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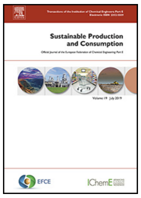

Research article

Environmental Impact Assessment of crystalline solar photovoltaic panels' End-of-Life phase: *Open* and *Closed-Loop Material Flow* scenarios

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ABSTRACT

The full life cycle of today's crystalline photovoltaic (PV) panel is dominated by a linear, open material flow paradigm. The Cradle-to-Cradle philosophy (C2C) applied in a Closed-Loop-Material-Cycle (CLMC) scenario seems promising to move towards a Circular Economy (CE). Environmental impacts associated with the End-of-life (EoL) phase of PV panels, particularly a CLMC scenario, have not yet been evaluated. To this end, this article uses the Life Cycle Assessment methodology to compare a linear Open-Loop-Material-System (OLMS) scenario with a novel CLMC system. Based on our results, the environmental impacts of a PV CLMC scenario are then compared with a Cadmium telluride (CdTe) panel CLMC scenario.

In terms of environmental impacts, the recovery of PV materials in a CLMC scenario results in substantial improvements over an OLMS scenario. Closing the material flow has reduced the Climate Change impact factor (kg CO2 eq) by 74%, compared with the OLMS scenario. However, EoL PV recycling technology still remains behind in environmental and energy intensity terms when compared to the EoL CdTe panel recycling technology within a CLMC scenario. Furthermore, during the recycling processes, our results showed that the highest specific energy uptake was 3264 TJ for PV, while for CdTe it was 2748 TJ. On the other hand, the use of toxic chemicals to recover *Si* and *Cd* are shown to significantly contribute to the environmental impacts of both EoL PV and CdTe CLMC scenarios.

Results show that the CLMC based on C2C principles has a favorable impact by reducing the environmental burden at the EoL. Nevertheless, it is imperative to reduce environmental burdens from the current thermochemical processes used to recycle silicon and to start considering the key role of C2C principles for PV panel design and recycling processes, aiming at the introduction of a CLMC system based on new standards and consistent regulations in order to reduce the environmental impacts of current PV panels, if a sustainable PV technology is desired.

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1. Introduction

In recent decades, crystalline photovoltaic (PV) panel technology deployment has been steadily growing around the world with the promise of a clean and sustainable future. However, current inefficient recovery of materials coming from PV sector at end-of-life (EoL) (Contreras-Lisperguer et al., 2017), in fact, contributes to massive waste generation and toxic emissions, and therefore increasing our dependency on non-renewable primary resources (NRPR) (Klee and Graedel, 2004). These impacts will continue impacting us if we are not able to shift current manufacturing paradigm, where the material flow is linear from its extraction, manufacturing of products (e.g., PV panels), to the EoL when the products are decommissioned and disposed as waste in a landfill or a so called *open-loop* material cycle associated with current take-make-waste economy. This life cycle paradigm is also called *cradle to grave* (McDonough and Braungart, 2002). PV panels are

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not being designed with the *reuse* of the materials at the EoL in mind, therefore, some of the materials used to manufacture the PV panels will either be disposed of or incinerated because they are neither recyclable nor reusable (Contreras-Lisperguer et al., 2017).

PV panels are and will be leading the global PV market share for the next decades to come (IRENA, 2016). It is expected that current global PV power plants will generate 1.7-8 Mt of waste in 2030 reaching 60-78 Mt by 2050 (IRENA, 2016). Furthermore, it is necessary to consider that many of the current photovoltaic technologies use exotic metals, which, in addition to their scarcity, are fundamental for the proper functioning of these technologies (Leopoldina et al., 2018). In view of a potential shortage of some of these raw materials, it is important to improve the efficiency of the current recovery rates of the materials used by the PV industry (Ardente et al., 2019), not only because of their value, but also because, if not properly recovered, they can cause serious environmental damage. Consequently, it is imperative to optimize the design of the PV technology aiming to improve EoL waste recovery and reuse of materials used in manufacturing.

In recent decades, European Union's e-waste legislation has fully considered the treatment and recycling of e-waste. In fact, a European Union (EU) directive on Waste Electrical and Electronic Equipment (WEEE) gave the proper attention to issues related to the disposal and recycling of PV panels. This new European regulation is favorably changing the way the PV industry currently perceives the EoL of PV panels (PV CYCLE, 2014). It also triggered an interest in current recycling technologies and the future material recovery of PV panels (Contreras-Lisperguer et al., 2017). However, many countries without regulation outside the EU where PV panels may still end up as waste in a landfill.

