Innovative device for mechanical treatment of End of Life photovoltaic panels: Technical and environmental analysis

Original Citation:

Innovative device for mechanical treatment of End of Life photovoltaic panels: Technical and environmental analysis / Del Pero F.; Delogu M.; Berzi L.; Escamilla M.. - In: WASTE MANAGEMENT. - ISSN 0956-053X. - ELETTRONICO. - 95:(2019), pp. 535-548. [10.1016/j.wasman.2019.06.037]

Published version:

DOI: 10.1016/j.wasman.2019.06.037

Final published version is available at:
https://doi.org/10.1016/j.wasman.2019.06.037

Manuscript Draft

Title: Innovative device for mechanical treatment of End of Life photovoltaic panels: technical and environmental analysis

Article Type: Full Length Article

Section/Category: Environmental Assessment

Keywords: End-of-Life; Photovoltaic panels; Mechanical treatment; Recycling; Recovery; Environmental impact

Corresponding Author: Dr. Francesco Del Pero, Ph.D.

Corresponding Author's Institution: Department of Industrial Engineering - University of Florence

First Author: Francesco Del Pero, Ph.D.

Order of Authors: Francesco Del Pero, Ph.D.; Massimo Delogu; Lorenzo Berzi; Marta Escamilla

Abstract: The paper contributes at filling the lack of knowledge on Photovoltaic (PV) panels recycling through the analysis of a mobile mechanical treatment plant developed within the context of a European project. The process, the machinery installed in the system and their main functionalities are described. The data are used to perform a Life Cycle Assessment (LCA) focused on the End-of-Life (EoL) process, assuming as Functional Unit (FU) the treatment of a 20 kg PV panel. The system boundaries include construction and operation of the device as well as recycling and incineration of different material fractions performed outside the plant. The inventory is mainly based on primary data coming from a collection carried out directly on the recycling device. The results show that impacts are concentrated on operation stage mainly due to energy consumption involved in milling and separation activities. The analysis of different operation steps reveals that pre-treatment gives the highest contribution, followed by glass and silicon separation with the lowest quota attributable to copper and polymeric fraction separation. Considering also recycling and incineration processes of EoL waste, the environmental credits due to the avoided production of virgin raw materials counterbalance the burdens of construction and operation for most of impact categories. The comparison of results with existing LCAs of fixed recycling installations stresses that the use of a mobile system involves considerable environmental benefits thanks to the reduction of transports needed to move EoL PV waste to the recycling facility site.

Innovative device for mechanical treatment of End of Life photovoltaic panels: technical and environmental analysis

Francesco Del Pero[a], Massimo Delogu[a], Lorenzo Berzi[a], Marta Escamilla[b]

[a] Department of Industrial Engineering, University of Florence, Via di Santa Marta 3, 50139 Florence, Italy
[b] Leitat Technological Centre, C/ de la Innovació, 2, 08225 Terrassa Barcelona, Spain

ABSTRACT

The paper contributes at filling the lack of knowledge on Photovoltaic (PV) panels recycling through the analysis of a mobile mechanical treatment plant developed within the context of a European project. The process, the machinery installed in the system and their main functionalities are described. The data are used to perform a Life Cycle Assessment (LCA) focused on the End-of-Life (EoL) process, assuming as Functional Unit (FU) the treatment of a 20 kg PV panel. The system boundaries include construction and operation of the device as well as recycling and incineration of different material fractions performed outside the plant. The inventory is mainly based on primary data coming from a collection carried out directly on the recycling device. The results show that impacts are concentrated on operation stage mainly due to energy consumption involved in milling and separation activities. The analysis of different operation steps reveals that pre-treatment gives the highest contribution, followed by glass and silicon separation with the lowest quota attributable to copper and polymeric fraction separation. Considering also recycling and incineration processes of EoL waste, the environmental credits due to the avoided production of virgin raw materials counterbalance the burdens of construction and operation for most of impact categories. The comparison of results with existing LCAs of fixed recycling installations stresses that the use of a mobile system involves considerable environmental benefits thanks to the reduction of transports needed to move EoL PV waste to the recycling facility site.

Keywords: End-of-Life, Photovoltaic panels, Life Cycle Assessment, Recycling, Recovery, Environmental impact.

Acronyms used in the text

CdTe: Cadmium/Tellurium based materials
Disposal: process as defined in Directive 2008/98/EU definition
EoL: End of Life
EVA: Ethylene-vinyl acetate polymer
FU: Functional unit
LCA: Life Cycle Assessment
LCI: Life Cycle Inventory
LCIA: Life Cycle Impact Assessment
LME: La Mia Energia (Company)
PV: Photovoltaic
PV–MOREDE: Photovoltaic Panels Mobile Recycling Device (Project)
Recovery: process as defined in Directive 2008/98/EU definition
Recycle: process as defined in Directive 2008/98/EU definition
WEEE: Waste from Electric and Electronic Equipment
WtE: Waste to Energy

1. Introduction

Our global society is strongly dependent on natural resources consumption involved in production and operation of consumer goods (Hawkins at al., 2012; Delogu et al., 2016). At the same time the disposal of End-of-Life (EoL) products represents one of the most challenging sustainability aspects (Tian and Chen, 2014; Pagnanelli et al., 2016). In the last years, the need for environmentally friendly processes has been fast growing in several different areas, the most influential being transportation (Banar and Özdemir, 2015; Del Pero et al., 2017) and energy production (Somorin et al., 2017; Stenzel et al., 2017). Considering energy production systems, Photovoltaic (PV) panels technology is providing a fundamental contribution to the shift from traditional fossil fuels to renewable energy sources. Solar panels have been installed since the eighties but it is during the past decade that PV market has expanded exponentially with a world cumulative installed capacity of 402.5 GW in 2017, of which about 28% is installed in Europe (EPIA, 2014; IEA, 2018). Further growth is expected, which could lead to 530 GW installed capacity at the end of 2019 according to recent assessment (SPE, 2018). Today energy coming from PV panels is one of the most promising renewable sources and forecasts for subsequent decades expect that it will provide up to 25 % of the global electricity demand by 2050 (Dias et al., 2017; Silva et al., 2014; Zuser and Rechberger, 2011).

Following such installation rate for PV systems, a parallel growth of e-waste coming from the sector is expected. According to International Renewable Energy Agency data (IRENA 2018), the approximate life-span of solar panels is

estimated in the range of 30 years; however, effective life can differ since early substitution are possible due to so called "infant", "mid-life" and "wear out" failures (Weckend et al., 2016). Therefore, the amount of PV waste on a global scale is estimated to pass from the current 870 t/y to a level of at least 1.5 million t/y in 2030, with a worst case prediction of 8 million t/y. Other authors confirm a growth determining the need to process more than 2 million t/y in 2038 (Jung et al., 2016). For 2050 scenarios, IRENA predictions provide an estimation of 60 to 78 million t/y of EoL PV panels to be processed. Amongst various reasons for which landfilling of PV panels is not an option, a relevant observation is that many products contain hazardous materials (such as lead, cadmium and bismuth) but also high-value elements (such as silver, titanium, tellurium) (Marwede and Reller, 2012; Savvilotidou et al., 2017); the content depends on the technology adopted by the panel. In this regard, the study by BioIS (BioIS, 2011) evidences the environmental issues related to the improper disposal of solar panels, such as leaching of hazardous substances and losses of both conventional and precious material resources. The introduction of efficient recovery systems for EoL modules would involve two main beneficial effects. On one hand the use of recycled materials for the production of new panels would strongly reduce the need for virgin resources; on the other hand, the development of specific EoL treatments would avoid the dispersion in the environment of dangerous materials typical of PV modules. Regarding the characteristics of panels installed up to now and the prevision for next years, it has to be considered that PV industry is constantly being developed, thus leading to a possible modification of technologies and solutions adopted for modules. Indeed, performance analyses of polycrystalline silicon PV panels in comparison with thin-film PV panels highlight that the effective potential for energy production and profitability depends not only on maximum efficiency but also on the overall condition of installation (Munshi et al., 2018). Therefore, according to recent efficiency growth estimations for various technologies (IRENA, 2018) a definitive PV module technology strategy remains difficult to predict. From an End-of-Life (EoL) point of view, this means that it is worth to investigate on treatment technologies for all the PV families. Crystalline silicon-based cells, for example, currently represent a predominant share of the market (Lee and Ebong, 2017) so that, given a certain time-delay from installation, a large amount of elements will need EoL treatment. Regarding other notable technologies such as CdTe-based panels, the potential release of toxic substances on the environment EoL stage has been demonstrated to be particularly worrying (Ramos-Ruiz et al., 2017). As a consequence, even if a favorable overall environmental impact is assessed, EoL treatment different from landfilling is advisable (Vellini et al., 2017; Tao and You, 2015). Other authors are stating that the risk of toxic contamination is not critical even in case of landfilling, but their analysis still highlights the importance of recycling due to the favorable environmental impact of secondary raw material production (Rocchetti and Beolchini, 2015). Another important point is the European regulatory framework of PV panels EoL (Directive 2012/19/EU; Contreras-Lisperguer et al., 2017). For solar modules, the regulation fixes collection rate up to 85% and recycling rate up to 80%. As European manufacturers and distributors are legally obliged to guarantee take-back, recovery, and recycling of their products, the last years have seen a great improvement in efficient collection programs and recovery processes for PV panels. Therefore PV recycling is justified not only on the basis of mere economic feasibility or environmental assessment, but it is mandatory, even if the implementation of the regulation is still affected by significant barriers (Besiou et Wassenhove, 2015). The approach is coherent with "waste hierarchy" criteria (Directive 2008/98/EU) and to other binding regulations (such as those for End of Life Vehicles, see Berzi et al., 2013).
Considering the economic aspect, various framework for economic profitability assessment have been proposed but they appear to be still affected by uncertainties of data which are difficult to assess with precision (Perez-Gallardo et al., 2018; Duflou et al., 2018). The reduction of plant cost for WEEE treatment is a relevant condition for effective economic operation (Cucchiella et al., 2016). Regarding the general category of WEEE, a few examples of portable recycling plants are described in literature; such treatment plants are characterized by small capacity and treatment rate, in the range of a few tons per hour or even less. Small plants have been proposed in order to achieve multiple targets, such as reducing the investment needed for installation, enhancing the availability of recycling plants over territories, reducing material transport needs, setting up highly specialized processes which can be suitable for relatively small waste flows; a few examples of such systems will be described in the next paragraph.

The document contents following the introduction to the topic are organized as follows: section 1 provides a description of the international context of PV panel recycling. Section 2 describes PV-MOREDE plant in detail, also summarizing data used for impact assessment (LCA) analysis. Section 3 presents the results of the activity. Section 4 contains concluding observation.

