lead to an increasingly greater land occupation [14].

On the other hand, PV modules contain conventional materials, such as glass, copper (Cu) and aluminum (Al), critical substances, such as silver (Ag), as well as energy intensive highly pure material such as the silicon (Si) wafer [9,7]. These materials could be recovered and reused in different production chains or reinjected in the PV sector (Raw Material Information System - [15], thus leading to a reduction in resource depletion and sustaining the growing amount of solar installations, in line with the principles of Circular Economy (CE) [16,17,18]). Indeed, due to the investments planned by governments in renewable energy, including solar, the amount of silicon needed for the PV sector is expected to increase from 33 ktons in 2015 to 235 ktons in 2030, in the EU area [19]. The same applies to silver, for which the demand from the PV sector increased by 7% in 2019 [12,20].

Furthermore, the recovery of energy intensive materials (Si, Al) reduces the energy necessary to extract the raw materials and to produce semi-finished products for PV panels. For example, the production of recycled aluminium requires only 1/20 of the energy of the corresponding virgin material, while having the same quality (FIRE). As a consequence, also the carbon emissions associated to energy production and, hence, the overall environmental impact of the PV technology decrease [7,21].

Moreover, the use of Secondary Raw Materials (SRMs) retrieved from PV waste would imply a guaranteed supply that does not depend on political instabilities, and, hopefully, at lower costs [22,23].

Therefore, as highlighted in previous studies [24,25,9,26], it is essential to develop sustainable methods for EoL PV panels disposal, in order to prevent any contamination and improve resource efficiency.

Moreover, the European Commission (EC), in 2012, issued the so-called WEEE Directive (2012/19/EU, EU 2012), indicating the minimum targets for recovery (85%) and recycling (80%) of Waste Electrical and Electronic Equipment (WEEE), including PV waste.

Currently, the crystalline silicon (c-Si) based PV technology is the most widespread, across the globe [27,13,28]. Therefore, most of PV waste derive from this typology of panel. Crystalline silicon PV modules contain several layers and a central unit, mainly consisting of Cu and plastic. The solar (mono- or multi-crystalline) silicon cell, that is the semiconductor, and the electric connectors, usually made of metals such as silver (Ag) and copper (Cu), are placed between two encapsulating layers, commonly made of ethyl vinyl acetate (EVA). The front layer is usually made of glass whilst, in the back, there is a sheet mainly made of Tedlar ® (polyvinyl fluoride, PVF), in combination with PET (polyethylene terephthalate) [29,30,4]. The layers are held together by an aluminium frame. By weight, common c-Si PV panels contain, on average, 75–80% glass (front layer), 10% polymer (encapsulant and backsheet), 10% aluminium (mostly the frame), 3–5% silicon (solar cells), 1% copper (connectors), less than 0.1% silver (contact lines) and other metals (such as tin and lead) at lower content [3].

Hence, by recovering only glass and aluminium frame from EoL c-Si PV panels, it would be possible to achieve the objectives set by the WEEE Directive. However, the PV recycling process can become even more economically and environmentally sustainable, if other valuable materials, such as Si, Ag and Cu are retrieved.

Therefore, in recent years, various EoL PV recycling methods aiming at the recovery of other materials, in addition to glass and Al, have been developed [31,32,33,34]. However, their environmental appropriateness, in terms of reduced impacts over the entire value chain, has been scarcely assessed and the few available studies often focused only on specific aspects of recycling [35]. For example, Aryan et al. [9] explored the environmental impact associated with the recycling of the fluorinated and fluorine-free PV backsheets. Analogously, Giacchetta et al. [36] limited the investigation of a novel recycling method for thin film PV waste, to the pre-treatment phase. In other studies, only environmental burdens [37,38,39] or benefits [40] of recycling processes were analysed.

On the other hand, other authors [41,42,43,44,45] evaluated both loads and benefits of the whole recycling processes, but using essentially secondary data or primary data at laboratory scale, that need to be confirmed by further assessments, based on up-scaled data (e.g., at pilot plant or industrial scale).

To the best of our knowledge, only few authors [40,46,47,26,48] carried out a comprehensive analysis of the environmental performances (loads and gains), using primary data, at least at pilot plant scale. Hence, the EoL of PV panels remains a topic not fully covered in the scientific literature, in particular the environmental assessment of the treatment processes to recover materials and energy.

In order to contribute to an improved knowledge about the environmental pros and cons associated to PV waste recycling, in this study the environmental performance of an innovative recycling process of EoL c-Si PV panels was thoroughly evaluated by means of the Life Cycle Assessment (LCA) methodology, based on primary data provided at TRL7 (pilot plant scale). The investigated process was developed in the framework of the ReSiELP (Recovery of Silicon and other materials from the End-of-Life Photovoltaic Panels) project, funded by the European Institute of Innovation and Technology (EIT) and aimed at recovering critical and precious substances such as Si and Ag, as well as co-product materials like glass, Al and Cu, from EoL c-Si PV panels. Following the principles of the CE and the Roadmap to a Resource Efficient Europe (COM (2011) 571), the ReSiELP project promoted the reinjection of Si in the PV sector and the reuse of glass in the building manufacturing industry, to generate a low carbon building material. Therefore, in order to ascertain the potential environmental benefits gained thanks to the use of secondary materials from PV panels, it is of great importance to analyse primary data, as those provided in the framework of the ReSiELP project, to have a clear picture of the environmental implications of a treatment process that is ready to be commercialized. To this aim, the loads of the ReSiELP process were examined, to identify the critical steps that need to be improved, from an environmental point of view. Moreover, the benefits from the recovery of secondary materials were evaluated and compared with the burdens of the treatments, in order to assess whether the whole recycling process was environmentally advantageous.

The use of primary data allowed to achieve reliable and realistic results which could be usefully exploited to suggest improvements and best practices for PV waste recycling, thus favouring their spread in line with the European circular economy strategy. Indeed, the innovative aspect of this study, in comparison with available literature studies, consists in the application of a full life cycle perspective to investigate the environmental impacts of EoL c-Si PV panels, including all the treatment and recovery steps implemented at pilot scale. The reliability of the achieved results ensures a good assessment of the resource efficiency of PV recycling, that remains an unexplored gap in the scientific literature at the moment, especially focusing on the advantages of enhanced recovery rates for different materials in PV waste. Therefore, the contribution provided by this study to the energy sector consists in a careful evaluation of the EoL phase of c-Si PV panels to ascertain the sustainability of the recovery treatments and make the photovoltaic

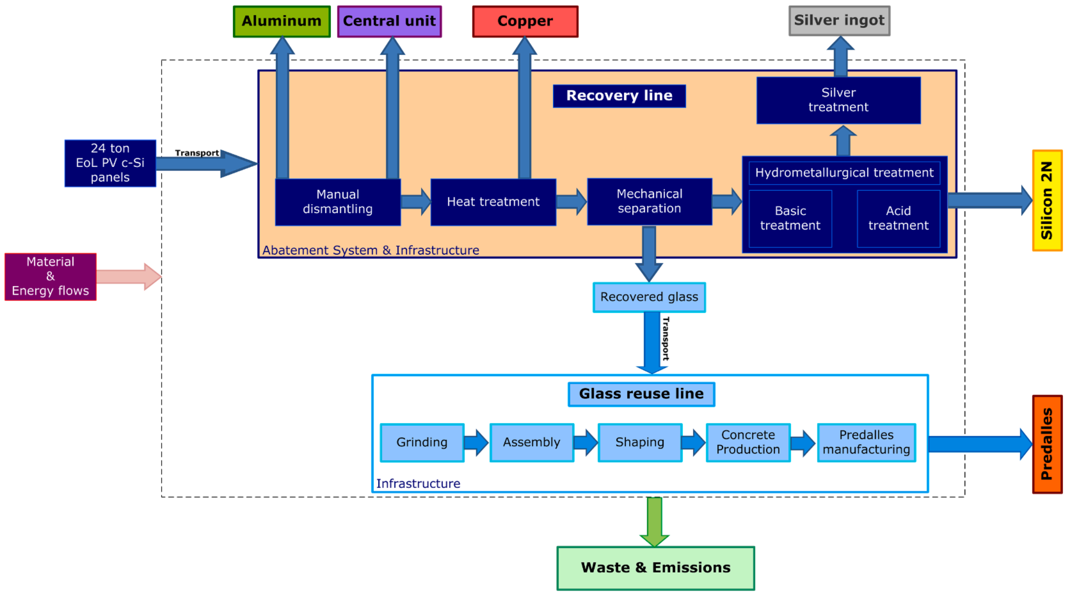

Fig. 1. System boundaries (dashed line) of the ReSiELP system including the Recovery and Glass reuse lines.

technology even more environmentally sustainable, through a closed loop approach.

2. Material and methods

In this study, the LCA of the ReSiELP process was performed in compliance with the ISO Standards 14040-44: 2006 [49,50] and the ILCD Handbook recommendations [51].

Life Cycle Assessment (LCA) is a methodology used to evaluate the potential environmental impacts of products or services along all their entire life cycle, with a “cradle to grave” approach. LCA allows to (i) assess the environmental burdens associated with a product, process or activity, by identifying and quantifying energy and material hotspots and (ii) identify and evaluate opportunities for environmental improvements (Guidelines for Life-Cycle Assessment: A ’Code of Practice’, SETAC).