Lately, the PV industry has been working to develop an appropriate framework to decommission PV panels. Despite their efforts, there are many concerns about disposing them in landfills (IRENA, 2016). Assessing the environmental impacts at the EoL phase does not only illuminate the importance of reuse and recycling, but also reinforces the advances in current recycling technologies as we identify the necessary steps to move towards a cleaner and more environmentally friendly PV technology. Among the frameworks available that tackle the challenges for reducing the level of waste and toxic emissions, the novel *Closed Loop Material Cycle* (CLMC) based on *Cradle-to-Cradle* (C2C) principles looks promising. In a *closed-loop* cycle, all materials are used indefinitely. Consequently, all products are designed and engineered to be reused at EoL. Thus, *closed-loop* implies a circular industrial system on a Circular Economy (CE) framework, where PV panel is designed in such a way that all materials used to manufacture it at the EoL can become a primary resource without generating waste and sacrificing quality, the overall process can be regarded as "up-cycling" (Contreras-Lisperguer et al., 2017). Further, it has already been demonstrated that entropy can be kept contained for a CLMC system (Ayres, 1999).Therefore, we can reuse materials to manufacture the same or a different product as intended in a C2C system, where the "waste" of one system becomes food for another (McDonough and Braungart, 2002). However, moving from current "re-cycling" to "up-cycling" is still a challenge since PV panels are not designed with such purpose in mind and current "re-cycling" are still producing toxic by-products and waste. Here it is important to mention that the C2C approach is an advanced methodology that goes beyond re-cycling, therefore, it means an innovation in the PV technology sector (Contreras-Lisperguer et al., 2017). Furthermore, re-cycling of PV panels does not solve the problem of waste generation, because only a small fraction of materials is typically recovered during the "re-cycling phase" and put through a new life cycle. In addition, PV panels has not been designed with this idea in mind, and some of the material in a panel is neither recyclable nor reusable. Consequently, even in a "cleaner production" scenario, all materials recycled are intrinsically degraded in quality and usability, so that they eventually end up in a landfill. Overall, the C2G process can be regarded as "down-cycling" (Braungart et al., 2007; Contreras-Lisperguer et al., 2017).

Generally speaking, the metal and glass used to manufacture a PV panel can be infinitely recyclable (Reck and Graedel, 2012), however, in the PV industry, reuse of PV materials and waste generation at the EoL are challenges that still needs to be overcome to fully implement a closed-loop in the PV industry.

This article illustrates the comparison of an Open-Loop-Material cycle and a novel Closed-Loop-Material cycle scenario at the EoL phase for a PV panel using the Life Cycle Assessment (LCA) methodology. Since the shift from a linear to a circular material flow for crystalline PV panels industry is no trivial undertaking, the study is main focused on assessing the main environmental impacts associated with a Closed-Loop-Material-Cycle (CLMC) based on C2C principles (Contreras-Lisperguer et al., 2017). Unfortunately, no environmental impact assessment has been performed for most of the current recycling technologies because detailed data inventories are not disclosed because of proprietary issues. However, using to the best of our knowledge, the only experimental open inventory data available from current recycling technology is from the 'Full Recovery End of Life Photovoltaic' (FRELP) project (FRELP Project, 2018). Additionally, in order to closing the material flow, we have included a transportation phase from the recycling facility to an industrial facility for reuse of the recovered materials. Finally, we discuss about the role of PV design to reduce negative environmental impacts at the EoL. Further, the analysis developed here represents the life-cycle of a novel theoretical CLMC system (not commercially available). Models like this can help to lay the foundation helping to grasp the challenges ahead for a circular economy society.

The paper is divided into the following sections. Section 2 describes the alternative recycling pathways available for crystalline silicon-based PV panels. Section 3 presents a summary of relevant LCA for the EoL of PV panels, and both sections 2 and 3 explain the urgency for open data inventories to perform environmental assessment for PV recycling technologies. In section 4 we discuss methodology, goal and scope of the LCA, along with some challenges of PV disposal. Subsequently, in section 5 LCA methodology is applied to study EoL scenarios and results are discussed, along with some key suggestions for policy-makers and the private sector. In section 6, the environmental impacts of PV and CdTe technologies are assessed and compared, while suggestions and limitations are given at section 7. Finally, conclusions are presented in section 8.

2. Recycling pathways for crystalline silicon-based PV panels

Deutsche Solar has been investigating ways to recycle panels, achieving encouraging results using a combination of thermal and chemical treatment (Müller et al., 2006), In the United States, SunPower and other PV manufacturers have launched the Solar Energy Industries' Association's (SEIA) where recycling technologies are being developed (SunPower, 2017). Fraunhofer IBP has been implementing a mechanical process where PV panels are shred and separated and only aluminum and glass are recovered for recycling (Fraunhofer IBP, 2012; Held, 2013).