1.1. Recycling plants for EoL photovoltaic panels

The literature provides numerous studies regarding the EoL of solar panels (Jungbluth et al., 2005, 2012; Klugmann-Radziemska et al., 2010b). Several papers (Dias et al., 2016; Gustafsson et al., 2014; Klugmann-Radziemska and Ostrowski, 2010a) propose panels EoL routes based on two steps: a physical treatment (made up of shredding and thermal process) and a thermo-chemical treatment (mainly based on ethylene-vinyl-acetate degradation and recovery through pyrolysis). Further researches focus on alternative procedures for the extraction of resources from EoL solar panels, such as organic solvent methods to recycle silicon cells used for conventional crystalline silicon PV modules (Kanga et al., 2012; Doi et al., 2001). These studies show that recycling and recovery rates are comprised within 80 and 90 % depending on the specific material (silicon, copper, silver) with a value of more than 99% recoverability for the polymeric ones. Potential values for glass recyclability if treated using proper physical processes are demonstrated to be in the range of 80-85%, considering direct recycling as glass, while further 10% (corresponding to fraction finer than 0.08 mm) is estimated to be recoverable or recyclable through other processes (Granata et al., 2014). Therefore, an highlight coming from literature is that the process of PV shredding and physical treatment is critical, since the undesirable reduction of glass into small fines is potentially reducing the direct recyclability.

The studies hitherto presented deal with the development of PV panels recycling processes exclusively from a technical point of view, without taking into account the eco-profile of the proposed methods. On the other hand, many papers investigate the environmental impacts of the production and use of PV technologies as confirmed by some review articles that deal with the topic (Bhat Varun et al., 2011; Evans at al., 2009; Hsu et al., 2012; Peng et al., 2013; Shervani et al., 2010). Frisson et al. (2000) perform a comparison based on energy consumption of a standard PV panel and one built using recycled wafers; the results show that the recycled wafer panel can lead to 40 % lower impacts. Frankl et al. (2005) investigate the production of electricity by different PV technologies. The authors find that decommissioning and disposal of a ground mounted PV plant represents roughly 4 % of total Life Cycle (LC) greenhouse gas emissions while other impact categories present lower impacts. Shibasaki et al. (2006) investigate the production of 1 GJ of electricity produced by thin film solar modules. The research takes into account the impacts related to the recycling technology which includes module delamination, removal of the EVA layer, removal and recycling of metals. The study reveals significant environmental advantages of thin film PV modules compared to conventional energy supplying systems. Even if the relative environmental burdens are reduced, the impact expressed as absolute value is potentially significant according to the expected growth of EoL panel arising in next decades. Additionally, the high impact of PV panels EoL stage and the mandatory compliance with WEEE directive (Directive 2012/19/EU) highlight the need to improve recyclability methods. Held and Ilg (2011) perform the Life Cycle Assessment (LCA) of the recycling of 1 m^2 CdTe PV modules basing on the “First Solar” process as a sequence of mechanical and hydrometallurgical treatments (First Solar, 2019). The results prove that solar power involves a notable environmental advantage with respect to the country specific grid mixes. Wild-Scholten (2009) estimates some draft figures of energy consumption involved in PV panels recycling. The author calculates that 250 MJ, 240 MJ and 150 MJ are needed for the taking back and recycling respectively of mono-Si, multi-Si and CdTe PV devices. Rocchetti et al. (2013) and Zeng et al. (2015) deal with portable e-waste recycling plants. Rocchetti et al. (2013) present a mobile plant installed in a container lorry that processes e-waste residues through a hydrometallurgical process while Zeng et al. (2015) deal with an integrated mobile e-waste recycling facility which combines dismantling, shredding and multi-level separation. These studies show that valuable resources such as metals, plastic and glass can be fully separated for further recycling, thus leading to remarkable benefits in terms of environmental protection and human health.

All the studies shown above do not consider the EoL stage since information regarding PV modules decommissioning and recycling/disposal are lacking or the researches do not provide disaggregated information on the considered recycling processes. A brief selection of papers that thoroughly examine the Eol of PV panels are Muller et al. (2005), Fraunhofer Institut (2012) and, more recently, Carnevale et al. (2014), Corcelli et al. (2015) and Latunussa et al. (2016). Muller et al., 2005 provide an environmental analysis concerning the EoL treatments of crystalline silicon PV modules according to the “Deutsche Solar” recycling process. The study shows that even if the environment is damaged by the inputs and outputs of the recycling process, the reuse of panels implies notable environmental advantages in terms of CO_2/SO_2 emissions and resources depletion due to the avoided production of new cells. The research also compares the impacts of the “Deutsche Solar” recycling process to the treatment in a municipal incineration plant and to the shredding. The results show that the incineration and the shredding involve lower impacts, but also lower recyclability rates. The authors justify these results with the different scale of incineration plant and recycling facility. The major limitation of the study is that it does not explicitly declare material and energy input/output flows occurring in the investigated processes. The research by Fraunhofer Institut (Fraunhofer Institut, 2012) performs a LCA analysis of a recycling plant for EoL silicon modules. The first step of the treatment is the manual removal of aluminum frames and junction boxes. Then the pre-treated modules are shredded and subsequently they enter the glass recycling line which performs manual pre-sorting, laminates shredding, separation and materials extraction. Finally, the mix is separated according to the different material fractions. The outcomes show that treatment activities have a much lower impact than the potential credits achievable through the recycling of valuable materials. The study also stresses the significant influence that transport activities have on eutrophication and photochemical ozone creation impact categories. The authors evidence also that the recycling facility presents a low level of technological innovation and that it does not allow a cost-effective recycling process for precious material fractions. Carnevale et al. (2014) perform a LCA comparison between photovoltaic (both silicon based and thin film modules) and solar thermal systems including EoL examination. The results highlight that the systems based on thermal solar collector are environmentally preferable while thin film modules and solar thermal collector present the lowest values of energy and CO_{2eq} payback time. On the other hand, the emissions and energy saving associated to material recycling are relevant, especially for Si-based modules. Corcelli et al., 2015 deal with an LCA applied to a laboratory-scale recycling process for silicon PV modules based on thermal treatment. The authors build a scale-up scenario in order to assess the effective environmental convenience of thermal treatment with respect to physical and chemical ones; different recycling scenarios according to

lower and higher recycling/recovery rates are taken into account. The LCA is performed by means of the SimaPro software and the ReCiPe (H) midpoint is used for the impact assessment. The results are shown in aggregated and normalized form, without the detail of the specific treatment steps. The study reveals negative environmental impacts due to credits obtainable thanks to materials recycling. The authors conclude that recycling ensures the supply chain sustainability in the long-term by enhancing potential credits for secondary materials production. Latunussa et al., 2016 deal with the LCA of an innovative process for the recycling of silicon PV panels. The process is composed of physical (mechanical and thermal) and chemical (acid leaching and electrolysis) treatments. The focus of the paper is the environmental impact due to the recycling treatment while credits coming from the potential production of secondary raw materials are outside the system boundaries of the study. The research provides transparent and disaggregated data for each stage of the recycling process. The authors stress that the impacts are mainly due to the incineration of the panel encapsulation layers followed by the recovery of silicon metal, silver, copper and aluminum; the contribution of transportation is also relevant for several impact categories.
The review of environmental studies of EoL PV modules recycling treatments highlights the following issues:

- Many relevant studies are type tailored, as they take into account EoL treatments for specific typologies of solar panels, mainly crystalline silicon and Cd-Te modules (Kanga et al., 2012; Held and Ilg, 2011; Xu et al., 2018). The existing processes developed specifically for PV panels recycling are based on fixed plants.
- The LCAs from literature do not always investigate in detail the inventories related to the considered treatment systems. Data such as energy consumption, efficiency of recycling and recyclability/recoverability rates are still under investigation, while many treatments are only described as laboratory process, still not consolidated at industrial level (Bogacka et al., 2017; Pagnanelli et al., 2017).
- A direct comparison of EoL assessment data between different literature studies is often not possible due to the adoption of different boundary conditions, such as FU, system definition and input materials considered;,
- Several LCA studies deal with the environmental impacts due to the production and use of PV technologies. Even though EoL is recognized as a critical phase for the LCA of solar panels, the accurate analysis of this phase is often excluded from the system boundaries or roughly estimated (Fraunhofer Institut, 2012; Corcelli et al., 2015; Latunussa et al., 2016). Only a few papers examine the EoL of solar modules (Carnevale et al., 2014; Corcelli et al., 2015). However, these studies focus only on potential reuse and they do not investigate in detail the LCI as well as the environmental effects of materials recycling. Additionally, the information about the efficiency of PV panels EoL processes and the achievable recycling/recovery rates are generally lacking or quite incomplete.

This article performs the LCA of an innovative recycling process for EoL PV panels conceived and calibrated to be used for mechanical recycling of crystalline-silicon based modules. The size of the plant is quite small and it is chosen in order to make it tailored on the PV technology. The innovation is that the process is based on a mobile plant which can operate in different locations over its life-time treating on-site and on demand modules characterized by different composition/structure, thus representing a flexible and easily accessible alternative with respect to current fixed waste systems. The system has been developed within the context of the European project "Photovoltaic panels Mobile Recycling Device" (PV-MOREDE) and it has been constructed by the Italian company "La Mia Energia" (LME). The study is built on a detailed LC inventory mostly based on primary data and it is aimed at filling the lack of knowledge regarding the environmental benefits achievable by PV waste recycling.

2. Materials and method

The LCA methodology is applied to the PV-MOREDE pilot scale process for the recycling of solar panels. The LCA is performed according to the ISO standards 14040, 14044 (ISO 14040/14044, 2006) and the ILCD handbook (Hiederer et al., 2011). The study is described in detail in the following paragraphs.

2.1. Goal and scope

The scope of the study is assessing the potential environmental impacts of the PV-MOREDE recycling process and identifying the main hotspots related to its operation. The Functional Unit (FU) is the recycling of a 20 kg EoL PV panel (an average value observed on EoL panels) assuming a plant processing capacity of 0.8 t/h and 8 years as service life-time. The processing capacity was assessed through preliminary operability test on the machine. Regarding plant life, two main elements are used for the estimation:

- considering a yearly depreciation value of 12% (suitable for generic industrial machinery, according to Italian system – see DM 31/12/1988) 8 years corresponds to zero residual value. In absence of other references, the authors consider that this is a suitable assumption for the European context;
- since the whole PV-MOREDE project is motivated by the aim of promoting the machine on the market, an investigation among potential buyers was performed. According to such confidential contacts, 8 years life is indicated as a minimum requirement for the recycling system.

The study is based on a “cradle-to-gate” approach; the system boundaries includes construction of the PV-MOREDE plant up to the operation stage, including recovery and disposal processes of EoL PV waste. Table 1 reports the mass composition of the 20 kg panel taken into account for the study. Even if panels are coming from different manufacturers, significant differences in terms of mass or dismantlability have not been found during the testing of the system. However, a certain variability is expected depending on panel manufacturer, age and technology.