According to the ISO standard procedures, the following LCA stages are reported in this paper: goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and interpretation of results.

2.1. Goal and scope definition

The goal of this LCA study was to provide an overall picture of the environmental loads and benefits as well as to identify the critical points related to the recycling of EoL c-Si PV panels, in the ReSiELP process. The investigated system consists of two lines of activities (hereafter referred to as subsystems): (i) the Recovery line, dedicated to the recovery of SRMs from EoL c-Si PV panels, and (ii) the Glass reuse line for the employment of the glass recovered from PV in prefabricated building materials (predalles).

According to the ILCD Handbook [51], an attributional LCI modelling framework was applied. The selected functional unit for the ReSiELP process was the estimated annual productivity of the recycling process, corresponding to the treatment of 24 tons of EoL c-Si PV panels. In the Recovery line subsystem, the inventoried input and output flows were modelled with reference to 24 tons of EoL c-Si PV panels. In the Glass reuse line subsystem, the reference flow corresponds to the amount of recycled glass deriving from 24 tons of EoL c-Si PV panels treated in the Recovery line, i.e. 16.8 tons, used to produce 654 predalles ready for the building and construction market.

Table 1
Allocation fractions to the different products of the analysed system.

Phase	Co-products	Allocation by mass (%)
Dismantling	Dismantled panels Aluminum frame Central units	79.6 18.0 2.4
Heat treatment	Copper Treated panels (glass + Si cells)	0.9 99.1
HM treatment (acid treatment)	Silicon AgCl	96.7 3.3

Moreover, the investigated system boundary was focused on the recycling process of EoL c-Si PV panels, developed in the framework of the ReSiELP project. Therefore, in a zero burden perspective [52], the production, use and maintenance of c-Si PV panels were not considered and a “gate-to-gate” analysis was performed. In addition to the operating activities and infrastructures, in the studied subsystems (Recovery line and Glass reuse line), the transport (i) of the EoL PV panels from national PV waste collection points to the Recovery line and (ii) of the PV glass fraction from the Recovery line to the Glass reuse line, were also included in the study. The outlined system boundaries are depicted in Fig. 1.

A mass allocation procedure was applied to solve the multi-output issue and to assign an environment load to each identified co-product in the Recovery line. Table 1 shows the percentages allocated to each co-product for each investigated recycling phase.

Since the goal of this study is two-fold, namely assessing both the environmental burdens and benefits of the recycling process, a system

Table 2
LCI of Recovery line, referred to the selected FU.

Materials/Energy	Amount/FU	Unit	References
Transport of EoL PV panels to the Recovery line	3000.0	tkm	*Continental website*
Total energy consumption	62100.0	kWh	*ReSiELP partners data*
Common Infrastructures and Equipment			
Inputs			
Materials			*ReSiELP partners data*
steel	36.1	kg	
polypropylene	97.2	kg	
HDPE	8.0	kg	
Chemicals	10.9	kg	*ReSiELP partners data*
Tap water	43.6	m^3	*ReSiELP partners data*
Outputs			
Wastewater	43.65	m^3	*ReSiELP partners data*
Manual dismantling			
Inputs			
EoL PV panels	24.0	ton	*ReSiELP partners data*
Equipment (working tables, containers, hammer, cutter)			*ReSiELP partners data*
steel	33.9	kg	
wood	3.0	kg	
HDPE	550.0	g	
polystyrene	1.7	kg	
Outputs			
Products			*ReSiELP partners data*
Al frames	4.3	ton	
Copper from Central units	234.4	kg	
Plastic (polycarbonate) from Central units	345.6	kg	
Emissions			*ReSiELP partners data*
Glass powder	24.0	kg	
Heat Treatment			
Inputs			
Furnace	0.06	item	*ReSiELP partners data*
Conveyor belt	1.1	m	*ReSiELP partners data*
Ventilation system	0.06	item	*ReSiELP partners data*
Other equipment (trays, extractor hood, cooling chamber, rake, container)			*ReSiELP partners data*
steel	27.6	kg	
wood	0.1	kg	
aluminium	0.1	kg	
HDPE	0.6	kg	
galvanized sheet	0.2	m^2	
Outputs			
Products (Copper ribbon)s	168.0	kg	*ReSiELP partners data*
Emissions (VOCs, particulates, chromium, lead)	9.1	kg	*ReSiELP partners data*
Waste flows (ashes)	1.2	kg	*ReSiELP partners data*
Mechanical separation			
Inputs			
Equipment (separating machine, containers, extractor hood, big bags)			*ReSiELP partners data*
steel	40.6	kg	
aluminium	15.0	kg	
polycarbonate	200.0	g	
polypropylene	25.2	kg	
galvanized sheet	0.3	m^2	
Outputs			
Products			*ReSiELP partners data*
Glass	16.8	ton	
Silicon cells to be purified (intermediate product)	403.6	kg	
Emissions (particulates, silicon powder)	15.4	kg	*ReSiELP partners data*
Waste flows (Glass, silicon)	480.0	kg	*ReSiELP partners data*
HydroMetallurgical (HM) treatment and Ag recovery			
Inputs			
Equipment/Infrastructures			*ReSiELP partners data*
steel	18.4	kg	
Cast iron	800.0	g	
polypropylene	80.0	kg	
polycarbonate	0.7	kg	
polyvinylchloride	3.7	kg	
High-density polyethylene	21.5	kg	
Glass tube	571.4	g	
Ceramic tile	2.4	kg	
graphite	2.4	kg	
Charging/discharging pumps	0.011	item	
Peristaltic pump	0.001	item	
furnace	0.007	item	
Tap Water	14583.4	L	
Deionized water	15742.0	L	
Chemicals (H_2SO_4, Na_2CO_3, NaCl, HNO_3, NaOH)	983.8	kg	
Outputs			
Products			*ReSiELP partners data*
Silicon cells (3 N purity grade)	319.0	kg	
Silver ingot	5.8	kg	
Waste flows			*ReSiELP partners data*
Wastewater	34.9	m^3	
slag	5.7	kg	
Emissions (CO_2, O_2)	1.2	kg	*ReSiELP partners data*

expansion of the avoided virgin materials production, thanks to the recovery of materials from EoL c-Si PV panels (Al, Ag, Cu, glass, metallurgical grade – MG – Si as well as plastic and Cu from the central units) was also performed. Therefore, the environmental burdens of the production of virgin materials or conventional products (manufacturing of conventional predalles) were subtracted from the environmental burdens of the investigated system.

The results of the study can be used to improve the management of the EoL c-Si PV panels, from an environmental point of view. In particular, this work is addressed (i) to recyclers, for a better understanding of the aspects that most affect environmental performance of EoL PV c-Si recycling processes, and (ii) decision-makers to help them in identifying the best recycling technologies to be supported and planning strategies in order to minimize the dispersion of the resources contained in PV waste.

2.2. Description of the system

In this study, the environmental performance of the recycling process of EoL c-Si PV panels developed, at TRL7, within the ReSiELP project, was analysed. In detail, the investigated system includes two different subsystems: 1) the Recovery line, located in northern Italy (Milan), where the so called "extraction phase" of secondary materials from PV waste is carried out, and 2) the Glass reuse line, located in southern Italy (Brindisi), where PV glass is employed in building materials (predalles), in place of natural aggregates.

In the following, a brief description of the two lines of the ReSiELP system is reported, according to the non-disclosure agreement among

Table 3
LCI of Glass reuse line, referred to the selected FU.

Materials/Energy	Amount/FU	Unit	References
Transport of the PV glass fraction from the Recovery line (northern Italy) to the Glass reuse line (southern Italy)	43000.0	tkm	*ReSiELP partners data*
<u>*Inputs*</u>			
PV Glass fraction from the Recovery line	16.8	ton	*ReSiELP partners data*
Concrete components (gravel, sand, cement)	186.9	ton	*ReSiELP partners data*
Steel	9.8	ton	*ReSiELP partners data*
Plasticizer	0.2	ton	*ReSiELP partners data*
Polystyrene	5.9	ton	*ReSiELP partners data*
Tap water	17.0	ton	*ReSiELP partners data*
Infrastructure & Equipment (scaffolding, excavation, cutter, concrete mixing factory, compressor, crane, forklift)			*ReSiELP partners data*
steel	430.0	kg	
electric components	5.0	kg	
diesel	662.1	kg	
concrete mixing plant	0.00005	item	
air compressor	0.04	item	
Energy consumption	797.0	kWh	*ReSiELP partners data*
<u>*Outputs*</u>			
Products (Predalles)	654.0	item	*ReSiELP partners data*
Waste flows treatment (concrete)	327.0	kg	*ReSiELP partners data*

the ReSiELP Partners.

2.2.1. Recovery line

The Recovery line ("extraction phase") refers to the treatment of EoL c-Si PV panels for recovering Al, Cu, glass, Ag and metallurgical grade (MG) Si. The process consists of a manual phase (manual dismantling step), in which the aluminum frame and the central units (made, mainly, of plastic and copper) are dismantled and the panels are cut to reduce their size, in order to make them suitable for the next step. Hence, in the Heat treatment step, the cut panels undergo a Heat Treatment (HT) into a furnace, to eliminate the polymeric fraction and to allow the separation of the other components. Once the panels are cooled down, at room temperature, in a cooling chamber, the copper strips are separated with a rake. Then, the mechanical separation step is carried out, introducing the treated PV panels into a separating machine which returns three fractions: glass, silicon cells and mixed material that is destined for further separation treatments. The glass is sent to the Glass reuse line for its reuse in building materials (predalles slabs), while the silicon cells are first subjected to a sieving, to reduce glass contamination, and then to a Hydrometallurgical (HM) treatment, to be purified up to 3 N purity grade (HM step). The HM treatment consists of a basic and an acid phase and leads to silicon 3 N, which is composed of fragments of de-metallized silicon cells.