According to the latest literature available for crystalline silicon-based PV panels, recycling pathways after recollection can be categorized into physical treatment, thermal treatment, chemical processes and a combination of these treatments. In this regard, the scientific literature about these different approaches is quite abundant and a complete analysis and summary of these approaches can be found in Padoan et al., 2019. Therefore, and in order to understand how these different approaches and their combinations are used for recycling PV panels, we have divided the recycling process into their main stages (adapted from Tao and Yu, 2015):

a. *Delamination*: Here the ethylene vinyl acetate (EVA) is removed to access the PV components materials. At this stage the panels can undergo many alternative treatments to remove the EVA layer. The main treatment pathways used are: high temperature pyrolysis (Dias et al., 2017; Doni and Dughiero, 2012), organic solvents (Doi et al., 2001), acids (Bruton et al., 1994), and a combination of organic solvents and heat treatment that can be achieved also by an assisted ultrasonic method to improve the dissolution rate of the EVA (Kim and Lee, 2012). In this review we have not considered the physical process where the Si recovered is heavily contaminated with impurities making the recycling process more complex requiring additional treatments.

Delamination can be considered the most crucial step for crystalline silicon-based PV panels' recycling because as long as proper treatment is applied, it will be possible to recover an undamaged solar cell that can be reutilized, avoiding complex treatments (Xu et al., 2018) and reducing the recycling costs (Pagnanelli et al., 2017).

b. *Material separation*: Subsequently, after EVA is fully removed, the glass, aluminum, and solar cells are manually or mechanically separated from the panel. According to the literature review, most of the process utilized at this stage is mostly manual or very low automated (Padoan et al., 2019; Tao and Yu, 2015; Xu et al., 2018). At this stage, glass and aluminum are directly recovered and can be sent to a facility for direct reuse and/or recycling. The undamaged solar cells recovered may be reused, however, if during the delamination stage solar cells are exposed to inorganic acids or temperatures greater than 450°, they get damaged and cannot be directly reused after recovery (Tao and Yu, 2015).

c. *Solar cells recovering and Silicon extraction*: If solar cells have been recovered undamaged, they are chemically treated to recover valuable metals (i.e. Ag) and to remove the antireflective layer. Some chemical treatments commonly used in crystalline Si based PV panels use a combination of potassium hydroxide to remove Al coating and nitric acid to extract Ag (Klugmann-Radziemska and Ostrowski, 2010; Shin et al., 2017). It has suggested that undamaged solar cells can be fully recovered by using a trichloroethylene solvent at 80°C for 10 days (Doi et al., 2001).

The main procedures used to remove the antireflective layer involve etching wafers with a combined sequence application of ethanoic acid, nitric acid, hydrofluoric acid and bromine (Klugmann-Radziemska and Ostrowski, 2010). Others authors suggest the use of an etching paste which contains phosphoric acid (Shin et al., 2017) and a single hydrofluoric acid solution (Xu et al., 2018). Generally, once PV panels undergo the process described above, the recycled wafers can be fully recycled and reutilized in a solar cell factory line.

Sometimes, it is not possible to integrally recover a silicon wafer, mostly because a PV panel breaks or a wafer gets damaged (i.e. micro-fractures, cracks, broken etc.). When this happens, more elaborate treatments are required, and alternatives have been studied. For example, PV panels can be immersed in an organic solvent to separate glass from PV panel following several high temperature treatments. Then, Si is recovered as crystalized fragmented particles and purified with a chemical etching process combining hydrofluoric acid, sulfuric acid and nitric acid for 20 minutes (Kang et al., 2012). Another approach has considered the use of a thermochemical process to separate solar cells from a damaged PV panel by immersing it in a silicic acid anhydride solution in combination with a thermal treatment, then, the damaged solar cells follow a thermochemical process to recover pure silicon (Klugmann-Radziemska and Ostrowski, 2010).

When panels are crushed multiple times to reduce their size, the fragments require multiple thermal treatments to remove EVA layer. After that, the fragments are thermochemically treated to recover Si and other metals with a mix of hydrogen chloride, hydrogen peroxide, and nitric acid in a microwave digester at 220 °C (Pagnanelli et al., 2017).

The Si recovered is sent back to a solar cell manufacturing facility because it is generally the pure form of the element (> 99.8% Si).

PV panel recycling technologies are still relatively new and they come with new challenges that need to be solved (Padoan et al., 2019). In the following section, we describe the main PV panel recycling pathways. Because PV panel recycling requires chemical and thermal processes, we have been keen to take the environmental impact associated with each methodology into consideration. Although we tried to find sources detailing these issues, no detailed disaggregated data was found about them.

3. Life Cycle Assessment of EoL PV recycling pathways

Life Cycle Assessment (LCA) can be considered an effective tool to evaluate the environmental impacts the PV industry has on the environment (Fthenakis and Kim, 2011). LCA is a tool that has evolved rapidly in the last decade and has become the preferred tool used by researchers and academia to identify resource flows and environmental issues associated with the provision of services and products (Poudelet et al., 2012) . Additionally, the increasing interest in climate change and reduction of greenhouse gases has made the use of LCA even more widespread due to its ability to assess these emissions in a wide variety of industrial and service sectors, while also being convenient to assess other environmental impacts.