Component	**Quantity [kg]**	**Percentage [%]**
Glass	13.60	68.0
Frame (aluminum)	4.00	20.0
Polymer-based adhesive (EVA) encapsulation layer	1.10	5.5
Solar cell (silicon metal)	0.70	3.5
Back-sheet layer (Polyvinyl Fluoride)	0.20	1.0
Cables (copper and polymers)	0.20	1.0
Conductor (aluminum, copper)	0.16	0.8
Metals (silver, lead, tin)	0.04	0.2
Total	**20.00**	**100.0**

Table 1. Mass composition of the 20 kg PV panel as input to the PV-MOREDE recycling process. Data are adapted from literature (Latunussa et al., 2016)

The construction takes into account the environmental impacts due to the manufacturing of the entire PV-MOREDE system in terms of material/energy consumption, emissions to the environment and waste production. This stage includes also transportation of the different plant components from the suppliers to the assembly facility site as well as the transportation of PV-MOREDE plant to the operation site.

The operation stage assesses the impacts, which are originated by energy and materials consumption, as well as the emissions to the environment due to the treatments performed within the plant. The operation of the PV-MOREDE process is divided into four steps: pre-treatment, glass separation, silicon separation and copper & polymeric fraction separation. The potential environmental impacts and credits related to further processing of materials (e.g. Aluminum to foundry, Glass production from cullet, residuals to WtE) have been included since PV-Morede systems is enabling such recycling and recovery processes. Therefore, the system boundaries of the EoL stage of PV waste include all the EoL processes performed outside the PV-MOREDE plant:

- transportation of PV waste materials to recovery facilities;
- recycling of different material fractions separated within the PV-MOREDE system (mainly recycling of aluminum, copper, glass, Silicon-rich fractions; segregation of polymeric and residual fractions);
- incineration with energy recovery of polymeric fraction (including polymers, elastomers and organic materials in general). The amount of energy produced is considered a co-product of the recycling process and it is modeled through an “incineration with energy recovery” process which implies both an environmental credit (due to energy production) and an environmental impact (due to incineration emissions).

The study does not take into account the decommissioning of the recycling system.

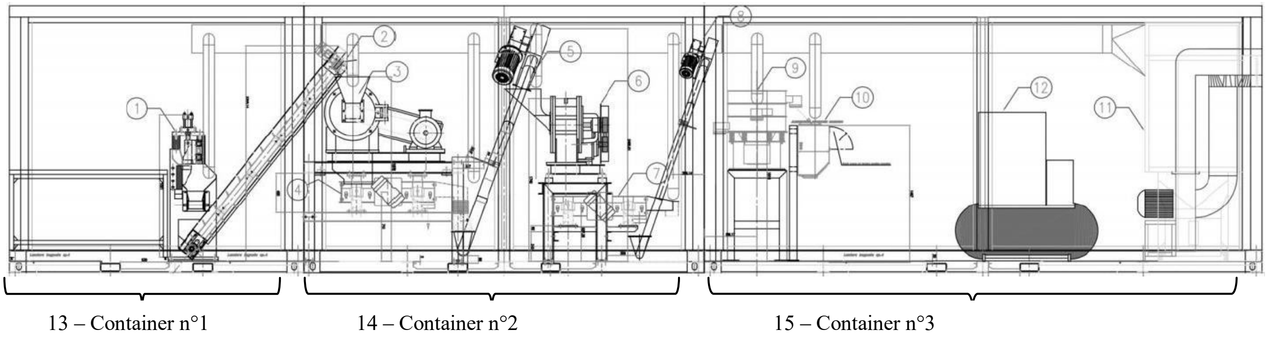
2.2. Life Cycle Inventory (LCI)

2.2.1. Description of the recycling process

The PV-MOREDE system consists of a mobile device that guarantees a complete treatment of solar panels directly in the installation site and it is able to treat any type of Mono and polycrystalline PV panels. The pilot scale plant has a processing capacity of 0.8 t/h and 8 years service life-time. The system is aimed at reducing the panels into small parts in order to enable recycling through proper segregation of different materials. As the plant is conceived and designed to be transported within the limits of ordinary freight vehicles, all the machineries are arranged in three containers disposed in a single line, thus allowing a continuous treatment process after being assembled.

The system is conceived for mono and polycrystalline panel type. The results of the study are expected not to vary significantly between different PV panels manufacturers. A strong attention is paid on calibration of the separation system of back-sheet polymers. In case that new technologies arise in the future (e.g. substitution of Tedlar-based back-sheets with others), the expectation is that the system can be adapted with proper set-up and substitution of certain parts (e.g. changing mesh size and vibration frequency in vibrating screen or modifying air flow speed for separator and transport systems).

Figure 1 provides a schematic overview of the plant layout, including all sub-systems employed in the different separation steps; the components are grouped according to the macro-phase they refer to. Pictures of the assembled system, ready for operation, have been published on unrestricted documents, still available online (LME, 2015).



PRE-TREATMENT	**GLASS SEPARATION**	**SILICON SEPARATION**	**COPPER & POLYMERIC FRACTION SEPARATION**	**AUXILIARIES**
Removal of Aluminum frame, electrical cables and junction box (not represented in the picture) **PANEL SHEARING** 1. Shearing machine	2. Conveyor 3. Hammer mill 4. Vibrating screen	5. Conveyor 6. Hammer mill 7. Vibrating screen	8. Conveyor 9. Three-stages circular separator	10. Dust aspiration system 11. Filtering system 12. Compressed air generator 13. Container n°1 14. Container n°2 15. Container n°3

Figure 1. Layout and machineries of the PV-MOREDE system

Below each separation step is described in detail; numbers refer to subsystems numbering adopted in Figure 1.

Pre-treatment and panel shearing (separation of cables, connectors, aluminum frame, first size reduction and introduction in the system). After a preliminarily weighting of the module, the pre-treatment is performed through the separation of connection cables and junction boxes, usually by manual dismantling. This task is not labor-intense. Handling of the panel is performed manually, but optionally a manipulator can be used to reduce effort of the operators. After removal of the above mentioned electrical hardware, the panel is placed on a device for aluminum frame removal, defined as “expander table”. Removal of the frame is done using a semi-automated hydraulic system, which applies forces from the inside of the panel to the outside along all the perimeter of the panel. The expander machine has been specifically developed for this application. The expander machine as well as a treatment plant which is a variant of the here described PV-MOREDE system is visible on public website (Veolia, 2018). After preparation, the panel is reduced to 100x100 mm pieces through the shearing machine (1). The shearing machine has also been developed for this application and it is composed by an hydraulic shear-press system able to cut the panel into squares in order to make its size suitable for the insertion in further size reduction machines (see also Figure 2) The machine acts on the panel “as-is”, just cleaned from electrical connections and metal frame, shearing the layers all together. The aim is to reduce its size for further processing. Each square still includes glass, cell materials, backsheet layer (see Figure 3).

Glass separation (grinding and mechanical separation of fragments). A conveyor (2) moves the squares to the impact swinging hammers mill (3) where further fragmentation occurs (see also Figure 4). The fragments are sifted by the first vibrating screen (4), which is in the form of rectilinear sieve. The size of the mesh network hole is 6 mm. This section provides three main flows:

- the over-screen fraction, which mainly comprehends glass fragments and heavy fraction which is sent to the refinement;
- the under-screen fraction, which comprehends a flow with low content of glass and high content of silicon parts and copper;
- dust (mainly silicon fines), which is recovered by the dust collection system.

The refinement of the scrap glass is performed through an optical micro-sorting machine. A scrap in compliance with the EU Regulation no. 1179/2012 (Commission regulation, 2012) is obtained, so that recycling of glass is effectively possible.

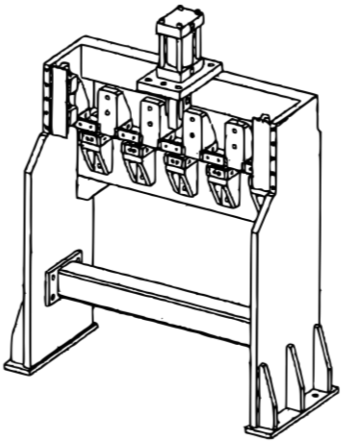


Figure 2. Shear-press machine used for the panel size reduction into 100x100 mm squares (first fragmentation stage). Component as described in EP3089825B1 (Reggi, 2017)

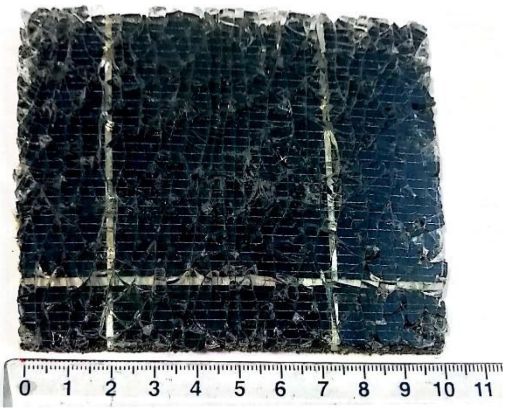


Figure 3. Panel square portion, output of the shearing machine.

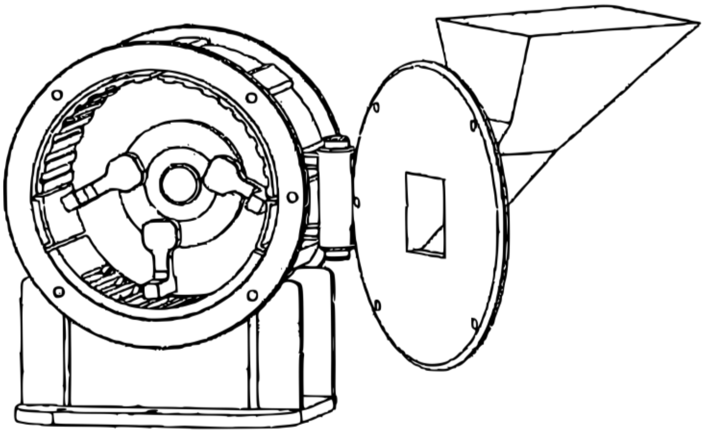


Figure 4. Swinging hammers mill (second fragmentation stage). Component as described in EP3089825B1 (Reggi, 2017)

Silicon separation (further grinding/shredding of the small fraction and mechanical treatments for material separation). The under-screen fraction coming from glass separation are transported by a conveyor (5) which carries the material to a second impact mill (Figure 5) with a fixed hammer (6) whose outputs are:

- plastic fraction, considered useful for WtE processes, separated through a mesh screen of 2 mm;

- a mixed compound of plastic materials, copper and silicon;
- dust, recovered by the collection system.