Moreover, silver is obtained from the acidic waste solution, through a salt precipitation process (AgCl) followed by a reduction reaction, in an induction oven (Ag recovery step).

All emissions into the air are captured by a specifically designed abatement system.

2.2.2. Glass reuse line

The Glass reuse line is based on the use of the glass recovered from the EoL c-Si PV panels, treated in the Recovery line, as inert in the concrete of predalles slabs which are prefabricated building components made of concrete, polystyrene and steel. The first step is a grinding operation (grinding step) to obtain a glass of the size necessary to make it usable as a filler in concrete. Then, all the input materials (glass, cement, sand, gravel and so on) are weighted and suitably stored (assembly step). Afterwards, the shaping step, where polystyrene is shaped by means of an electric wire (cutter), is carried out and the concrete mix is produced in a concrete mixing plant and, hence, put into a speedy machine which distributes the concrete on a vibrating desk, in order to level it.

In the last production step (Fig. 1), the predalles are manufactured and left to mature for a certain period, in order to be ready for the building and construction market.

2.3. Life cycle inventory and main assumptions

Table 2 reports the input (energy and material flows) and output (products, emissions, waste flows) data for the Recovery line. All data are split according to the different phases, in order to facilitate the interpretation of the results obtained, and are referred to 24 tons of EoL c-Si PV panels (see section 2.1). Analogously, the inventory data for the Glass reuse line (Table 3) are related to 654 predalles produced from 16.8 tons of recycled glass, obtained from the Recovery line.

Since the ReSiELP recycling process is protected by nondisclosure agreements, the detailed data relative to the operations carried out in the Recovery and Glass reuse lines can not be disclosed and aggregated data are reported.

In the inventory for the Recovery line, the transport of EoL c-Si PV panels from the PV collection points to the Recovery line, is set to the average Italian national distance of 125 km [53]; on the other hand, the transport of the PV glass fraction from the Recovery line to the Glass reuse line, is based on the actual distance travelled between the two investigated plants (Recovery plant and Glass reuse plant).

With regard to equipment lifetimes, 10 years, for working equipment, and 15 years, for furnaces and HM plant, were assumed, in the case of the Recovery line. For the Glass reuse line, lifetimes, ranging from 15 years, for electric cutter and crane, up to 50 years, for concrete mixing plant, were considered (primary data from the ReSiELP process).

Both the recycling costs and benefits related to materials recovery were accounted for. In particular, the avoided production of primary aluminium, copper, MG silicon and silver was assumed for crediting materials recovery, with processing losses estimated at 10% for plastic, 3% for Cu, 5% for Al, Ag and MG Si [40,54].

Regarding the data quality, multiple sources of input/output flows were used. Personal interviews were integrated with bibliographic sources. In detail, primary and site-specific data, obtained from the ReSiELP Partners by means of tailored questionnaires, as well as secondary data retrieved from EcoInvent v.3.5 database (allocation at point of substitution, dataset of unit processes) [55,56], and from pertinent scientific literature [53] were used as foreground information. Moreover, background data related to energy generation, use of energy, auxiliary materials and impacts of the waste management (wastewater treatment, airborne/waterborne emissions) were derived from the EcoInvent v.3.5 database.

Averaged European data were used for materials and chemicals, while, for the supply of electricity, the Italian medium-voltage electric mix was selected, as the examined lines are located in Italy.

Table 4
Characterized impacts generated at the Recovery line, referring to the selected FU.

Impact category	Unit	Total	Transport*	Dismantling	Heat Treatment	Mechanical Separation	HM treatment	Ag recovery	Abatement System & Infrastructures
GW	kg CO_2 eq	3.36E+04	4.90E+02	1.44E+02	2.07E+04	5.45E+02	2.65E+03	7.11E+01	9.09E+03
PMF	kg PM2.5 eq	5.23E+01	4.44E−01	2.80E−01	3.29E+01	9.60E−01	3.84E+00	1.30E−01	1.37E+01
OF	kg NOx eq	7.10E+01	7.75E−01	3.40E−01	4.37E+01	1.21E+00	5.72E+00	1.50E−01	1.91E+01
TA	kg SO_2 eq	1.56E+02	9.23E−01	4.50E−01	1.01E+02	2.16E+00	9.51E+00	3.20E−01	4.16E+01
FE	kg P eq	1.24E+01	3.92E−02	9.00E−02	7.98E+00	2.60E−01	8.30E−01	3.00E−02	3.21E+00
ME	kg N eq	1.49E+00	3.15E−03	1.00E−02	6.50E−01	2.00E−02	2.70E−01	1.00E−02	5.30E−01
HCT	kg 1,4-DCB	2.30E+03	1.02E+01	5.73E+01	1.66E+03	1.23E+02	1.05E+02	4.57E+00	3.40E+02
MRS	kg Cu eq	1.59E+02	9.08E−01	4.02E+00	1.13E+02	8.04E+00	1.01E+01	3.10E−01	2.28E+01
FRS	kg oil eq	9.54E+03	1.70E+02	3.45E+01	5.85E+03	1.57E+02	6.04E+02	2.15E+01	2.71E+03
WD	m^3	6.03E+02	1.40E+00	1.13E+00	3.83E+02	9.16E+00	3.56E+01	1.25E+00	1.71E+02

*The transport of EoL c-Si PV panels was referred to an average Italian national distance of 125 km (from the PV collection points to the Recovery plant).

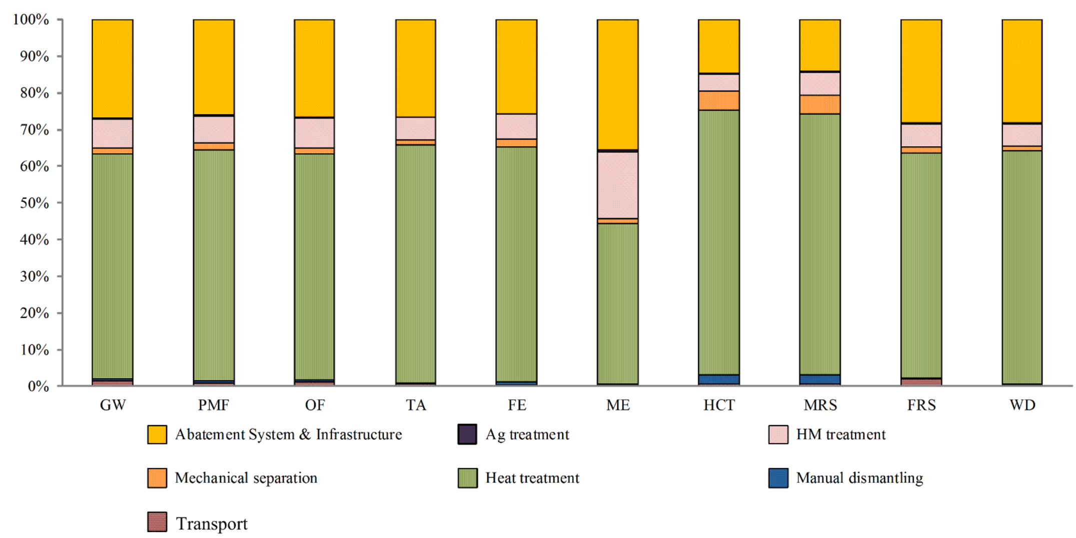

Fig. 2. Percentage contribution of each step to the total impact of the Recovery line, for each impact category, referred to the selected FU.

The time reference for primary data was 2019. For the secondary data retrieved from EcoInvent v.3.5, the most recent available datasets were chosen.

2.4. Life cycle impact assessment (LCIA)

The Professional software SimaPro v.9.0.0.48 (Pre-Consultants) was used to set up the LCA model of the investigated process and implement the impact assessment calculations.

The selected impact assessment method was the ReCiPe2016 method (ReCiPe 2016 Midpoint (H) V1.1 [57]; [58]. This method provides characterization factors to quantify the contribution of different flows, to and from a process, to several impact categories [57], such as global warming, abiotic depletion, acidification, eutrophication, human toxicity, among others. Both upstream (such as fossil, metal and water depletion categories) and downstream impact categories (such as impacts generated on natural matrices, like terrestrial acidification or marine and freshwater eutrophication) [59] were analysed. It is crucial to rely on midpoint indicators for identifying the hotspots of a process and optimizing the energy and material recovery processes, thus improving the overall circularity.

In this study, the LCIA focused on ten midpoint environmental impact categories (among those included in ReCiPe 2016), which were identified as most relevant for EoL c-Si PV panels recycling process. In detail, the selected impact categories were: global warming (GW), fine particulate matter formation (PMF), ozone formation (OF), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), human carcinogenic toxicity (HCT), mineral resource scarcity (MRS), fossil resource scarcity (FRS), water consumption (WD).