Even though the environmental impacts coming from PV panels has been a widely studied subject using the LCA methodology, today most of the LCA performed on this subject has been focused on a cradle-to-grave perspective. Sources consider environmental impacts mostly coming from the production, installation, and use phases. Very few have assessed the EoL (Fthenakis and Kim, 2011; Fu et al., 2015; Tsang et al., 2016). Further, some PV recycling technologies that claim small environmental impacts (Huang et al., 2017) do not provide detailed disaggregated data or inventories in order to assess such claims using the LCA methodology.

A review of scientific literature available on LCAs of PV panels confirms the above statement and also shows that few studies consider the environmental impacts coming from existing recycling pathways for the EoL of PV panels (Gerbinet et al., 2014). Consequently, one of the biggest challenges when evaluating the life cycle environmental impacts of a PV panel is the lack of reliable Life Cycle Inventories (LCI) and the reduced number of LCA studies modeling the EoL phase with disaggregated data. Specifically, there is a gap in scientific literature when it comes to the assessment of environmental impacts coming from different recycling methods and reusing PV panel materials.

Most of the current recycling technologies described in section 2 lack of data inventories since they are not disclosed because of proprietary issues. Additionally, many PV panel recycling facilities are still in their pilot stage and very little is known about their environmental impacts. A summary from scientific literature of some LCI and LCA of PV recycling technologies is available in Table 1.

Table 1
Summary of scientific literature regarding main LCI and LCA of PV recycling technologies

Reference	Process	Data
Müller et al., 2005	LCA study of Solar Module Recycling Process based on the thermal and chemical Deutsche Solar's recycling technology	Disaggregated data and Lifecycle Inventories of the recycling technology are not provided
Bayod-Rújula et al., 2011	LCA study with an EoL scenario where the environmental impacts have been linked to the waste treatment processes of Ecoinvent (disposal in a landfill)	Disaggregated data and Lifecycle Inventories of the recycling technology are not provided
Zhong et al., 2011	LCA study with an EoL scenario that do not describe both technology and processes involved in the recycling of PV panels. No functional unit is provided.	Disaggregated data and Lifecycle Inventories of the recycling technology are not provided
Proietti et al., 2012	LCA study with an end-of-life scenario is modeled considering the thermal and chemical Deutsche Solar's recycling technology	Disaggregated data and Lifecycle Inventories of the recycling technology are not provided
C. Latunussa et al., 2016a	LCA study with an end-of-life scenario modeled based on the FRELP project. This study does not consider the return of material to the industrial cycle and re-use.	Disaggregated data and full Lifecycle Inventories of the recycling technology are provided
Lunardi et al., 2018	LCA study with an EoL scenario that does not describe the recycling technology assessed. Breakdown percentage of materials is not provided.	Disaggregated data and Lifecycle Inventories of the recycling technology are not provided

Table 2
Benefits of a Closed Loop Material Cycle (CLMC) based on Cradle-to-Cradle (C2C) principles

Reference	Benefits
Braungart et al., 2007	It defines the principles of a CLMC and provides a classification for technical and biological closed-loop-cycle.
Bridgens et al., 2017	It is recognized that a CLMC facilitates the recovery of valuable functional components and metals from e-waste and reduces the amount of e-waste.
Ruben Contreras-Lisperguer et al., 2017	The value of a CLMC as a new alternative way to control materials flow and a new business opportunity are identified. To provide sustainability, the authors suggest the use of C2C principles.
Niero and Hauschild, 2017	Identified that a CLMC based on C2C principles is today the most comprehensive and still operational framework and best at preventing burden shifting between stakeholders in the value chain.
Hahladakis and Iacovidou, 2018	Identified that a CLMC enabling recirculation of materials back in the economy.
Kalmykova et al., 2018	Based on the C2C principles, it is asserted that a CLMC should necessarily aim for eco-effectiveness rather than eco-efficiency (here a CLMC is symbolized as Circular Economy)

Based on our literature review, it is evident that there is little to no research regarding the environmental impacts of a Closed-Loop-Material-Cycle (CLMC) system. These issues become relevant if we are aiming to fully describe the implications and the benefits of reusing PV panel materials. Hence, some authors have suggested the value of a CLMC, and the potential sustainability of a CLMC when Cradle-to-Cradle (C2C) principles are applying within it, however, further research to support robust business decisions and policy development is still required to closed the material loop (Niero and Hauschild, 2017). A description of these benefits based on the literature reviewed is provided in Table 2.

Here, we draw on the imperative to assess the environmental benefits and impacts for the EoL of PV panels (Perez-Gallardo et al., 2018). We have used the open and *disaggregated* LCI data available for PV recycling technology from the 'Full Recovery End of Life Photovoltaic' (FRELP) project (FRELP Project, 2018) to model an innovative CLMC system and assess the potential environmental impacts coming from a CE point of view.