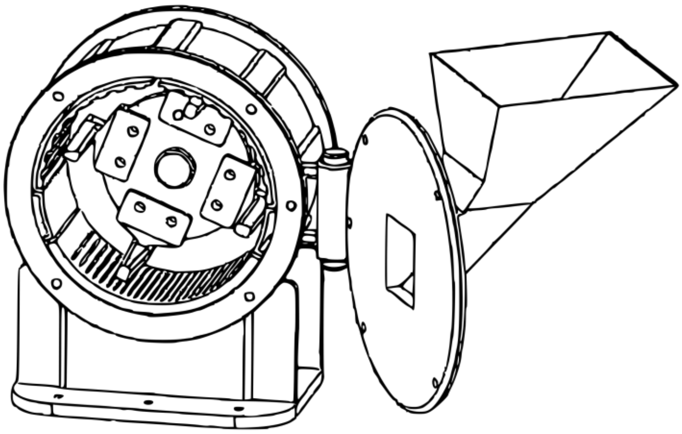


Figure 5. Fixed hammers mill (third fragmentation stage). Component as described in EP3089825B1 (Reggi, 2017)

<u>Copper & polymeric fraction separation</u> (further sieving of the plastic-copper compound). A conveyor (8) moves the compound plastic/copper to the third vibrating screen (9) (Figure 6), a circular one, which performs the separation of silicon and copper fractions:

- mixed compound of plastic and copper (and, eventually, small fractions of other metals) with 0.5-2 mm grain size. This fraction is sent to eddy current separator which performs the final segregation of non-ferrous metals and the separation of polymers;
- fraction with 0.315-0.500 mm grain size, low silicon content and classified as recyclable (see also Table 4);
- fraction with grain size less than 0.315 mm, high silicon content and classified as recyclable (see also Table 4), but also potentially valuable for further refinement.

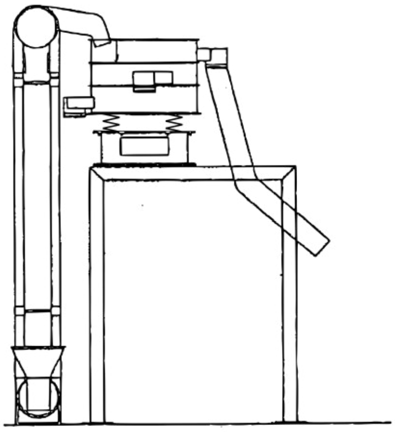


Figure 6. Three stages screen for fines separation. Component as described in EP3089825B1 (Reggi, 2017)

Where possible, transportation of materials and fines is performed through pneumatic systems. In conclusion, the entire recycling process can be divided into three main size reduction and separation phases:

1) Shearing from panel to squares

2) Shredding from squares to particles with 6 mm grain size
   a) Over-screen: glass sent to refinement
   b) Under-screen: material to further shredding

3) Shredding from 6 mm to 2 mm grain size particles
    a) Over-screen: mainly plastics (expected destination: recovery through WtE processes)
    b) Under-screen: to three-stages sieving
        i) 0.5-2 mm grain size particles: to eddy current separation for metal recovery
        ii) 0.500-0.315 mm grain size particles: low-silicon product
        iii) <0.315 mm grain size particles: high-silicon product.

The containers, as well as the supporting structures, are designed and built specifically for this application (Grassi et al., 2018). In comparison with standard freight containers, the structures offer increased stiffness and resistance in order to hold up the basement of the machineries. The three containers present different lengths in order to adapt to systems disposition and dimensions. Each container has doors and openings for operation and maintenance activities. The main machines of the plant are covered by patent EP3089825B1 (Reggi, 2017) and they are listed in Table 2.

2.2.2. LCI data collection

The inventory is mainly based on primary data coming from a detailed gathering performed on the pilot scale plant. As secondary data the Ecoinvent database v3 (Ecoinvent database, 2017) and GaBi Thinkstep database 8.6.0.20 are used. Below the LCI data collection is described in detail for each one of the LC stages of the PV-MOREDE recycling process.

Plant construction. Data collection regarding plant manufacturing is the typology and quantity of materials that constitute the entire PV-MOREDE system. Table 2 reports material composition of each machine/component of the device as well as the LCI datasets adopted for the environmental modelling of the manufacturing stage.

PLANT CONSTRUCTION (manufacturing)

Equipment	**Component**	**Sub-component**	**Material**	**Mass [kg]**	**Ecoinvent DB process**
Shearing machine	Gear motor	Fixed dye and counter die	High Speed Steel (HSS)	15	Steel, chromium steel 18/8 - Hot rolled {GLO}
	Oleo dynamic & hydraulic equip.	Material extraction tape	Rubber	5	Synthetic rubber {GLO}
Chain conveyor n°1	Gear motor	Conveyor tape	Rubber	2	Synthetic rubber {GLO}
		Transfer and control unit	Steel S 235 JR	8	Steel, unalloyed {GLO}
		Rollers	Inox steel AISI 304	10	Steel, chromium steel 18/8 {GLO}
		Tensioners		5	
Hammer mill	Four-pole three-phase asynchronous electric motor	Swinging hammers	Steel (high content of Mn and Cr)	85	Steel, low-alloyed {GLO}
Vibrating screen n°1	N° 2 gear motors	Frame	Inox steel AISI 304	4	Steel, chromium steel 18/8 {GLO}
		N° 4 springs	Steel Si-Cr-Ni	2	Sinter, iron {GLO}
Chain conveyor n°2	Three-phase electric motor	Straps	Steel S 235 JR	7	Steel, unalloyed {GLO}
		Pulleys			
		Conveyor chains	Inox steel AISI 304	5	Steel, chromium steel 18/8 {GLO}
		Pipes			
Hammer mill	Four-pole three-phase asynchronous electric motor	Impact mill (structure)	Cast Iron	50	Cast iron {GLO}
		Fixed hammer	Steel (high content of Mn and Cr)	35	Steel, low-alloyed {GLO}
Rectangular vibrating sifter	N° 2 gear motors	Frame	Inox steel AISI 304	4	Steel, chromium steel 18/8 {GLO}
		N° 4 spring	Steel Si-Cr-Ni	2	Sinter, iron {GLO}
Chain conveyor n°3	Three-phase electric motor	Straps	Steel S 235 JR	5	Steel, unalloyed {GLO}
		Pulleys			
		Conveyor chains	Inox steel AISI 304	7	Steel, chromium steel 18/8 {GLO}
		Pipes			
Three- stage circular separator	Three-phase electric motor	Lower band with exhaust pipe	Inox steel AISI 304	40	Steel, chromium steel 18/8 {GLO}
		Intermediate band with cone for recycling and discharge			
		Lower band with exhaust pipe			
		N° 2 rings for grid holding			
Separator of non-ferrous materials	Electric motor	Full-magnetic drum housing vibrating feeder and control panel	Steel S 235 JR	45	Steel, unalloyed {GLO}
Collecting container	Metal container internal bag	Steel S 235 JR	Steel S 235 JR	-	Steel, unalloyed {GLO}
Dust aspiration system Filtering system	Electrum vacuum cleaner	N° 7 receiving hoods / pipes/ fittings	Inox steel AISI 304	90	Steel, chromium steel 18/8 {GLO}
	Three-phase electric motor				
	Compressor (600 l)	N° 1 over-pressure shutter	Aluminum	50	Aluminum, cast alloy {GLO}
Metallic structure box	Container n°1		Steel S 235 JR	1800	Steel, unalloyed {GLO}
	Container n°2		Steel S 235 JR	2885	
	Container n°3		Steel S 235 JR	3200	
				Total: 8361	

Table 2. Components of PV-MOREDE system LCI data collection for plant construction

For the transportation of

- plant components from suppliers to the assembly site
- assembled plant to the operation site and subsequent transportation events during its life

data collection involves the determination of transport typology and travelled distance. Table 3 reports the LCI data collection for transportation, including LCI datasets used for the environmental modelling.

PLANT CONSTRUCTION (transportation)

	Component	**Transport typology**	**Travelled distance (Supplier – Assembly site) [km]**	**Ecoinvent DB process**
Transportation plant components	Hammer mill	Freight transport EURO 5	676	Transport freight, lorry 3.5-7.5 metric ton, EURO5 {GLO}
	Vibrating screen	Freight transport EURO 5	704	Transport freight, lorry 3.5-7.5 metric ton, EURO5 {GLO}
	Chain conveyor n°2	Freight transport EURO 5	713	Transport freight, lorry 3.5-7.5 metric ton, EURO5 {GLO}
	Hammer mill	Freight transport EURO 5	676	Transport freight, lorry 3.5-7.5 metric ton, EURO5 {GLO}
	Rectangular vibrating sifter	Freight transport EURO 5	704	Transport freight, lorry 3.5-7.5 metric ton, EURO5 {GLO}
	Chain conveyor n°3	Freight transport EURO 5	713	Transport freight, lorry 3.5-7.5 metric ton, EURO5 {GLO}
	Three- stage circular separator	Freight transport EURO 5	704	Transport freight, lorry 3.5-7.5 metric ton, EURO5 {GLO}
	Separator of non-ferrous materials	Freight transport EURO 5	2230	Transport freight, lorry 3.5-7.5 metric ton, EURO5 {GLO}
	Collecting container	Freight transport EURO 5	539	Transport freight, lorry 3.5-7.5 metric ton, EURO5 {GLO}
	Dust aspiration system Filtering system	Freight transport EURO 5	133	Transport freight, lorry 3.5-7.5 metric ton, EURO5 {GLO}

	Transport typology	**Travelled distance (Operation site) [km]**	**Ecoinvent DB process**
Transportation PV MOREDE plant	Freight transport EURO 5	3000*	Transport freight, lorry 11 metric ton, EURO5 {GLO}

* Travelled distance to reach operation sites during plant LC

Table 3. LCI data collection for transportation during plant construction (plant components and PV-MOREDE plant)

Plant operation. For the operation stage the inventory is built with the following data:

- the amount of material processed within each separation step;
- the electricity consumption for each treatment step;
- the LC inventory datasets used for the environmental modelling of electricity production.

Regarding the treatment processes performed within the PV-MOREDE system, the inventory is based on primary data coming from preliminary machine testing activities and measured on the pilot plant by the LME company experts. Where data are not available or not accurate enough, assumptions on the basis of machine nominal capabilities are used. Table 4 reports the LCI data collection for the operation stage in terms of material and energy inputs.

EoL PV waste. Concerning the EoL PV waste stage, the inventory consists of the following data:

- transport typology and travelled distance for transporting PV waste materials to recovery facilities;
- transportation, material recycling and incineration with energy recovery processes performed within plants external to the PV-MOREDE facility;
- typology and amount of materials processed within the recycling and incineration with energy recovery processes;
- LCI datasets used for the environmental modelling of transportation, recycling and incineration with energy recovery processes.

The LCI data are from the GaBi Thinkstep database and they refer to average processes in the market. Table 4 shows the LCI data collection for the EoL PV waste stage in terms of material flows to transportation, material recycling and incineration with energy recovery processes. For each flow the table reports separation step, recovery process and LC inventory dataset used for the environmental modelling. The assumptions for material treatment are summarized as follows.