Furthermore, a sensitivity check was performed to ascertain (i) the environmental sustainability of the investigated system, by a comparison with the equivalent system based on conventional, not recycled materials and (ii) the improvement achieved by means of tailored actions on an identified hotspot. In particular, since the flows related to transport were detected as sensitive inputs, alternative scenarios were proposed, based on progressive reductions of the travelled distances, and effects of these changes on the final results were discussed.

3. Results and discussion

In the following sections, the results of the environmental evaluation are shown first separately for the subsystems “Recovery line” and “Glass reuse line” and then for the whole ReSiELP process. In each subsystem, the main hotspots were identified and the total generated impacts were

Table 5
Characterized impacts calculated for the Recovery line (broken down into different recovered coproducts) and referred to the selected FU (24 ton of EoL c-Si PV panels). Negative values correspond to the avoided impacts thanks to materials recovery.

Impact category	Unit	Total	Al recovery	CU* recovery	Cu recovery	Glass recovery	Ag recovery	Si recovery	Abatement System & Infrastructure	Avoided primary Al	Avoided primary Cu	Avoided primary Ag	Avoided MG Si	Avoided plastic and Cu from CU
GW	kg CO_2 eq	−9.23E+03	1.11E+02	1.48E+01	1.97E+02	2.06E+04	1.87E+02	3.41E+03	9.09E+03	−3.40E+04	−2.99E+02	−2.18E+03	−3.37E+03	−3.06E+03
PMF	kg PM2.5 eq	−4.09E+01	1.25E−01	1.67E−02	3.12E−01	3.28E+01	3.06E−01	5.05E+00	1.37E+01	−6.72E+01	−4.07E+00	−7.14E+00	−6.77E+00	−8.04E+00
OF	kg NOx eq	−4.24E+01	1.92E−01	2.56E−02	4.15E−01	4.36E+01	3.99E−01	7.30E+00	1.90E+01	−7.65E+01	−2.96E+00	−1.72E+01	−8.58E+00	−8.20E+00
TA	kg SO_2 eq	−8.03E+01	2.37E−01	3.16E−02	9.53E−01	9.95E+01	7.74E−01	1.33E+01	4.16E+01	−1.81E+02	−8.56E+00	−1.64E+01	−1.27E+01	−1.80E+01
FE	kg P eq	−2.71E+01	2.20E−02	2.93E−03	7.52E−02	7.94E+00	6.55E−02	1.12E+00	3.21E+00	−2.01E+01	−3.75E+00	−9.25E+00	−1.27E+00	−5.19E+00
ME	kg N eq	−2.43E+01	1.71E−03	2.28E−04	6.10E−03	6.46E−01	1.70E−02	2.87E−01	5.33E−01	−1.81E+00	−9.98E+00	−2.13E−01	−8.39E−02	−1.37E+01
HCT	kg 1,4-DCB	−9.26E+03	1.16E+01	1.54E+00	1.59E+01	1.75E+03	1.05E+01	1.73E+02	3.40E+02	−1.07E+04	−1.53E+02	−3.80E+02	−9.30E+01	−2.63E+02
MRS	kg Cu eq	−1.55E+03	7.95E−01	1.06E−01	1.09E+00	1.19E+02	8.06E−01	1.46E+01	2.28E+01	−7.11E+02	−2.65E+02	−3.65E+02	−1.69E+00	−3.63E+02
FRS	kg oil eq	5.12E+02	3.58E+01	4.77E+00	5.59E+01	5.87E+03	4.96E+01	8.23E+02	2.71E+03	−6.95E+03	−7.94E+01	−5.71E+02	−6.44E+02	−7.90E+02
WD	m^3	−7.67E+02	4.19E−01	5.58E−02	3.58E+00	3.75E+02	2.95E+00	4.97E+01	1.71E+02	−1.28E+03	−6.87E+00	−1.64E+01	−3.97E+01	−2.58E+01

*Central Unit = CU.

also shared among the different production/recovery steps, for each investigated impact category. A system expansion was also included to quantify not only the environmental burdens, but also the benefits achieved through the recovery of materials and avoided production of the virgin counterparts (Al, Cu, Si and Ag) and the reuse of the recovered glass in an added value supply chain (building sector). All the reported results were calculated with reference to the selected functional unit (24 ton of EoL c-Si PV panels).

3.1. Recovery line

The total impacts generated from the materials recovery process implemented at the Recovery line as well as the impacts generated in each phase are shown in Table 4. For this subsystem, the selected FU corresponds to 24 tons of treated EoL c-Si PV panels, matching the annual productivity of the investigated plant.

The % values are also displayed in order to highlight the relative contribution of each phase (Fig. 2).

In all the investigated impact categories, the HT results to be the most impacting phase, with a relative contribution ranging from 44%, in ME, to 72%, in HCT. The abatement system, together with the other infrastructures, generates relevant impacts in all the impact categories, ranging from 14%, in MRS, to 36%, in ME. Regarding the HM treatment, its share to the investigated impact categories is always below 10%, except for ME, where it amounts to 18%, due to the significant contribution of the used acid and basic solutions. The contribution from the steps of manual dismantling and mechanical separation appear restrained (nearly 3% and 5%, respectively), whilst the impacts from Ag treatment and transport are negligible (around 1% in all the investigated impact categories).

An in-depth analysis of the heat treatment shows that the main responsible for the generated impacts is the electricity consumption of the used furnace. Also the impacts attributable to the abatement system are actually due to the electricity required for its operation. Therefore, the reliance on the grid electricity is responsible for almost the totality of the impacts. As far as the other steps are concerned, a key role is played by the use of chemicals in the HM treatment and of disposable containers employed for the storage of products and residues.

The identified hotspots suggest (i) the necessity of improvement in the energy consumption through a reduction of energy requirements or through the adoption of renewable alternatives and (ii) the need for an efficient use of chemicals and equipment, such as the repeated use of storage containers.

Besides the identification of the hotspots (flows and process steps) of the Recovery line, another main objective of this analysis consists in quantifying the environmental benefits derived from the recovery of materials from EoL c-Si PV panels. The latter issue calls for a system expansion, regardless of the allocation procedure, according to the ISO standards (14040-44, 2006), in order to consider the avoided impacts deriving from the recovery of materials, allowing a saving of primary materials. In the present study, the environmental impacts related to the production of virgin materials (primary Al, primary Cu, primary Ag, MG Si, fossil-based plastic) were subtracted from the impacts generated by the Recovery line. When the resulting impacts are negative, it means that a potential environmental benefit is achieved.

The total net environmental impacts, deriving from the Recovery line, are listed in Table 5. Moreover, in this Table, the impacts (absolute values) related to the recovery of materials from EoL c-Si PV panels and to the corresponding avoided primary material production are shown. The observed negative values mean that the credits (or benefits) associated to the recovery of goods (namely Al, Cu, Si and Ag) are greater than the environmental burdens generated during the whole life cycle of the recovery process.

A net environmental gain is reached in all the impact categories (negative total values), except for FRS where the impact generated. amounts to 512 kg oil eq (as shown in Table 5 as total value and in

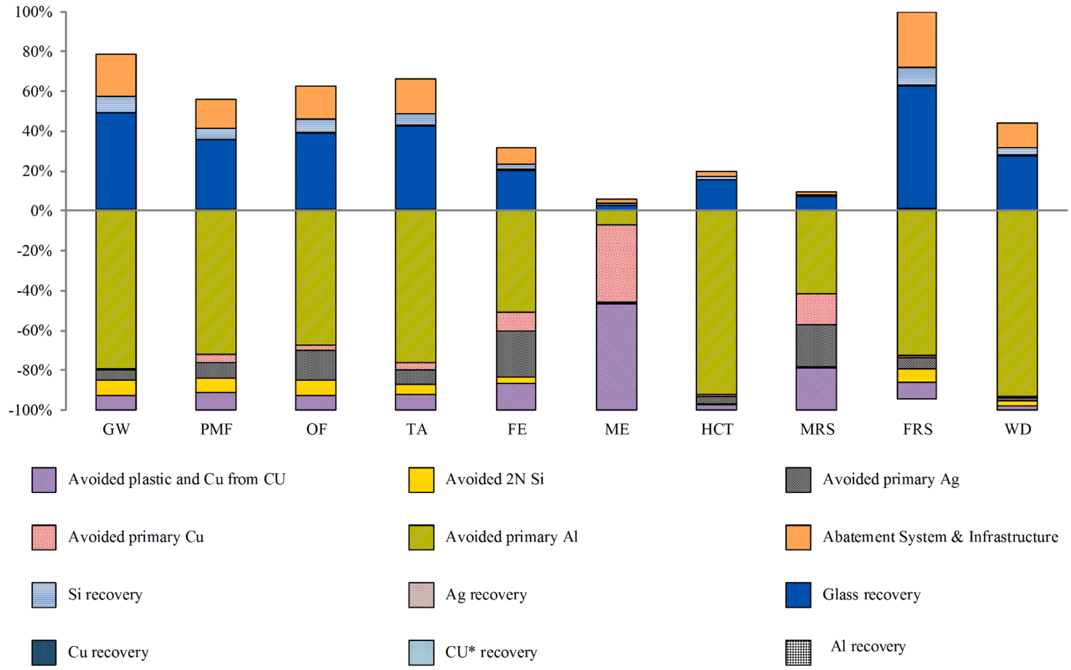

Fig. 3. Percentage contribution of each co-product to the overall environmental impacts of the Recovery line, referred to the selected FU. Results include avoided impacts (negative values) due to recovery of material flows.