4. Methodology

In this research, LCA methodology is used to evaluate the environmental impacts at the EoL of PV panels for an *Open-Loop-Material-System* (OLMS) and *Closed-Loop-Material-Cycle* (CLMC) scenarios. This LCA study was conducted according to ISO 14040 (ISO 14040, 2006) and ISO 14044 (ISO 14044, 2006). The LCA has been modelled using the SimaPro software version 8.0. For the impact assessment of both scenarios the ReCiPe impact assessment methodology was utilized. The ReCiPe[1] methodology is widely accepted and used in academia (Hauschild et al., 2011), and represents an intermediate solution between different methodologies while sustaining advantages and lessening drawbacks (Goedkoop et al., 2009). In order to evaluate impact scores, the ReCiPe midpoint (H) evaluation method was used in this study (ReCiPe, 2010). Finally, the study compared results of both scenarios for the chosen impact categories. Results and interpretation are presented.

Here, LCI data about FRELP was obtained from FRELP reports (Latunussa et al., 2016a, 2016b) and the latest scientific literature available (section 2). As supplementary data, the latest international reports available were used (IRENA, 2016; Lee and Komoto, 2017; Wambach, 2017), and when data was not available in the sources mentioned above, we used the information available at the Ecoinvent 3.1 database, which is globally recognized as one of the most consistent LCI databases available (Ecoinvent, 2013).

4.1. Goal, Scope and Functional Unit

The goal of this LCA is to assess and compare the environmental impacts for the EoL of PV panels within an open and closed loop material cycle framework:

a) an *Open-Loop-Material-System* (OLMS) scenario, where there is no recovery, and recycling. Here, PV panels are incinerated as

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[1] Version 1.11. Available here: https://www.rivm.nl/documenten/lcarecipenormalisation2000factors-revised2010

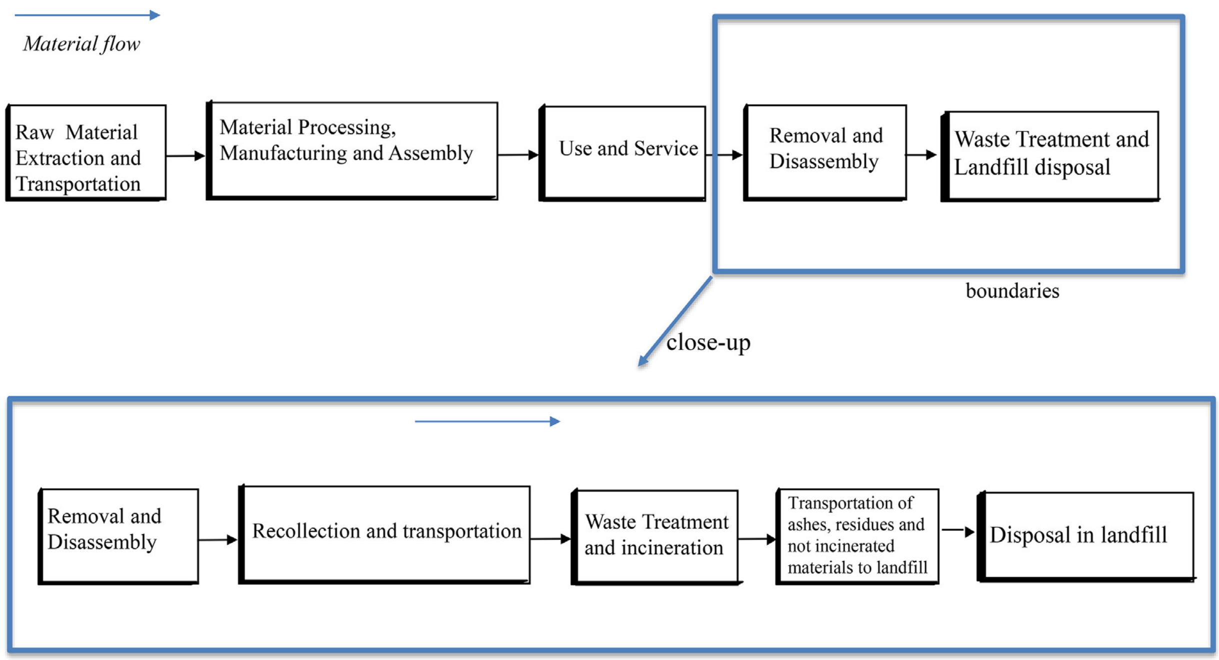

Figure 1. Simplified LCA system boundaries for the EoL PV *Open-Loop-Material-System* scenario

municipal waste, then waste/residues from incineration are disposed in a landfill as final step of the EoL phase;