The recycling of aluminum (2.0 kg), copper (0.2 kg), glass (13.1 kg) and junction boxes (0.05 kg Polyamide and 0.05 kg Polyethylene) scrap is modeled as open loop recycling through the implementation of a specific substitution rate. The substitution rate provides the impact credits due to the substitution of primary with secondary material (avoided production of primary material) and it is calculated net of

- lower quality of secondary material with respect to primary material
- impacts caused by energy consumption and emissions associated with recycling processes (i.e. removal of impurities/washing, re-melting and refining).

Concerning aluminum, literature generally estimates the substitution rate in a range between 10 % and 94 % (LCI 8.6.0.20 version GaBi dataset; (Koffler and Florin, 2013; Schrijvers et al., 2016). Lower values are suitable for low-quality aluminum scrap (low-grade irony Alu), higher values are suitable for scrap aluminum extrusions. The case of PV-MOREDE frames is comparable to high quality aluminum extrusions scraps, so that even a substitution factor of about 90-95 % would be suitable. Considering that in large treating plants it is possible the mixing of aluminum scraps coming from different sources, a substitution rate of 0.4 is conservatively assumed.

The substitution rate for copper scrap is assumed 0.65, coherently with recycling potential estimation provided by LCI 8.6.0.20 version GaBi dataset.

The substitution rate for glass scrap is assumed 0.8, basing on LCI 8.6.0.20 version GaBi dataset and literature references which suggest high values (Ferreira et al., 2017; Rigamonti et al., 2009); even if known data are mainly referred to glass cullet originated by packaging, we assume that the glass cullet provided by the PV-MOREDE has similar substitution rate due to its high quality (obtained through screening with optical sorting).

For junction boxes, on the basis of the material examined during plant operativity it has been assumed that 50 % (0.1 kg) is sent to incineration with energy recovery (Latunussa et al., 2016) due to degradation, damage and/or impossibility to recognize the constituting material - most time being PVC, PA or PE as usual for WEEE insulating components. The remaining 50 % is recycled as material. For this fraction, the substitution rate (sample considered: 0.05 kg Polyamide and 0.05 kg Polyethylene) is assumed 0.5, a conservative factor on the basis of literature references for WEEE-derived plastics (Wäger and Hischier, 2015). Reuse, even if cited in literature (Park and Park, 2014), has not been considered.

For the remaining quota of material scrap

- 0.2 kg cables
- 2.0 kg polymeric fraction
- 1.5 kg low/high-content silicon material
- 0.8 kg residual

the assumed waste EoL scenario is incineration with energy recovery. It is assumed, therefore, that also fractions comprehending mostly inert materials (e.g. silicon) are sent to incineration with energy recovery as mixed residuals; in this case, a model specific for inert fraction in incinerators is used.

A specific model has been adopted for each fraction, as described in Table 4. The environmental modeling of incineration with energy recovery accounts for both impacts due to energy consumption/emissions and credits associated with energy production. However, the environmental burdens due to energy consumption/emissions are much higher with respect to credits coming from energy production. As a confirmation, the EoL PV waste impact reported in Figure 9 is positive for all materials/parts forwarded to incineration process (cables, junction boxes, polymeric fraction, silicon materials and residual).

		Item	Quantity	PV MOREDE process	Ecoinvent DB process
PLANT OPERATION	**Input to the PV MOREDE plant**	PV waste panel	20.00 kg	Pre-treatment	-
			17.60 kg	Glass separation	
			3.30 kg	Silicon separation	
			1.00 kg	Copper & Polymeric fraction separation	
		Electricity	0.79 kWh	Pre-treatment	Electricity, medium voltage {RoW}
			0.51 kWh	Glass separation	
			0.46 kWh	Silicon separation	
			0.16 kWh	Copper & Polymeric fraction separation	

		Item	Quantity	Origin (PV MOREDE process)	Destination (recovery facilities)	GaBi Thinkstep DB process
EoL PV WASTE	**Recycling route (including transportation)**	Aluminum	2.00 kg	Pre-treatment	Retrieving foundry	- GLO: Truck, Euro 5, 7.5-12t gross weight / 5t payload capacity ts (Transportation)* - EU-28: Diesel mix at refinery ts (Transportation) - Aluminum - Scrap credit open loop (User) (Recycling) - Aluminum ingot mix ts (Recycling)
		Junction boxes (Polyamide)	0.05 kg		Retrieving in conventional plants	- GLO: Truck, Euro 5, 7.5-12t gross weight / 5t payload capacity ts(Transportation)* - EU-28: Diesel mix at refinery ts (Transportation) - Polyamide 6.6 - Scrap credit open loop (User) (Recycling) - DE: Polyamide 6.6 Granulate (PA 6.6) Mix ts (Recycling)
		Junction boxes (Polyethylene)	0.05 kg			- GLO: Truck, Euro 5, 7.5-12t gross weight / 5t payload capacity ts (Transportation)* - EU-28: Diesel mix at refinery ts (Transportation) - Polyethylene High Density (HDPE/PE-HD) - Scrap credit open loop (User) (Recycling) - DE: Polyethylene High Density Granulate (HDPE/PE-HD) Mix ts (Recycling)
		Glass	13.10 kg	Glass separation	Retrieving in glassware	- GLO: Truck, Euro 5, 7.5-12t gross weight / 5t payload capacity ts (Transportation)* - EU-28: Diesel mix at refinery ts (Transportation) - Glass - Scrap credit open loop (User) (Recycling) - EU-28: Float flat glass ts (Recycling)
		Copper	0.20 kg	Copper & Polymeric fraction separation	Retrieving foundry	- GLO: Truck, Euro 5, 7.5-12t gross weight / 5t payload capacity ts (Transportation)* - EU-28: Diesel mix at refinery ts (Transportation) - Copper - Scrap credit open loop (User) (Recycling) - EU28: Copper sheet
	Incineration route (including transportation)	Cables	0.20 kg	Pre-treatment	Incineration of EVA	- GLO: Truck, Euro 5, 7.5-12t gross weight / 5t payload capacity ts (Transportation)* - EU-28: Diesel mix at refinery ts (Transportation) - EU-28: Cable waste in waste incineration plant ts (Incineration)
		Junction boxes (Polyamide/Polyethylene)	0.10 kg			- GLO: Truck, Euro 5, 7.5-12t gross weight / 5t payload capacity ts (Transportation)* - EU-28: Diesel mix at refinery ts (Transportation) - EU-28: Waste incineration of plastics (unspecified) ts (Incineration)

		Polymeric fraction	1.20 kg	Glass separation		- GLO: Truck, Euro 5, 7.5-12t gross weight / 5t payload capacity ts (Transportation)* - EU-28: Diesel mix at refinery ts (Transportation) - EU-28: Waste incineration of plastics (unspecified) ts (Incineration)
		Low-content silicon materials	0.60 kg	Silicon separation		- GLO: Truck, Euro 5, 7.5-12t gross weight / 5t payload capacity ts (Transportation)* - EU-28: Diesel mix at refinery ts (Transportation) - EU-28: Waste incineration of glass/inert material ELCD/CEWEP ts (Incineration)
		High-content silicon materials	0.90 kg			
		Polymeric fraction	0.80 kg	Copper & Polymeric fraction separation		- GLO: Truck, Euro 5, 7.5-12t gross weight / 5t payload capacity ts (Transportation)* - EU-28: Diesel mix at refinery ts (Transportation) - EU-28: Waste incineration of plastics (unspecified) ts (Incineration)
		Residual	0.80 kg			- GLO: Truck, Euro 5, 7.5-12t gross weight / 5t payload capacity ts (Transportation)* - EU-28: Diesel mix at refinery ts (Transportation) - EU-28: Waste incineration of glass/inert material ELCD/CEWEP ts (Incineration)
	* Assumed distance to recycling / recovery treatment facilities = 150 km					

Table 4. LCI data collection for plant operation and EoL of PV waste (all data refer to 1 FU - 20 kg PV crystallin-silicon based panel)

2.3. Life Cycle Impact Assessment (LCIA)

The base methodology chosen for the impact assessment of the considered system is the ILCD midpoint method (Hiederer, 2011), recommended by the European Commission and scientifically accepted. This LCIA method includes 16 midpoint impact categories. Considering the goal of the study, the following impact categories are selected:

- Global Warming Potential
- Ozone Depletion Potential
- Photochemical Ozone Formation Potential
- Acidification Potential
- Terrestrial Eutrophication Potential
- Freshwater Eutrophication Potential
- Mineral, fossil & renewable resource depletion Potential

3. Interpretation of results and discussion

The LCIA results of the recycling of 20 kg PV panel through the PV-MOREDE process are illustrated in Table 5.

		Global Warming Potential [kg CO_2 eq.]	**Ozone Depletion Potential [kg CFC11-eq.]**	**Photochemical Ozone Formation Potential [kg NMVOC eq.]**	**Acidification Potential [Mole of H+ eq.]**	**Terrestrial Eutrophication Potential [Mole of N eq.]**	**Freshwater Eutrophication Potential [kg P eq.]**	**Mineral, fossil & renewable resource depletion Potential [kg Sb eq.]**
Plant construction	**Manufacturing**	3.38E-02	1.34E-09	1.36E-04	1.73E-04	3.44E-04	1.28E-05	1.82E-06
	Transportation	5.00E-03	1.33E-16	1.44E-05	1.65E-05	8.34E-05	2.48E-08	1.83E-09
Plant operation		1.39E+00	4.03E-08	4.00E-03	1.03E-02	1.38E-02	6.53E-04	3.87E-06
EoL PV waste	**Transportation**	6.47E-01	1.74E-14	1.87E-03	2.15E-03	1.08E-02	3.24E-06	2.39E-07
	Recovery processes	-1.26E+01	5.87E-09	-6.92E-02	-1.66E-01	-3.58E-01	-9.54E-06	-1.40E-03
Total		-1.06E+01	4.75E-08	-6.32E-02	-1.54E-01	-3.33E-01	6.60E-04	-1.39E-03

Table 5. Potential LC impacts for the recycling of 20 kg PV panel through the PV-MOREDE process

Figure 6 reports the contribution analysis of impacts due to plant construction and operation stages. The LCIA results show that operation is definitely more influential than the construction, with a contribution that exceeds 95% for 6 of 7 impact categories. The reason for this is the considerable energy consumption required by the operation of the PV-MOREDE process. On the other hand for the impact category *Mineral, fossil & renewable resource depletion Potential* the contribution of construction stage is considerable (32 %) and it is due to the large amount of metals required to build up the system.