Table 8 as the value referred to the Recovery line). The impact generated in the FRS impact category is due to the fossil share of electricity used in the Recovery line for silicon recovery, in particular in the Glass recovery step and in operating the Abatement System, overcoming the benefits achieved by avoiding the investigated primary materials production.

In Fig. 3, the contribution of each material to the total impacts is depicted in percentage terms.

Concerning the environmental savings (negative bars), it clearly appears that the avoided production of primary aluminium ranks above the other primary materials production in generating environmental benefits, with contributions higher than −90%, in WD and HCT. The ME impact category is mainly benefited by the recovery of copper from panels (−39%) and of plastic and copper from central units (53%), whereas the benefit gained for the MRS impact category is distributed among the recovery of aluminium (42%), copper (16%) and, at the same extent, of silver and plastic & copper from central units (21%).

3.2. Glass reuse line

The total impacts generated from the production process implemented at the Glass reuse line as well as the impacts generated by each input flow (materials, energy, equipment, waste treatment) are shown in Table 6, with reference to the selected FU (24 tons of treated EoL c-Si PV panels, allowing the recovery of 16.8 tons of glass, used to produce 654 predalles ready for the building and construction market).

Fig. 4 shows the different contribution of each input to the generated impacts for all the investigated impact categories.

In all the investigated impact categories, the production of cement and steel (as material components of the produced predalles) represents the main hotspots of the Glass reuse line. Cement contribution ranges from 7%, in HCT, to 42%, in GW, whilst steel impacts vary from 29%, in WD, to 79%, in MRS. Sand contributes to WD at a significant extent, corresponding to 29%, and polystyrene shows an average impact of 7% for all the investigated impact categories. Infrastructure and equipment, although distributed along their lifetimes (primary data from the ReSiELP project), affect some impact categories at an extent higher than 10% (PMF and TA), up to 20%, for OF. Other material and energy input flows generate negligible impacts as well as the treatment of cement waste. The benefits deriving from the avoided disposal in landfill of glass waste (coming from the Recovery line) are also very low (minor than 1%). The transport to the Glass reuse plant of the PV glass fraction obtained from the Recovery line is included in the assessment and the deriving impacts are around 10% in GW, PMF and TA and reach 21%, in FRS.

However, an in-depth analysis was dedicated to the comparison of the ReSiELP process, related to the reuse of the glass fraction for the production of predalles, with that employing conventional materials (primary materials rather than recovered glass). Additionally, for sensitivity purposes, different transport scenarios were developed to fully ascertain the environmental sustainability of the Glass reuse line. In particular, besides the ReSiELP scenario (described above and shown in Table 6 and Fig. 4), hereafter referred to as Business As Usual (BAU) scenario, the following three other scenarios were investigated, namely: (i) Scenario I, in which a regional transport for recovered glass was assumed (100 km); (ii) Scenario II, in which transport was not considered, assuming that the glass can be recovered in the same plant where it is reused for manufacturing building materials; (iii) Scenario III, in which the conventional production of predalles was accounted for. In the latter, the transport of each input for the production of conventional predalles was included, according to the EcoInvent v.3.5 database.

The impacts generated by the previously described scenarios are shown in Table 7 and Fig. 5.

Table 6
Characterized impacts generated at the Glass reuse line, referring to the selected FU.

Impact category	Unit	Total	Grinding	Transport	Sand	Gravel	Cement	Plasticiser	Water	Steel	Polystyrene	Infrastructure & Equipment	Electricity	Waste treatment	Avoided glass waste
GW	kg CO_2 eq	6.79E+04	6.61E+01	6.96E+03	1.14E+03	3.88E+02	2.83E+04	2.57E+02	6.19E+00	2.13E+04	6.21E+03	2.90E+03	3.45E+02	1.75E+00	−4.50E+01
PMF	kg PM2.5 eq	7.33E+01	1.07E−01	6.31E+00	2.41E+00	7.12E−01	1.59E+01	5.04E−01	1.10E−02	3.46E+01	3.98E+00	8.42E+00	5.13E−01	4.50E−03	−1.08E−01
OF	kg NO_x eq	1.63E+02	1.43E−01	1.10E+01	6.88E+00	2.20E+00	4.76E+01	6.89E−01	1.51E−02	4.93E+01	1.18E+01	3.33E+01	7.12E−01	1.52E−02	−2.65E−01
TA	kg SO_2 eq	1.54E+02	2.96E−01	1.31E+01	5.40E+00	1.69E+00	4.48E+01	1.13E+00	2.54E−02	5.77E+01	1.13E+01	1.71E+01	1.62E+00	1.00E−02	−2.68E−01
FE	kg P eq	1.36E+01	2.84E−02	5.57E−01	2.56E−01	1.05E−01	3.24E+00	8.94E−02	4.68E−03	7.77E+00	8.58E−01	5.96E−01	1.18E−01	1.95E−04	−7.04E−03
ME	kg N eq	7.65E−01	2.00E−03	4.48E−02	1.70E−02	8.08E−03	2.22E−01	6.33E−03	3.65E−04	3.49E−01	6.47E−02	4.05E−02	1.06E−02	1.49E−05	−5.49E−04
HCT	kg 1,4-DCB	3.71E+03	9.40E+00	1.45E+02	5.14E+01	3.58E+01	2.76E+02	8.39E+00	1.99E+00	2.90E+03	1.08E+02	1.69E+02	9.16E+00	4.54E−02	−1.48E+00
MRS	kg Cu eq	9.41E+02	6.12E−01	1.29E+01	3.67E+00	3.28E+00	1.53E+02	6.27E−01	6.44E−02	7.40E+02	9.99E+00	1.62E+01	5.22E−01	3.32E−03	−1.05E−01
FRS	kg oil eq	1.12E+04	1.83E+01	2.42E+03	3.57E+02	1.17E+02	2.44E+03	1.33E+02	1.55E+00	3.56E+03	1.18E+03	9.22E+02	1.01E+02	1.21E+00	−4.79E+01
WD	m^3	4.68E+02	1.15E+00	1.98E+01	1.38E+02	2.21E+01	7.23E+01	5.16E+00	1.71E+01	1.36E+02	4.45E+01	7.98E+00	6.71E+00	5.55E−02	−2.76E+00

In all the investigated impact categories, the BAU scenario is more impactful than the conventional production system (Scenario III). If the transport distance is lowered at regional scale (Scenario I) or eliminated (Scenario II), the generated impacts respectively result comparable or lower than the impacts of the conventional production system, thus highlighting the relevance of the transport in determining the environmental performance of the system under study.

3.3. ReSiELP system – recovery line & glass reuse line

The total environmental impacts (loads and benefits) generated from the investigated ReSiELP process are shown in Table 8 and in Fig. 6, in percentage terms. The impacts are reported separately for the Recovery line and for the Glass reuse line, in which the transport from the Recovery plant to the Glass reuse plant was split off in order to better ascertain the improvement options for the transport issue. Both the Recovery line and the Glass reuse line were treated in a system expansion approach, as described in Section 2.1.

The Recovery line includes the benefits achieved by avoiding the production of primary materials (see Table 5). Analogously, in the case of Glass reuse line, the impacts generated by the conventional predalles production (Scenario III, in Table 7) are subtracted from the impacts of the Glass reuse line (Scenario II, in Table 7), in order to consider the net environmental impacts.

Environmental gains (total negative values) are recorded in all the investigated impact categories, except for FRS. The benefits gained are mainly due to the recovery of Al, Cu, Si and Ag in the Recovery line, whereas the loads are basically generated by the transport (positive values in Table 8). The impact of the transport is particularly high on GW and FRS categories, amounting to 6.96E+03 kg CO_2 eq and 2.42E+03 kg oil eq, respectively. In the GW category, however, the benefits of the Recovery line overcome the burdens, resulting in a total impact of −3.27E+03 kg CO_2 eq and an environmental net gain is achieved. In the FRS category, instead, the environmental burden related to the transport (83%) and to the electricity consumption in the Recovery line (17%) dominates and a net load of 2.77E+03 kg oil eq is produced. Therefore, if the transport is reduced or eliminated (considering the implementation of the whole ReSiELP production system in the same plant), further environmental benefits could be achieved.