b) a *Closed-Loop-Material-Cycle* (CLMC) scenario. At this point we attempted to model an innovative CLMC system based on C2C principles (Contreras-Lisperguer et al., 2017). A CLMC resembles a circle where materials are continually reused. Using C2C principles in a CLMC system implies that the amount of what is considered waste should be equal to the amount of resources. In other words, the system should be powered exclusively by renewable energy sources and should support biodiversity and socio-cultural diversity (Ankrah et al., 2015). In order to model such a system, we have built a scenario were PV panels are disassembled, recycled, and then salvaged for reuse as final step of the EoL phase. Despite these efforts, it was not possible to avoid waste generation after the recycling process because of the recycling method used in the FRELP project and a lack of studies and data about a CLMC system, since this is the first attempt to model it. In order to close the loop of material flow, we have included a transportation phase from the recycling facility to an industrial facility for reuse of the recovered materials, and an energy scenario based on C2C principles was also formulated. As of now, all recycling processes include a disposal phase for waste/residues after all salvageable PV materials are recycled. Figure 1 and Figure 2 show the LCA system boundaries modeled in this study.

In addition to the scenarios described above, we have developed two *EoL-energy scenarios*. For the *CLMC* based on C2C principles, PV panels has been used to generate the electricity needed during the recycling process. However, due to the current FRELP recycling technology used, the incineration and transportation are still powered by fossil fuels. For the *OLMS* scenario, and based on LCI data power and heat used in all stages are generated by fossil fuels. For consistency with available data and new EU directive on European recycling sector (Gazbour et al., 2018), the electricity consumed is based on the European average electricity mix at medium voltage, (with 24 countries being interconnected in the synchronous grid of Continental Europe) and is based on data available from Ecoinvent (Ecoinvent, 2013).

Table 3
Summary of the mass breakdown of a FU obtained during the recycling of the decommissioned C-PV panel

Material	Mass (kg)
Glass	700
Aluminum (Frame + internal conductor)	185.3
EVA	51
Solar cell (Silicon)	36.5
Back foil sheet (plastic)	15
Silver	0.53
Tin	0.18
Led	0.35
Copper (cable and internal conductor)	11.13
Total	~1000 kg

The functional unit (FU) considered in this study is 1000 kg of PV material. The *CLMC* is representative of 1000 kg of materials recycled at the EoL phase, otherwise known as a "gate-to-cradle" approach. The *OLMS* is representative of 1000 kg of PV material that is incinerated and disposed in a landfill at the EoL phase, otherwise known as a "gate-to-grave" approach.

To maintain the integrity of both scenarios, in this study the results obtained in the *CLMC* did not include any kind of credits.

4.2. Life Cycle Inventories for the EoL scenarios

As described above, the life cycle inventories of the EoL phase scenarios are based on disaggregated data from sources from the latest scientific literature available and the background data is based on disaggregated data available in more general reports and studies (IRENA, 2016; Lee and Komoto, 2017; Stolz and Frischknecht, 2017; Wambach, 2017), If some background data (e.g., transportation, incineration, disposal on landfill, municipal waste treatment, use of electricity, etc.) was not available in the literature mentioned above, the data was collected from the Ecoinvent database (Ecoinvent, 2013) and/or from similar processes, and older data if necessary (European Commission, 2010). The mass composition of PV waste is described in Table 3. Concerning the LCI, both scenarios are described in Table 4. In the following sec-