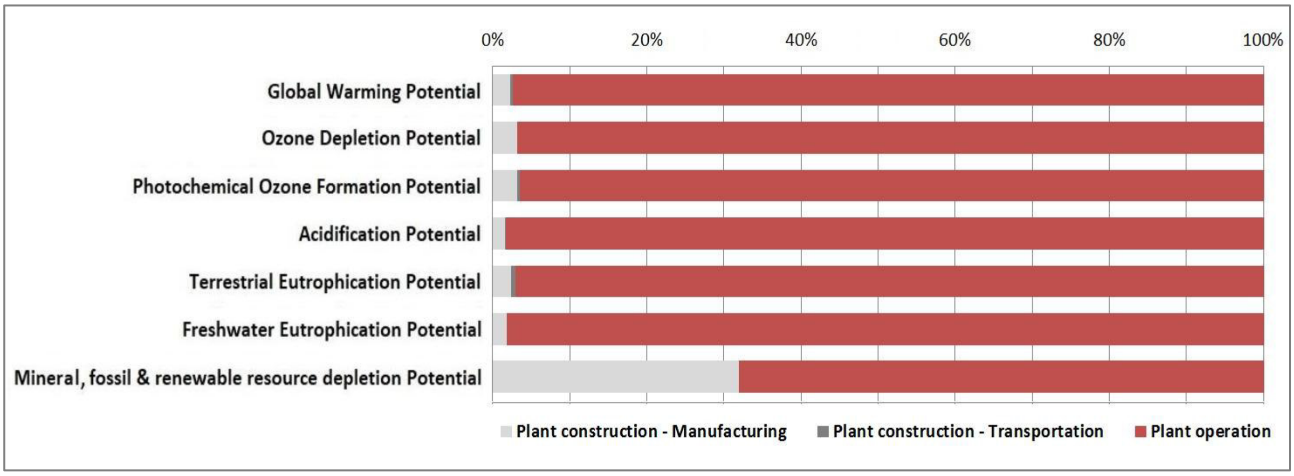


Figure 6. Contribution analysis of impacts due to plant construction and operation

Figure 7 shows the contribution of each separation step to the overall operation stage impact. The pre-treatment and panel shearing phases (considered together) present the highest contribution (about 40 %) for all the impact categories mainly due to the amount of energy required for separating the aluminum frame and reducing the size of panel. This step is also crucial in order to allow a high efficiency of the recycling process in terms of quantity and quality of the different recyclable fractions. The contribution of both glass and silicon separation is about 25 % for all the impact categories with the lowest contribution of copper & polymeric fraction separation (approximately 10 % for all the categories). An interesting point emerges from the analysis of the operation stage. Unlike literature LCAs referring to fixed recycling plants (Fraunhofer Institute, 2012; Latunussa e al., 2016), no contribution due to the transportation of waste modules to the recycling/recovery facilities is added up, since the PV-MOREDE system is placed relatively close to the installation site of EoL panels.

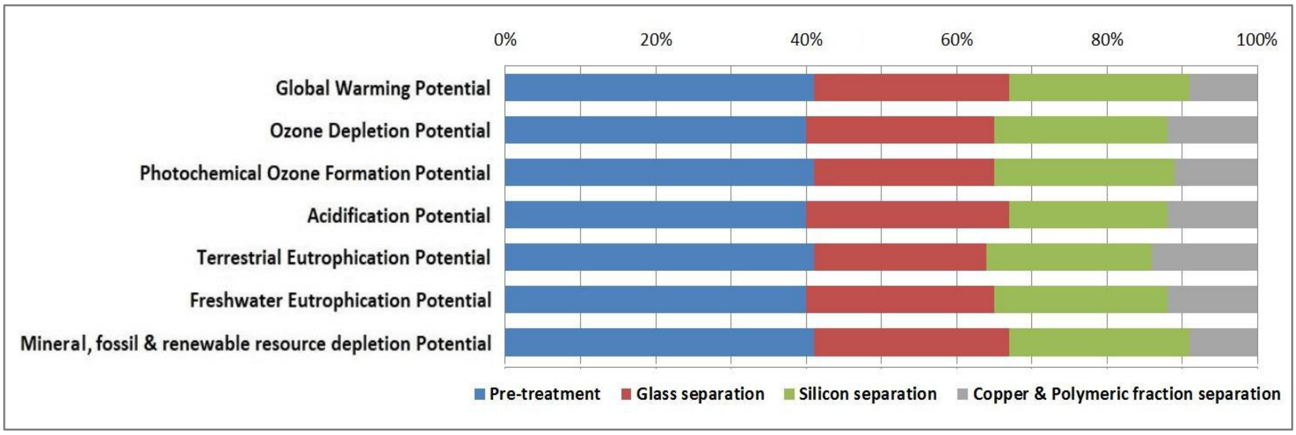


Figure 7. Contribution analysis by separation step of impacts due to plant operation. "Pre-treatment" includes also panel shearing into squares.

Figure 8 reports the contribution analysis by LC stage of impacts including also recovery processes performed outside the PV-MOREDE system (EoL PV waste stage). Recycling of aluminum, glass and copper for new PV panel manufacturing or for other industrial activities yields significant environmental benefits due to avoided impacts for production of virgin materials. Similarly, WtE recovery processes allow avoiding impacts due to the generation of energy. Results show that credits from recovery of EoL waste counterbalances by far the environmental load related to plant construction and operation, thus leading to a considerable reduction (negative values) of total LC impacts. This is true for all the LCIA categories with the exception of impact categories *Ozone Depletion Potential* and *Freshwater Eutrophication Potential*. For the *Ozone Depletion Potential* all LC stages provide positive impacts, the operation being the most influential one; the burdens associated with EoL PV waste stage are primarily caused by air emissions of incineration processes (incineration of polymeric fraction). Considering the *Freshwater Eutrophication Potential*, the credits from recovery processes do not counterbalance the impacts of the other LC stages, especially plant operation.

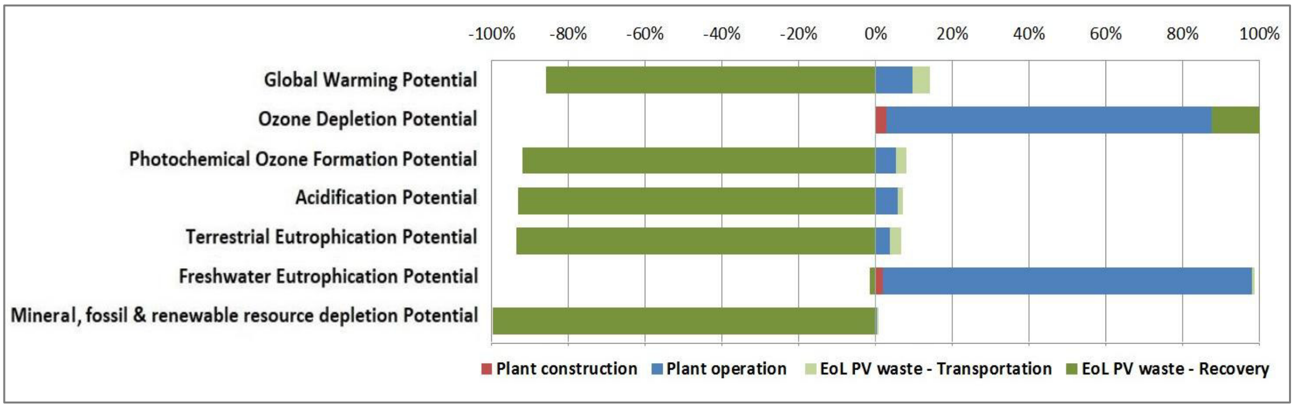


Figure 8. Contribution analysis by LC stage of the overall LC impacts (plant construction, plant operation and EoL of PV waste)

Figure 9 shows the contribution analysis by material category of the impacts due to EoL PV waste stage. For the environmental credits, the major quota is attributable to recycling of aluminum, glass and copper. On the other hand, the incineration processes of polymeric and residual fractions provide a positive impact for all impact categories, especially for the *Ozone Depletion Potential* for which credits do not counterbalance the impacts.

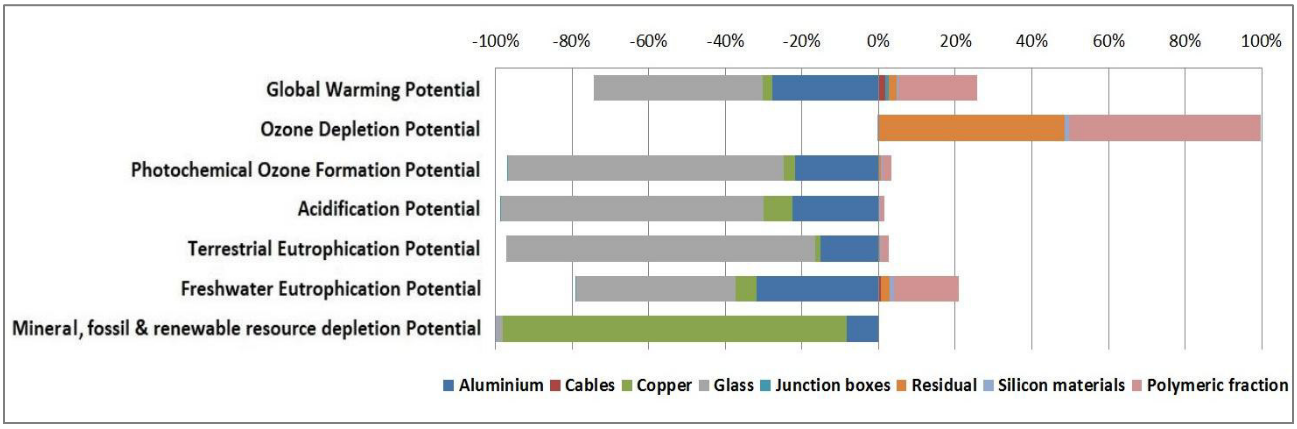


Figure 9. Contribution analysis by material category of impacts due to EoL PV waste

Considering literature regarding LCA of PV panels recycling processes, a direct comparison of results is not feasible since existing studies often make use of different LCIA methods/impact categories, present results in aggregated form or do not explicitly declare boundary conditions of the study (i.e. FU, system boundaries, assumptions on data source and cut-off criteria). In particular, the main difference between the data here presented and other literature studies is that the focus is not on the PV panel itself, but on the activity of recycling a panel using a certain plant (PV-MOREDE). That said, it can be argued that the PV-MOREDE recycling system allows the achieving of notable environmental benefits with respect to fixed installations thanks to the reduction of transportation processes for moving EoL panels and resulting materials to the recycling site. As a confirmation, existing LCAs of fixed plants (Fraunhofer Institute, 2012; Latunussa et al., 2016) reveal that waste supply covers a significant amount of operation impact.

The main limitations of the work concern primarily two aspects. The first one is that LCI primary data regarding system operation (technical/operational features of the plant, energy consumption for operation, amount of input/output materials) refer to the pilot case plant built up by LME; as a consequence, process parameters could vary in the transition to the industrial scale production. The second limitation is related to the modelling of processes performed outside the PV-MOREDE facility (plant construction and recovery of EoL PV waste). These are production and construction of different plant machines, transportation of system components to the LME assembly site, materials and energy recovery processes. For these steps primary data are not available, and the LCI data collection is based on secondary data coming from commercial LCI databases. Since recycling and incineration processes have a strong influence on LC impact for all the considered impact categories, the representativeness of the used LCI databases is crucial.