The overall results related to the environmental performance of the investigated ReSiELP process are environmentally favourable, also when compared to the few available EoL PV panels recycling scenarios reported in literature [40,48,26]. If the recycling is mechanical and based on simple techniques, such as the baseline scenario in Ardente et al. [40], it does not require any auxiliary materials and the energy consumption is much lower than in a complex treatment process, such as the ReSiELP system. Therefore, the environmental loads generated in a low value recycling scenario are of course minor, but, at the same time, the process is not able to efficiently separate different materials (only 10% of the glass is recovered, whereas PV cells and plastics are landfilled) and the achieved benefits result to be restrained. Thanks to the higher environmental gains derived from the recovery of valuable materials, the ReSiELP system shows better performances in all the investigated impact categories. Similar results are also recorded in the comparison with the low value averaged recycling scenario reported in Stolz et al. [48], in which EoL c-Si PV modules are mechanically treated, yielding the bulk materials glass cullets, aluminium scrap and copper scrap. When dealing with a high value recycling scenario, characterized by the recovery of Si ingots, Al, Ag, glass fragments and junction boxes [26], the load generated by the thermal route for the EoL PV materials recovery is predominant, making the process less advantageous than the ReSiELP process in almost all the impact categories under study. On the other hand, the ReSiELP process shows a lower environmental performance than the FRELP scenario, as described in Ardente et al. [40], in most of the investigated impact categories. This result is due to the less efficient recovery of SRMs, in particular of silver and silicon

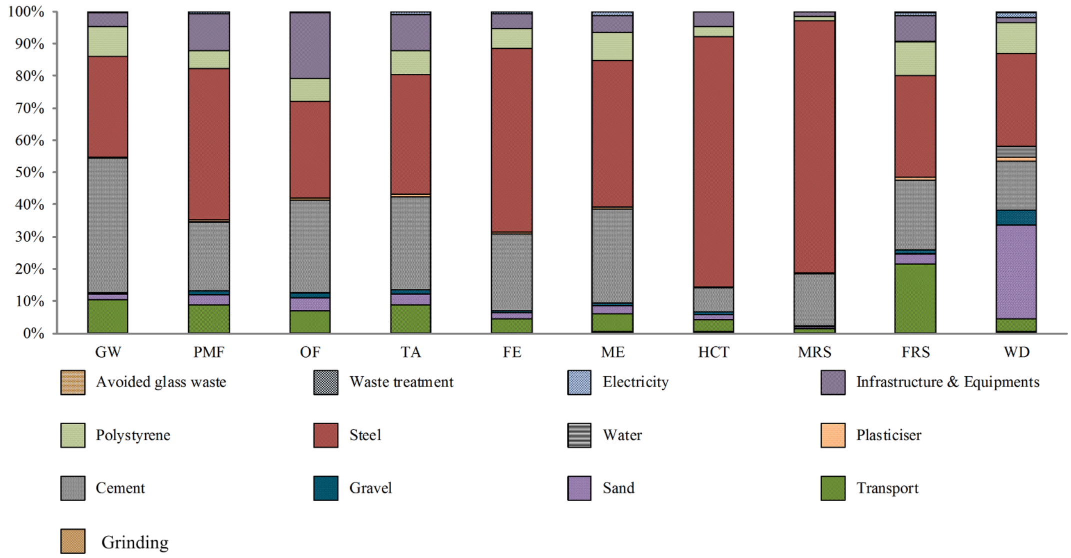

Fig. 4. Percentage contribution of each input to the total impact of the Glass reuse line for each impact category, referred to the selected FU.

Table 7
Comparison of characterized impacts in different transport scenarios and in the conventional production system, referring to the same FU.

Impact category	Unit	BAU[§]	Scenario I[#]	Scenario II*	Scenario III°
GW	kg CO_2 eq	6.79E+04	6.18E+04	6.09E+04	6.19E+04
PMF	kg PM 2.5 eq	7.33E+01	6.79E+01	6.70E+01	6.79E+01
OF	kg NO_x eq	1.63E+02	1.55E+02	1.52E+02	1.55E+02
TA	kg SO_2 eq	1.54E+02	1.43E+02	1.41E+02	1.43E+02
FE	kg P eq	1.36E+01	1.32E+01	1.31E+01	1.32E+01
ME	kg N eq	7.65E−01	7.27E−01	7.20E−01	7.29E−01
HCT	kg 1,4-DCB	3.71E+03	3.59E+03	3.57E+03	3.58E+03
MRS	kg Cu eq	9.41E+02	9.31E+02	9.28E+02	9.33E+02
FRS	kg oil eq	1.12E+04	9.08E+03	8.79E+03	8.95E+03
WD	m^3	4.68E+02	4.51E+02	4.48E+02	4.63E+02

[§] BAU = Glass reuse line with transport from ReSiELP primary data; [#]Scenario I = Glass reuse line with regional transport (100 km); * Scenario II = Glass reuse line without transport; ° Scenario III = Conventional production system with inputs transport according to the EcoInvent v.3.5 database.

(metallurgical grade), as well as to the high energy consumption in the heat treatment, which is absent in the FRELP process, and to the lack of energy recovery through the incineration of the polymeric fraction, such as in the case of the FRELP system. Therefore, although the ReSiELP process shows a higher level of competitiveness with respect to other recycling scenarios, its environmental performance can be further improved.

4. Conclusions

The large amount of cristalline-silicon photovoltaic modules to be disposed of in the next years requires the implementation of a circular value-chain to optimise the supply of raw materials (including critical ones) and to limit unnecessary waste. However, the urgent necessity to develop new recycling technologies cannot disregard an accurate evaluation of their environmental sustainability. The Life Cycle Assessment (LCA) perspective is widely acknowledged as providing a comprehensive picture of the environmental performance of a complex process. Therefore, in this study, a detailed LCA developed within the ReSiELP project and aimed at recovering secondary raw materials from photovoltaic panels, was carried out to evaluate the sustainability of a cutting edge treatment.

The achieved results show that the recovery of secondary materials makes the investigated photovoltaic recovery system advantageous from an environmental point of view, despite the loads generated by the implementation of the recycling treatment. In particular, the highest benefits come from the recovery of aluminum and, to a lesser extent, of copper. The relevance of higher recovery rates of secondary materials in producing more effective results in the environmental performance was also highlighted by the comparison with other recycling scenarios. In addition, the LCA results allow to identify the main hotspots of both the investigated subsystems, namely the Recovery line and the Glass reuse line. From a deeper analysis of the Recovery line it clearly appears that, in all the investigated impact categories, the highest loads are due to the electricity used for the heat treatment and for the abatement system. Therefore, an improvement in the energy consumption, would be advisable, for example, by reducing energy requirements, adopting renewable alternatives or generating energy from residual waste. The LCA analysis shows that also the environmental burden due to the use of acid and basic solutions in the hydrometallurgical treatment is significant. Therefore, the employment of such chemicals should be reduced or replaced with more eco-friendly reagents, to improve the environmental performance.

Concerning the Glass reuse line, in all the investigated impact categories, the production of cement and steel (as material components of the predalles) represents the main hotspots. The special focus carried out on the transportation issue was useful to show how the environmental sustainability of the process is sensitive to the travelled distances, suggesting the necessity of implementing the whole ReSiELP process (recovery and reuse) in the same plant.

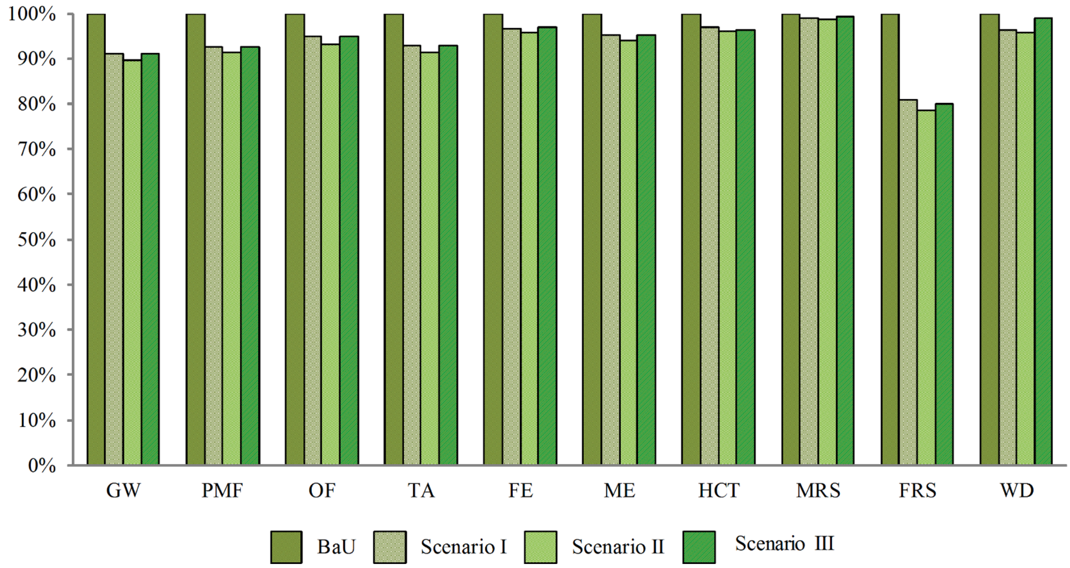

Fig. 5. Comparison of different transport scenarios in the Glass reuse line, referred to the selected FU.

Table 8
Characterized impacts of the ReSiELP system, including transport from the Recovery line to the Glass reuse line and the recovery of materials. Values are referred to the selected FU.