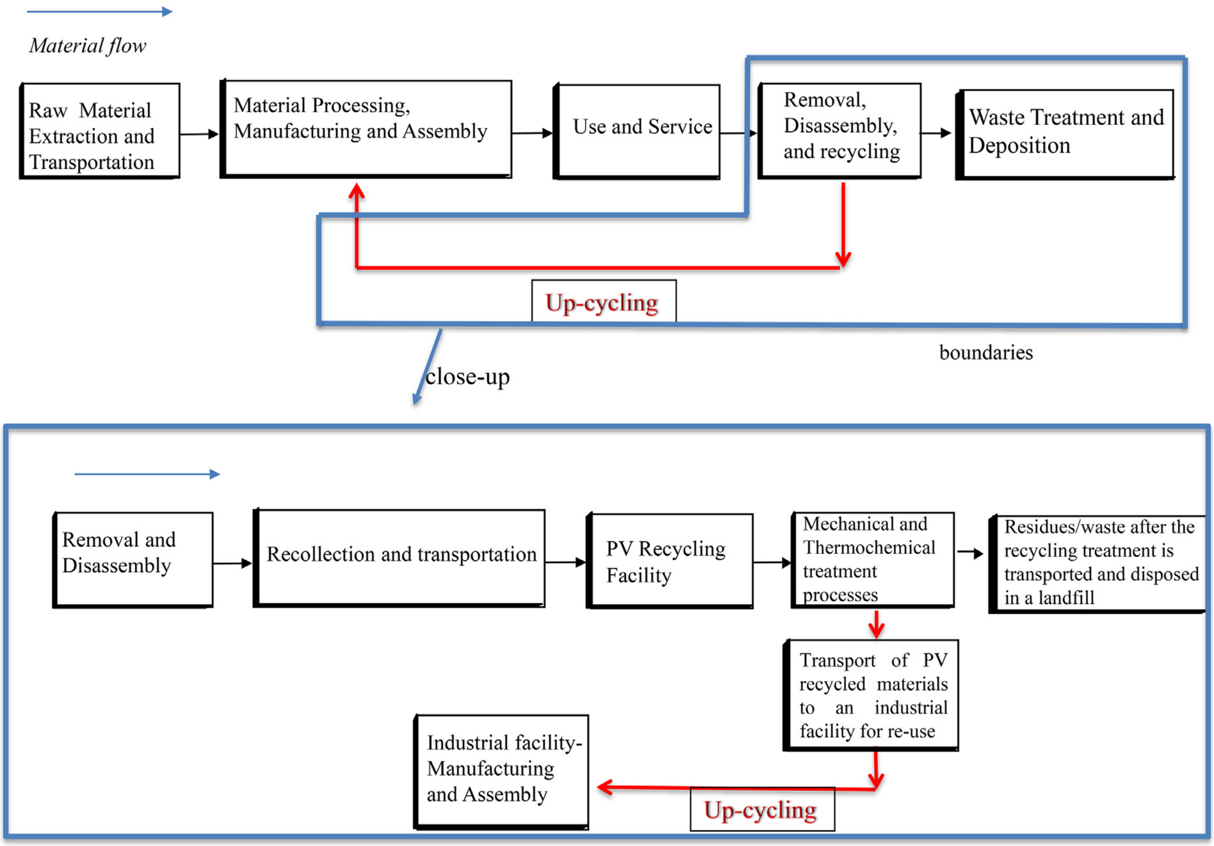

Figure 2. Simplified LCA system boundaries for the EoL PV *Closed-Loop-Material-Cycle* scenario

Table 4
Summary of LCI in both scenarios (excluding data from Ecoinvent database)

Open Scenario Input	Quantity	Unit	Closed Scenario Input	Quantity	Unit
PV Waste	1000	kg	PV Waste	1000	kg
Diesel fuel	1.14	l	Diesel fuel	1.14	l
			Electricity	114	kWh
			Water	309.71	kg
			HNO_3	7.08	kg
			Ca $(OH)_2$	36.5	kg
			Emissions		
			Outputs	**Quantity**	**Unit**
			NO_X	2	kg
Waste to landfill			**Recycling waste to landfill**		
Outputs	**Quantity**	**Unit**	**Outputs**	**Quantity**	**Unit**
PV Waste (incinerated* 1000 kg and landfilled**)			Contaminated glass	14.50	kg
			Fly ash (hazardous waste)	2	kg
*__Incineration__:			Liquid waste	306.13	kg
• disposal, plastics, mixture, 15.3% water, to municipal incineration; disposal, scraps metals, 0% water, to municipal incineration; disposal, glass, 0% water, to municipal incineration			Sludge (hazardous waste)	50.25	kg
			Recovered material	**Quantity**	**Unit**
**__Landfill__:			**Outputs**		
• disposal, slag from Metallurgical Grade (MG) silicon production, 0% water, to inert material landfill; disposal, waste, Si wafer, inorganic, 9.4% water, to residual material landfill; disposal, aluminum, 0% water, to sanitary landfill; inert material disposal, glass, 0% water, to landfill; plastics, mixture, 15.3% water, to sanitary landfill			Cooper	4.45	kg
			Glass	685.49	kg
			Aluminum	183.10	kg
			Metallurgical grade silicon	34.68	kg
			Silver	0.50	kg

tion we describe the LCI for the two scenarios developed in this study.

4.2.1. Life Cycle Inventory data – EoL Open and Closed-Loop material cycle scenarios

a. *In the Open-Loop scenario,* the PV panels are neither reused nor recycled, they go straight after recollection from the PV power plant location to an incineration facility to later be disposed as municipal waste. This was modeled following a suitable waste stream process according to the Ecoinvent database (incineration and disposal at a landfill). The transportation from the decommissioned PV power plant to the incineration facility is modeled as a truck (Lorry 7.5-16t/EURO 5) used to recollect and transfer the waste among locations and the forklift (loading/unloading truck) are based on the Ecoinvent database. The distance from the PV power plant to the incineration facility is assumed as an average distance of 200 km (for this study that distance can be considered appropriate since usually large PV power plants are in rural areas). Finally, the transportation from the incineration facility to the municipal landfill is modeled as a truck (Lorry 7.5-16t/EURO 5) with an average distance of 50 km.