The added value of the work is that it deals with a mobile recycling process able to treat on-site and on demand modules characterized by different composition/structure. The study provides transparent and disaggregated LCIA impacts with a LCI mainly based on primary data. Considering that a substantial increase in the amount of EoL solar panels is expected in the next decades, the need for recycling this type of waste will grow rapidly and the outcomes of the paper can be relevant for different professional figures such as recyclers, LCA practitioners and policy makers. The work could be also helpful in order to define strategies for the design of future PV panels characterized by higher recoverability rate and lower environmental impacts.

4. Conclusions

This article performs the LCA of an innovative recycling process for EoL solar panels, experimented at a pilot scale within the PV-MOREDE project. The investigation on plant construction and operation reveals that energy consumption during operation involves much higher impacts than the consumption of material and energy resources used for the construction. This is true for all the considered impact categories with the exception of *Mineral, fossil & renewable resource depletion Potential* for which the large amount of metals required to build up the system makes the contribution of construction comparable to the one of operation. Considering the operation stage, the pre-treatment step gives the highest contribution (about 40 %) for all the impact categories due to the high energy consumption of the shredding machine. Glass and silicon separation present similar quota (about 25 %) with the lowest contribution of copper and polymeric fraction separation (approximately 10 % for all the categories).

The investigation of all LC stages including also processes performed outside the PV MOREDE system points out that recycling from different material fractions (aluminum, glass, copper, silicon and plastics) allows achieving great environmental benefits due to avoided production of virgin materials and energy. The LCIA results show that credits from recovery counterbalance by far the burdens due to plant construction and operation for most of impact categories and this is mainly due to recovery of metals and glass. The only exceptions are represented by impact categories *Ozone depletion Potential* and *Freshwater Eutrophication Potential* for which the impact of plant operation is notably higher with respect to the other LC stages. The investigation of literature shows that the environmental benefits achievable through a mobile system are relevant with respect to fixed recycling installations not only due to the tailored process which can be obtained on small scale systems, but also thanks to the overall reduction of transportation processes needed to move EoL panels, materials and residuals to and from the recycling facility.

This LCA is the only work that deals with a mobile recycling process developed specifically for EoL PV panels. The contribution of the study to the sustainability assessment of PV waste recycling lies in providing transparent and disaggregated LCIA performed through a LC inventory mainly based on primary data. The findings of the research could be relevant for different professionals such as recyclers, LCA practitioners and policy makers committed to satisfying the ever-growing demand for environmentally friendly processes and products.

Acknowledgements

The present work is a part of the project PV–MOREDE (Photovoltaic Panels Mobile Recycling Device), co–funded by the Eco–Innovation initiative of the European Union, contract number ECO/12/333078.

https://ec.europa.eu/environment/eco–innovation/projects/en/projects/pv–morede http://www.pvmorede.it/

The Publication as provided reflects only the authors' view.

The authors would like to thank "La Mia Energia" Company (Venafro, Isernia – Italy) for their courtesy.

References

Banar, M., Özdemir, A., 2015. An evaluation of railway passenger transport in Turkey using life cycle assessment and life cycle cost methods, In Transportation Research Part D: Transport and Environment, Volume 41, 2015, Pages 88-105, ISSN 1361-9209, https://doi.org/10.1016/j.trd.2015.09.017.

Berzi, L., Delogu, M., Giorgetti, A., Pierini, M., 2013. On-field investigation and process modelling of End-of-Life Vehicles treatment in the context of Italian craft-type Authorized Treatment Facilities. Waste Management 33, 892–906. https://doi.org/10.1016/j.wasman.2012.12.004

Besiou, M., Wassenhove, L.N.V., 2016. Closed-Loop Supply Chains for Photovoltaic Panels: A Case-Based Approach. Journal of Industrial Ecology 20, 929–937. https://doi.org/10.1111/jiec.12297

Bhat Varun, I.K., Prakash, R., 2011. LCA of renewable energy for electricity generation systems - a review. Renew. Sustain. Energy. Rev.15 (2011) 1625-1636.

Bio Intelligence Service (BioIS), 2011. Study on photovoltaic panels supplementing the impact assessment for a recast of the WEEE directive - Final report, 2011.

Bogacka, M., Pikoń, K., Landrat, M., 2017. Environmental impact of PV cell waste scenario. Waste Management 70, 198–203. https://doi.org/10.1016/j.wasman.2017.09.007

Carnevale, E., Lombardi, L., Zanchi, L., 2014. Life Cycle Assessment of solar energy systems: Comparison of photovoltaic and water thermal heater at domestic scale. Energy 77, 434–446. https://doi.org/10.1016/j.energy.2014.09.028

Commission Regulation (EU) No 1179/2012 of 10 December 2012 establishing criteria determining when glass cullet ceases to be waste under Directive 2008/98/EC of the European Parliament and of the Council.

Corcelli, F., Ripa, M., Leccisi, E., Cigolotti, V., Fiandra, V., Tammaro, M., Sannino, L., Graditi, G., Ulgiati, S., 2015. Material recovery and energy savings from c-Si PV panels end-of-life. Life Cycle Assessment of PV panels thermal treatment. Proceedings of the Global Cleaner Production and Sustainable consumption Conference, Sitges, Spain, 1-4 November, 2015.

Contreras-Lisperguer, R., Muñoz-Cerón, E., Aguilera, J., Casa, J. de la, 2017. Cradle-to-cradle approach in the life cycle of silicon solar photovoltaic panels. Journal of Cleaner Production 168, 51–59. https://doi.org/10.1016/j.jclepro.2017.08.206

Cucchiella, F., D'Adamo, I., Lenny Koh, S.C., Rosa, P., 2016. A profitability assessment of European recycling processes treating printed circuit boards from waste electrical and electronic equipments. Renew. Sustain. Energy Rev. 64, 749–760. doi:10.1016/j.rser.2016.06.057

Del Pero, F., Delogu, M., Pierini, M., 2017. The effect of lightweighting in automotive LCA perspective: Estimation of mass-induced fuel consumption reduction for gasoline turbocharged vehicles. Journal of Cleaner Production, Volume 154, 2017, Pages 566-577, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2017.04.013.

Delogu, M., Del Pero, F., Pierini, M., 2016. Lightweight Design Solutions in the Automotive Field: Environmental Modelling Based on Fuel Reduction Value Applied to Diesel Turbocharged Vehicles. Sustainability 2016, 8(11), 1167; doi:10.3390/su8111167.

Dias, P., Javimczik, S., Benevit, M., Veit, H., 2016. Recycling WEEE: polymer characterization and pyrolysis study for waste of crystalline silicon photovoltaic modules. Waste Manage. http://dx.doi.org/10.1016/j.wasman.2016.08.036.

Dias, P., Javimczik, S., Benevit, M., Veit, H., 2017. Recycling WEEE: Polymer characterization and pyrolysis study for waste of crystalline silicon photovoltaic modules. Waste management, 60:716-722. doi: 10.1016/j.wasman. 2016.08. 036. Epub 2016 Sep 2.

DM 31/12/1988, 1988. Coefficients of depreciation of the cost of material assets used in for commercial activities, arts and professions.

Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE) (recast), 2012.

Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance), 2008. , 312.

Doi, T., Tsuda, I., Unagida, H., Murata, A., Sakuta, K., Kurokawa, K., 2001. Experimental study on PV module recycling with organic solvent method. Sol. Energy Mater. Sol. Cells 67, 397-403.

Duflou, J.R., Peeters, J.R., Altamirano, D., Bracquene, E., Dewulf, W., 2018. Demanufacturing photovoltaic panels: Comparison of end-of-life treatment strategies for improved resource recovery. CIRP Annals 67, 29–32. https://doi.org/10.1016/j.cirp.2018.04.053

Ecoinvent database, 2017. Available at: www.ecoinvent.org/database/database.html (accessed 12.12.17).

EPIA, European Photovoltaic Industry Association, 2014. Global Market Outlook for Photovoltaics 2014-2018.

Evans, A., Strezov, V., Evans, T.J., 2009. Assessment of sustainability indicators for renewable energy technologies. Renew. Sustain. Energy. Rev. 13 (2009) 1082-1088.

Ferreira, S., Cabral, M., De Jaeger, S., Da Cruz, N.F., Simões, P., Marques, R.C., 2017. Life cycle assessment and valuation of the packaging waste recycling system in Belgium. J Mater Cycles Waste Manag 19, 144–154. https://doi.org/10.1007/s10163-015-0383-x

First Solar, 2019. First Solar’s state-of-the-art recycling facilities [WWW Document]. URL http://www.firstsolar.com/Modules/Recycling (accessed 2.21.19).

Frankl, P., Menichetti, E., Raugei, M., Lombardelli, S., Prennushi, G., 2005. Final report on technical data, costs and life cycle inventories of PV applications - Deliverable no. 11.2-RSIa of the NEEDS (New Energy Externalities Developments for Sustainability) project, Rome, Italy, 2005.

Fraunhofer Institut für Bauphysik, 2012. Life Cycle Assessment (LCA) screening of the Maltha recycling process for Si-PV modules – Executive Summary, available at: http://www.pvcycle.org/wp-content/uploads/Exec-Sum mary-LCA-Screening-of-a-Recycling-process-of-silicon-based-PV-modules- 2012-07.pdf, (accessed 01.12.17).

Frisson, L., Lieten, K., Bruton, T., Declercq, K., Szlufcik, J., DeMoor, H., Goris, M., Benali, A., Aceves, O., 2000. Recent improvements in industrial PV module recycling, in: Proceedings of the 16th European Photovoltaic Solar Energy Conference, Glasgow, 1–5 May, 2000.

Granata, G., Pagnanelli, F., Moscardini, E., Havlik, T., Toro, L., 2014. Recycling of photovoltaic panels by physical operations. Solar Energy Materials and Solar Cells 123, 239–248. https://doi.org/10.1016/j.solmat.2014.01.012

Grassi, A., Delogu, M., Baldanzini, N., Berzi, L., Pierini, M., 2018. Structural analysis of a mobile device for the End–of–Life treatment of photovoltaic panels. Procedia Structural Integrity. Volume 8, Pages 594-603, ISSN 2452-3216.

Gustafsson, A.M.K., Foreman, M.R.S.J., Ekberg, C., 2014. Recycling of high purity selenium from CIGS solar cell waste materials. Waste Manage. 34 (10), 1775-1782.

Hawkins, T.R., Singh, B., Majeau-Bettez, Anders Hammer Strømman, A.H., 2012. Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. Journal of Industrial Ecology. DOI: 10.1111/j.1530-9290.2012.00532 (2012).

Held, M., Ilg, R., 2011. Update of environmental indicators and energy paybacktime of CdTe PV systems in Europe, Prog. Photovolt.: Res. Appl. 19 (2011) 614-626.

Hiederer, R., 2011. International reference life cycle data system (ILCD) handbook: general guide for life cycle assessment: provisions and action steps. European Commission, Joint Research Centre - Institute for Environment and Sustainability.