Impact category	Unit	Total	Recovery line	Glass reuse line	Transport
GW	kg CO_2 eq	−3.27E+03	−9.23E+03	−1.00E+03	6.96E+03
PMF	kg PM2.5 eq	−3.55E+01	−4.09E+01	−8.31E−01	6.31E+00
OF	kg NO_x eq	−3.42E+01	−4.21E+01	−2.48E+00	1.04E+01
TA	kg SO_2 eq	−6.93E+01	−8.03E+01	−2.13E+00	1.31E+01
FE	kg P eq	−2.67E+01	−2.71E+01	−1.25E−01	5.57E−01
ME	kg N eq	−2.42E+01	−2.43E+01	−8.81E−03	4.48E−02
HCT	kg 1,4-DCB	−9.13E+03	−9.26E+03	−1.34E+01	1.45E+02
MRS	kg Cu eq	−1.54E+03	−1.55E+03	−5.16E+00	1.29E+01
FRS	kg oil eq	2.77E+03	5.12E+02	−1.65E+02	2.42E+03
WD	m^3	−7.62E+02	−7.67E+02	−1.47E+01	1.98E+01

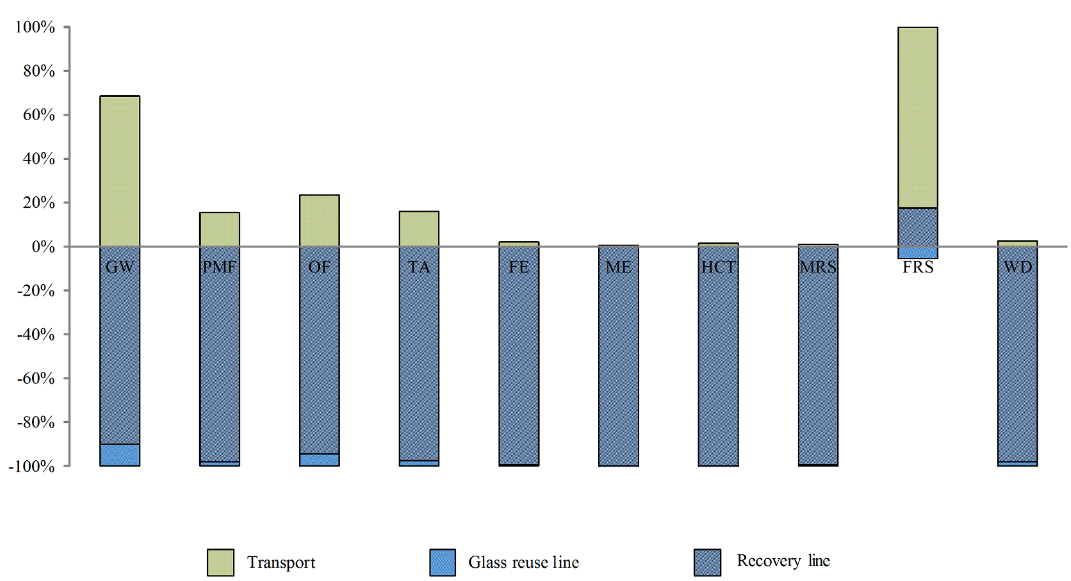

Fig. 6. Percentage contribution of each line and of transport from the Recovery line to the Glass reuse line to the overall environmental impacts of the ReSiELP system, referred to the selected FUs.

This study contributes to enhance the knowledge about the recycling processes of photovoltaic panels, using primary data provided at pilot scale. In so doing, it is possible to draw reliable information useful for: (i) improving more and more the photovoltaic panels recycling process design which, based on the lessons learned through the LCA studies, will avoid the hotspot phases as much as possible; (ii) helping policy makers to include in their support strategies those technologies and processes that are effectively able to contribute to sustainable development, and (iii) promoting the dissemination of the culture of recycling among professionals by showing its potential environmental benefits. Indeed, through the reuse of materials recovered from photovoltaic panels waste in the manufacture of new panels, a saving of energy requirement can be achieved, as demonstrated by the LCA results. Moreover, the supply of the raw materials needed in the production of new panels can rely on the secondary raw materials in a close loop. This, in turn, will contribute to further develop the photovoltaic sector and to make it even more environmentally sustainable, through the application of the circular economy principles.

CRediT authorship contribution statement

G. Ansanelli: Formal analysis, Investigation, Validation, Writing - review & editing. **G. Fiorentino:** Formal analysis, Investigation, Validation, Writing - review & editing. **M. Tammaro:** Conceptualization, Project administration, Funding acquisition. **A. Zucaro:** Formal analysis, Investigation, Validation, Writing - review & editing.

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.

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References

[1] Bahar H, Bojek P. Solar PV Tracking report - June 2020; 2020. Available at: https://www.iea.org/reports/solar-pv#tracking-progress [accessed 29 September 2020].
[2] IEA-PVPS. Task 1- 37:2020. Strategic PV Analysis and Outreach – 2020 Snapshot of Global PV Markets; 2020. https://iea-pvps.org/wp-content/uploads/2020/04/IEA_PVPS_Snapshot_2020.pdf [accessed 29 September 2020].
[3] IRENA and IEA-PVPS. End-of-Life Management: Solar Photovoltaic Panels. International Renewable Energy Agency and International Energy Agency Photovoltaic Power Systems; 2016. https://www.irena.org/documentdownloads/publications/irena_ieapvps_end-of-life_solar_pv_panels_2016.pdf [accessed 29 September 2020].
[4] Farrell C, Osman AI, Zhang X, Murphy A, Doherty R, Morgan K, et al. Assessment of the energy recovery potential of waste Photovoltaic (PV) modules. Sci Rep 2019;9:5267–79. https://doi.org/10.1038/s41598-019-41762-5.
[5] Tammaro M, Rimauro J, Fiandra V, Salluzzo A. Thermal treatment of waste photovoltaic module for recovery and recycling: experimental assessment of the presence of metals in the gas emissions and in the ashes. Renew Energy 2015;81:103–12. https://doi.org/10.1016/j.renene.2015.03.014.
[6] Malandrino O, Sica D, Testa M, Supino S. Policies and measures for sustainable management of solar panel end-of-life in Italy. Sustainability 2017;9(4):481–95. https://doi.org/10.3390/su9040481.
[7] Deng R, Chang NL, Ouyang Z, Chong CM. A techno-economic review of silicon photovoltaic module recycling. Renew Sust Energ Rev 2019;109:532–50. https://doi.org/10.1016/j.rser.2019.04.020.
[8] Tammaro M, Salluzzo A, Rimauro J, Schiavo S, Manzo S. Experimental investigation to evaluate the potential environmental hazards of photovoltaic panels. J Hazard Mater 2016;306:395–405. https://doi.org/10.1016/j.jhazmat.2015.12.018.
[9] Aryan V, Font-Brucart M, Maga D. A comparative life cycle assessment of end-of-life treatment pathways for photovoltaic backsheets. Prog Photovolt Res Appl 2018;26:443–59. https://doi.org/10.1002/pip.3003.
[10] Fthenakis VM. End-of-life management and recycling of PV modules. Energy Policy 2000;28:1051–8. https://doi.org/10.1016/S0301-4215(00)00091-4.
[11] Kang S, Yoo S, Lee J, Boo B, Ryu H. Experimental investigations for recycling of silicon and glass from waste photovoltaic modules. Renew Energ 2012;47:152–9. https://doi.org/10.1016/j.renene.2012.04.030.
[12] Dias PR, Javimczik S, Benevit M, Veit H, Bernardes AM. Recycling WEEE: Extraction and concentration of silver from waste crystalline silicon photovoltaic modules. Waste Manag 2016;57:220–55. https://doi.org/10.1016/j.wasman.2016.03.016.
[13] Dias PR, Benevit MG, Veit HM. Photovoltaic solar panels of crystalline silicon: Characterization and separation. Waste Manag Res 2016;34(3):235–45. https://doi.org/10.1177/0734242X15622812.
[14] Maurianne FA, Conte G, Ippolito NM, Medici F, Piga L, Santilli S. Photovoltaic module recycling, a physical and a chemical recovery process. Sol Energy Mater Sol Cells 2019;193:314–9. https://doi.org/10.1016/j.solmat.2019.01.035.
[15] Raw Material Information System (RMIS); 2020. http://rmis.jrc.ec.europa.eu/?page=policies-and-definitions-2d5b5e [accessed 29 September 2020].
[16] Dominguez A, Geyer R. Photovoltaic waste assessment of Mexico. Resour Conserv Recycl 2017;127:29–41. https://doi.org/10.1016/j.resconrec.2017.08.013.
[17] Dominguez A, Geyer R. Photovoltaic waste assessment of major PV installations in the United States of America. Renew Energy 2019;133:1188–200. https://doi.org/10.1016/j.renene.2018.08.063.
[18] Faircloth CC, Wagner KH, Woodward KE, Rakkwamsuk P, Gheewala SH. The environmental and economic impacts of photovoltaic waste management in Thailand. Resour Conserv Recycl 2019;143:260–72. https://doi.org/10.1016/j.resconrec.2019.01.008.
[19] European Commission (EC). Commission Staff Working Document - Report on Critical Raw Materials and the Circular Economy. SWD 2018:36 final.
[20] The Silver Institute. https://www.silverinstitute.org/silver-demand-3/ [accessed 29 September 2020].
[21] FIRE - Federazione Italiana per l'uso Razionale dell'Energia. Guida al fine vita degli impianti fotovoltaici. https://www.fire-italia.org/prova/wp-content/uploads/2014/03/Guida-al-fine-vita-degli-impianti-fotovoltaici.pdf [accessed 29 September 2020].
[22] Yamashita K, Umemoto A, Okamoto K. Research and development on recycling and reuse treatment technologies for crystalline silicon photovoltaic modules. 3rd World Conf Photovolt Energy Convers, 11-18 May 2003, 2003. p. 1996–1999.
[23] Cucchiella F, D'Adamo I, Rosa P. End-of-Life of used photovoltaic modules: a financial analysis. Renew Sustain Energy Rev 2015;47:552–61. https://doi.org/10.1016/j.rser.2015.03.076.
[24] Choi J-K, Fthenakis V. Crystalline Silicon Photovoltaic Recycling Planning: Macro and Micro Perspectives. J Clean Prod 2014;66:443–9. https://doi.org/10.1016/j.jclepro.2013.11.022.
[25] Katsigiannis Y, Rentoumis M, Katsamaki A, Chatzikokolaki A, Bilalis N. Estimation of Quantities of Waste Materials for Photovoltaic Installations in Crete Island. Int J Manufact Industr Eng 2014;1(3):18–22. ISSN 2374 – 1589.
[26] Ilias AV, Rentoumis GM, Katsigiannis AY, Bilalis N. Integration & assessment of recycling into c-Si photovoltaic module's life cycle. Int J Sustain Eng 2018;11(3):186–95. https://doi.org/10.1080/19397038.2018.1428833.
[27] Tao J, Yu S. Review on feasible recycling pathways and technologies of solar photovoltaic modules. Sol Energy Mater Sol Cells 2015;141:108–24. https://doi.org/10.1016/j.solmat.2015.05.005.
[28] Xu Y, Li J, Tan Q, Peters AL, Yang C. Global status of recycling waste solar panels: A review. Waste Manag 2018;75:450–8. https://doi.org/10.1016/j.wasman.2018.01.036.
[29] Pern J. Module encapsulation materials, processing and testing. In: APP international PV reliability workshop, Shanghai, China, 4–5 December 2008; 2008. Available at: http://www.nrel.gov/docs/fy09osti/44666.pdf [accessed 29 September 2020].
[30] Brouwer K, Gupta C, Honda S, Zargarian M. Methods and concerns for disposal of photovoltaic solar panels. Project Report, Master of Science in Engineering, San

Jose State University, San Jose; 2011. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.456.5648&rep=rep1&type=pdf [accessed 29 September 2020].

[31] Granata G, Pagnanelli F, Moscardini E, Havlik T, Toro L. Recycling of photovoltaic panels by physical operations. Sol Energy Mater Sol Cells 2014;123:239–48. https://doi.org/10.1016/j.solmat.2014.01.012.

[32] Zhang L, Xu Z. Separating and Recycling Plastic, Glass, and Gallium from Waste Solar Cell Modules by Nitrogen Pyrolysis and Vacuum Decomposition. Environ Sci Technol 2016;50:9242–50. https://doi.org/10.1021/acs.est.6b01253.

[33] Pagnanelli F, Moscardini E, Granata G, Abo Atia T, Altimari P, Havlik T, et al. Physical and chemical treatment of end of life panels: An integrated automatic approach viable for different photovoltaic technologies. Waste Manag 2017;59:422–31. https://doi.org/10.1016/j.wasman.2016.11.011.

[34] Shin J, Park J, Park N. A method to recycle silicon wafer from end-of-life photovoltaic module and solar panels by using recycled silicon wafers. Sol Energy Mater Sol Cells 2017;162:1–6. https://doi.org/10.1016/j.solmat.2016.12.038.

[35] Mahmoudi S, Huda N, Alavi Z, Islam MT, Behnia M. End-of-life photovoltaic modules: A systematic quantitative literature review. Resour Conserv Recycl 2019;146:1–16. https://doi.org/10.1016/j.resconrec.2019.03.018.

[36] Giacchetta G, Leporini M, Marchetti B. Evaluation of the environmental benefits of new high value process for the management of the end of life of thin film photovoltaic modules. J Clean Prod 2013;51:214–24. https://doi.org/10.1016/j.jclepro.2013.01.022.

[37] Müller A, Wambach K, Alsema E. Life Cycle Analysis of a Solar Module Recycling Process. 20th European Photovoltaic Solar Energy Conference, 6–10 June 2005, Barcelona, Spain; 2005. https://doi.org/10.1557/PROC-0895-G03-07.

[38] Berger W, Simon FG, Weimann K, Alsema EA. A novel approach for the recycling of thin film photovoltaic modules. Resour Conserv Recy 2010;54:711–8. https://doi.org/10.1016/j.resconrec.2009.12.001.

[39] Latunussa CEL, Ardente F, Blengini GA, Mancini L. Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels. Sol Energy Mater Sol Cells 2016;156:101–11. https://doi.org/10.1016/j.solmat.2016.03.020.

[40] Ardente F, Latunussa CEL, Blengini GA. Resource efficient recovery of critical and precious metals from waste silicon PV panel recycling. Waste Manag 2019;91:156–67. https://doi.org/10.1016/j.wasman.2019.04.059.

[41] Huang B, Zhao J, Chai J, Xue B, Zhao F, Wang X. Environmental influence assessment of China's multi-crystalline silicon (multi-Si) photovoltaic modules considering recycling process. Sol Energy 2017;143:132–41. https://doi.org/10.1016/j.solener.2016.12.038.

[42] Vellini M, Gambini M, Prattella V. Environmental impacts of PV technology throughout the life cycle: Importance of the end-of-life management for Si-panels and CdTe-panels. Energy 2017;138:1099–111. https://doi.org/10.1016/j.energy.2017.07.031.

[43] Corcelli F, Ripa M, Leccisi E, Cigolotti V, Fiandra V, Graditi G, et al. Sustainable urban electricity supply chain – Indicators of material recovery and energy savings from crystalline silicon photovoltaic panels end-of-life. Ecol Indic 2018;94(3):37–51. https://doi.org/10.1016/j.ecolind.2016.03.028.

[44] Lunardi MM, Alvarez-Gaitan JP, Bilbao JI, Corkish R. Comparative Life Cycle Assessment of End-of-Life Silicon Solar Photovoltaic Modules. Appl Sci 2018;8:1396–410. https://doi.org/10.3390/app8081396.

[45] Contreras-Lisperguer R, Muñoz Cerón E, de la Casa Higueras J, Díaz Martín R. Environmental Impact Assessment of crystalline solar photovoltaic panels' End-of-Life phase: Open and Closed-Loop Material Flow scenarios. Sustain Prod Consum 2020;23:157–73. https://doi.org/10.1016/j.spc.2020.05.008.

[46] Corcelli F, Fiorentino G, Petit-Boix A, Rieradevall J, Gabarrell X. Transforming rooftops into productive urban spaces in the Mediterranean. An LCA comparison of agri-urban production and photovoltaic energy generation. Resour Conserv Recycl 2019;144:321–36. https://doi.org/10.1016/j.resconrec.2019.01.040.

[47] Del Pero F, Delogu M, Berzi L, Escamilla M. Innovative device for mechanical treatment of End of Life photovoltaic panels: Technical and environmental analysis. Waste Manag 2019;95:535–48. https://doi.org/10.1016/j.wasman.2019.06.037.

[48] Stolz P, Frischknecht R, Wambach K, Sinha P, Heath G. Life Cycle Assessment of Current Photovoltaic Module Recycling, IEA PVPS Task 12, International Energy Agency Power Systems Programme, Report IEA-PVPS T12-13:2018; 2017. https://iea-pvps.org/wp-content/uploads/2020/01/Life_Cycle_Assesment_of_Current_Photovoltaic_Module_Recycling_by_Task_12.pdf.

[49] ISO 14040. ISO, International Standard. Environmental Management and Life Cycle Assessment and Principles and Framework. International Organization for Standardization, Geneva, Switzerland; 2006.

[50] ISO 14044. ISO, International Standard. Environmental Management - Life Cycle Assessment - Requirements and Guidelines. International Organization for Standardization, Geneva, Switzerland; 2006.

[51] ILCD Handbook, European Commission, Joint Research Centre and Institute for Environment and Sustainability, "International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance", First edition March 2010. EUR 24708 EN. Luxembourg. Publications Office of the European Union; 2010.

[52] Ekvall T, Assefa G, Björklund A, Eriksson O, Finnveden G. What life-cycle assessment does and does not do in assessments of waste management. Waste Manage. (Oxford) 2007;27:989–96.

[53] Continental website: https://www.continental-pneumatici.it/truck-autobus/press/news/la-distanza-media-nel-2018 [accessed 29 September 2020].

[54] Sinha P, Cossette M, Ménard J-F. End-of-Life CdTe PV Recycling with Semiconductor Refining, In: 27th European Photovoltaic Solar Energy Conference and Exhibition; 2012. p. 4353–6. doi: 10.4229/27thEUPVSEC2012-6CV.4.9.

[55] EcoInvent, "The EcoInvent Database,". https://www.ecoinvent.org/database/database.html [accessed 29 September 2020].

[56] Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B. The EcoInvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess 2016;21:1218–30. https://doi.org/10.1007/s11367-016-1087-8.

[57] Goedkoop M, Heijungs R, Huijbregts M, De Schryver A, Struijs J, van Zelm R. ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and endpoint levels. First edition. Report I: Characterization, The Netherlands: Ruimte en Milieu, Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer; 2009.

[58] Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira MDM, et al. ReCiPe 2016 v1.1: A harmonized life cycle impact assessment method at midpoint and endpoint level. Report I: Characterization. RIVM Report 2016-0104, National Institute for Public Health and the Environment; 2017.

[59] Frischknecht R, Jungbluth N, Althaus H-J, Doka G, Dones R, Heck T, et al.. Overview and Methodology. Final report ecoinvent v2.0 No. 1, Swiss Centre for Life Cycle Inventories, Dübendorf, CH. Retrieved from: www.ecoinvent.org; 2007.