Hsu, D.D., O'Donoughue, P., Fthenakis, V.S., Heath, G.A., Kim, H.C., Sawyer, P., Choi, J.K., Turney, D.E., 2012. Life cycle greenhouse gas emissions of crystalline silicon photovoltaic electricity generation: systematic review and harmonization. J. Ind. Ecol.16 (S1)(2012) 122-135.

IEA, 2018. Snapshot of global photovoltaic market 2018 - Report PVPS T1-33:2018 [WWW Document]. URL http://www.iea-pvps.org/?id=266 (accessed 10.21.18).

IRENA, 2018. Renewable power generation costs in 2017. International Renewable Energy Agency, Abu Dhabi.

ISO 14040/14044, 2006. Environmental management - Life Cycle Assessment - Principals and framework/ Requirements and guidelines. Genew, Switzerland.

Kanga, S., Yoo, S., Lee, J., Boo, B., Ryu, H., 2012. Experimental investigations for recycling of silicon and glass from waste photovoltaic modules. Renew. Energy 47, 152-159.

Klugmann-Radziemska, E., Ostrowski, P., Drabczyk, K., Panek, P., Szkodo, M., 2010a. Experimental validation of crystalline silicon solar cells recycling by thermal and chemical methods. Sol. Energy Mater. Sol. Cells 94, 2275-2282.

Klugmann-Radziemska, E., Ostrowski, P., 2010b. Chemical treatment of crystalline silicon solar cells as a method of recovering pure silicon from photovoltaic modules. Renew. Energy 35 (8), 1751-1759.

Koffler, C., Florin, J., 2013. Tackling the Downcycling Issue—A Revised Approach to Value-Corrected Substitution in Life Cycle Assessment of Aluminum (VCS 2.0). Sustainability 5, 4546–4560. https://doi.org/10.3390/su5114546

Jung, B., Park, J., Seo, D., Park, N., 2016. Sustainable system for raw-metal recovery from crystalline silicon solar panels: From noble-metal extraction to lead removal. ACS Sustainable Chem. Eng. 4, 4079-4083.

Jungbluth,N., 2005. Life cycle assessment of crystalline photovoltaics in the Swiss ecoinvent database, Prog. Photovolt. 13 (5) (2005) 429–446.

Jungbluth, N., Stucki, M., Flury, K., Frischknecht, R., Büsser, S., 2012. Life cycle inventories for photovoltaics: Version 2012 – Report by the ESU – services Ltd on behalf of the Swiss Federal Office of Energy (SFOE), 2012.

Latunussa, C.E.L., Ardente, F., G.A. Blengini, Mancini, L., 2016. Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels. Solar EnergyMaterials&SolarCells156(2016)101-111.

Lee, T.D., Ebong, A.U., 2017. A review of thin film solar cell technologies and challenges. Renewable and Sustainable Energy Reviews 70, 1286–1297. https://doi.org/10.1016/j.rser.2016.12.028

LME, 2015. PV-MOREDE DELIVERABLE D 3.1 First PV-Morede manufactured [WWW Document]. URL http://www.pvmorede.it/public/D%203.1%201st%20PVMOREDE%20MANUFACTURED.PDF

Marwede, M., Reller, A., 2012. Future recycling flows of tellurium from cadmium telluride photovoltaic waste. Resources, Conservation and Recycling 69, 35–49. https://doi.org/10.1016/j.resconrec.2012.09.003

Müller, A., Wambach, K., Alsema, E., 2005. Life cycle analysis of solar module recycling process. Proceedings of the 20th European Photovoltaic Solar Energy Conference, Barcelona, Spain, 6–10 June, 2005.

Munshi, A.H., Sasidharan, N., Pinkayan, S., Barth, K.L., Sampath, W.S., Ongsakul, W., 2018. Thin-film CdTe photovoltaics – The technology for utility scale sustainable energy generation. Solar Energy 173, 511–516. https://doi.org/10.1016/j.solener.2018.07.090

Pagnanelli, F., Moscardini, E., Altimari, P., Abo Atia, T., Toro, L., 2016. Cobalt products from real waste fractions of end of life lithium ion batteries. Waste Management, Volume 51, 2016, Pages 214-221, ISSN 0956-053X, https://doi.org/10.1016/j.wasman.2015.11.003.

Pagnanelli, F., Moscardini, E., Granata, G., Abo Atia, T., Altimari, P., Havlik, T., Toro, L., 2017. Physical and chemical treatment of end of life panels: An integrated automatic approach viable for different photovoltaic technologies.

Waste Management, Volume 59, 2017, Pages 422-431, ISSN 0956-053X, http://dx.doi.org/10.1016/j.wasman.2016.11.011.

Park, J., Park, N., 2014. Wet etching processes for recycling crystalline silicon solar cells from end-of-life photovoltaic modules. RSC Adv. 4, 34823–34829. https://doi.org/10.1039/C4RA03895A

Peng, J., Lu, L., Yang, H., 2013. Review on life cycle assessment of energy paybackand greenhouse gas emission of solar photovoltaic systems, Renew. Sustain. Energy Rev.19 (2013) 255–274.

Perez-Gallardo, J.R., Azzaro-Pantel, C., Astier, S., 2018. A Multi-objective Framework for Assessment of Recycling Strategies for Photovoltaic Modules based on Life Cycle Assessment. Waste Biomass Valor 9, 147–159. https://doi.org/10.1007/s12649-017-9878-0.

Ramos-Ruiz, A., Wilkening, J.V., Field, J.A., Sierra-Alvarez, R., 2017. Leaching of cadmium and tellurium from cadmium telluride (CdTe) thin-film solar panels under simulated landfill conditions. Journal of Hazardous Materials 336, 57–64. https://doi.org/10.1016/j.jhazmat.2017.04.052

Reggi, R., 2017. De-assembling system for a photovoltaic panel enabling salvage of original materials. EP3089825B1.

Rigamonti, L., Grosso, M., Giugliano, M., 2009. Life cycle assessment for optimising the level of separated collection in integrated MSW management systems. Waste Management 29, 934–944. https://doi.org/10.1016/j.wasman.2008.06.005

Rocchetti, L., Veglio, F., Kopacek, B., Beolchini, F., 2013. Environmental impact assessment of hydrometallurgical processes for metal recovery from WEEE residues using a portable prototype plant. Environ. Sci. Technol. 47, 1581-1588.

Rocchetti, L., Beolchini, F., 2015. Recovery of valuable materials from end-of-life thin-film photovoltaic panels: environmental impact assessment of different management options. Journal of Cleaner Production 89, 59–64. https://doi.org/10.1016/j.jclepro.2014.11.009

Savvilotidou, V., Antoniou, A., Gidarakos, E., 2017. Toxicity assessment and feasible recycling process for amorphous silicon and CIS waste photovoltaic panels. Waste Management 59, 394–402. https://doi.org/10.1016/j.wasman.2016.10.003

Schrijvers, D.L., Loubet, P., Sonnemann, G., 2016. Developing a systematic framework for consistent allocation in LCA. Int J Life Cycle Assess 21, 976–993. https://doi.org/10.1007/s11367-016-1063-3

Sherwani, A.F., Usmani, J.A., Varun, 2010. Life cycle assessment of solar PV based electricity generation systems: a review. Renew. Sustain. Energ. Rev.14 (2010) 540–544.

Shibasaki, M., Warburg, N., Springer, J., Lombardelli, S., 2006. Recycling of thin-film solar modules life cycle assessment case study, in: Proceedings of the 21st European Photovoltaic Solar Energy Conference, Dresden, Germany, 4–8 September, 2006.

Silva, M.D. et al., 2014. Integration of technologies and alternative sources of water and energy to promote the sustainability of urban landscapes. Resour. Conserv. Recycl. 91, 71-81.

Somorin, T.O., Di Lorenzo, G., Kolios, A.J., 2017. Life-cycle assessment of self-generated electricity in Nigeria and Jatropha biodiesel as an alternative power fuel, In Renewable Energy, Volume 113, 2017, Pages 966-979, ISSN 0960-1481, https://doi.org/10.1016/j.renene.2017.06.073.

SPE, 2018. Global Market Outlook 2018-2022 - Solar Power Europe. http://www.solarpowereurope.org/wp-content/uploads/2018/09/Global-Market-Outlook-2018-2022.pdf (last visualization: January 2019).

Stenzel, P., Schreiber, A., Marx, J., Wulf, C., Schreieder, M., Stephan, L., 2017. Renewable energies for Graciosa Island, Azores – Life Cycle Assessment of electricity generation. Energy Procedia, Volume 135, 2017, Pages 62-74, ISSN 1876-6102, https://doi.org/10.1016/j.egypro.2017.09.487.

Tao, J., Yu, S., 2015. Review on feasible recycling pathways and technologies of solar photovoltaic modules. Solar Energy Materials and Solar Cells 141, 108–124. https://doi.org/10.1016/j.solmat.2015.05.005

Tian, J., Chen, M., 2014. Sustainable design for automotive products: Dismantling and recycling of end-of-life vehicles. Waste Management, Volume 34, Issue 2, 2014, Pages 458-467, ISSN 0956-053X, https://doi.org/10.1016/j.wasman.2013.11.005.

Vellini, M., Gambini, M., Prattella, V., 2017. Environmental impacts of PV technology throughout the life cycle: Importance of the end-of-life management for Si-panels and CdTe-panels. Energy 138, 1099–1111. https://doi.org/10.1016/j.energy.2017.07.031

Veolia, 2018. Veolia opens the first European plant entirely dedicated to recycling photovoltaic panels [WWW Document]. Veolia. URL https://www.veolia.com/en/newsroom/news/recycling-photovoltaic-panels-circular-economy-france (accessed 3.1.19).

Wäger, P.A., Hischier, R., 2015. Life cycle assessment of post-consumer plastics production from waste electrical and electronic equipment (WEEE) treatment residues in a Central European plastics recycling plant. Science of The Total Environment 529, 158–167. https://doi.org/10.1016/j.scitotenv.2015.05.043

Weckend, S., Wade, A., Heat, G., 2016. End-Of-Life Management - Solar Photovoltaic panels - IEA-PVPS Report Number: T12-06:2016.

Wild-Scholten, M.J., 2009. Energy pay-back times of PV modules and systems. Proceedings of the Workshop Photovoltaik-Modultechnik. Koln, 26-27 November, 2009.

Xu, Y., Li, J., Tan, Q., Peters, A.L., Yang, C., 2018. Global status of recycling waste solar panels: A review. Waste Management 75, 450–458. https://doi.org/10.1016/j.wasman.2018.01.036.

Zeng, X., Song, Q., Li, J., Yuan, W., Duan, H., Liu, L., 2015. Solving e-waste problem using an integrated mobile recycling plant. Journal of Cleaner Production, 90 (2015) 55-59.

Zuser, A., Rechberger, H., 2011. Considerations of resource availability in technology development strategies: the case study of photovoltaics. Resour. Conserv. Recycl. 56 (1), 56-65.