The energy needs, as explained above, are modeled in an *EoL Open-Energy* scenario. In this scenario, all the electricity consumed in this scenario comes from the European average energy mix at medium voltage based on the data available from Ecoinvent[2].

b. In the Closed-Loop scenario, PV panels are collected and transported to a facility for disassembly. The diesel consumed by the truck (Lorry 7.5-16t/EURO 5) is also modeled based on the Ecoinvent database. In order to keep consistency across scenarios, we have assumed an average distance of 200 km from the recollection site to the recycling facility. The forklift used to transfer materials in this scenario is powered by diesel fuel as in the *Open-Power* scenario. The materials are then transported to the recycling facility. The recycling technology considered in the *Closed-Loop material scenario* and the mass composition of the breakdown is modeled based on the FRELP process. The mass composition breakdown is described in Table 3. As it was explained in section 4.2, we intended to use a C2C approach in a *closed-loop* material system (Contreras-Lisperguer et al., 2017). However, modeling a C2C system today exactly as is intended (McDonough and Braungart, 2002) is still not possible due to the lack of reliable data and '*C2C-ness*' *(C2C-ness can be defined as how much or how little a product adheres to C2C principles and can inform future C2C design solutions)* reliable data for the PV industry. *The scale used is based on a C2C Certification scheme that has the following categories: levels of silver, gold, and platinum content)* of the current PV panels available on the market. For purposes of the study, we adapted available data to simulate the C2C paradigm. Nevertheless, in this scenario it was impossible to avoid the incineration/disposal of some of the materials in a landfill (e.g., incineration of PV encapsulation, disposal of fly ash, etc.). Technically, based on C2C principles, the concept of a *quasi closed-loop material cycle* viewpoint has been introduced and modelled. In this scenario we consider that the incineration plant used to recover materials from the PV sandwich can be found in the same recycling facility. As a result, fly ashes are transported to a landfill located 50 km away from the recycling facility and the bottom ashes are treated in the recycling facility to recover the left-over materials. Once the materials finish the recycling process, all the recovered materials are transported from the recycling facility to an industrial facility for reuse. In this study, an average distance of 50 km from the recycling facility to the industrial material recovery facility is assumed as reasonable. It is expected that in the future, distance can be reduced once recycling facilities are universally accessible.

The energy needed for a successful *EoL Closed-Energy* scenario includes the needs of the entire recycling facility, which is powered by PV solar energy (excluding the incineration facility). This facility aims to improve the benefits of the *Closed-Loop material cycle* system and maximize efforts to emulate C2C principles. Electric power was modeled as a PV power plant (the system represents a set of PV panels ground mounted and standard BOS components) able to generate the 114 kWh required to satisfy the recycling facility electricity needs to process a FU. For the *EoL Closed-Energy* scenario, we use data mainly from the SimaPro Ecoinvent database to model the PV panels, Balance of System (BOS), storage system, and electricity generation. In the case of PV modules, data was complemented with the additional findings from the available literature (Eitner et al., 2017; Fraunhofer ISE, 2018; Held, 2013).

Table 5
Summary of the ReCiPe midpoint impact categories, and units

ReCiPe midpoint impact categories	Abbreviation	Unit
Climate change	CC	kg CO_2 eq
Ozone depletion	OZ	kg CFC-11 eq
Terrestrial acidification	TA	kg SO2 eq
Freshwater eutrophication	FE	kg P eq
Human toxicity	HT	kg 1,4-DB eq
Particulate matter formation	PMF	kg PM10 eq
Freshwater ecotoxicity	FET	kg 1,4-DB eq
Ionizing radiation	IR	kg U235 eq
Metal depletion	MD	kg Fe eq
Fossil fuel depletion	FFD	kg oil eq
Marine eutrophication	ME	kg N eq
Photochemical oxidant formation	POF	kg NMVOC
Terrestrial ecotoxicity	TET	kg 1,4-DB eq
Marine ecotoxicity	MET	kg 1,4-DB eq

This methodology described above must be interpreted cautiously as a quasi-CLMC system based on C2C principles is not currently in operation. Therefore, the present analysis represents the life-cycle of a novel theoretical prototype system. In the next section results are presented and discussed, which will be crucial to explain that circularity per se is not necessarily sustainable.

5. LCA comparison results open and closed system – interpretation, and discussion

The LCA of the FU modeled for these scenarios was implemented using the ReCiPe methodology. The impact categories assessed in this study using ReCiPe are: climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, human toxicity, particulate matter formation, freshwater ecotoxicity, ionizing radiation, metal depletion, fossil fuel depletion, marine eutrophication, photochemical oxidant formation, terrestrial ecotoxicity, and marine ecotoxicity (see Table 5). Due to the lack of consistent LCI data, the following impact categories were not considered: urban land occupation, natural land transformation, water depletion, and agricultural land occupation.

5.1. LCA comparison-environmental impacts: Open and Closed loop material cycles

On the basis of the scenarios constructed, the inventory results for the FU in both scenarios were normalized based on the Europe ReCiPe midpoint H methodology (The ReCiPe Team, 2010). This step facilitated the comparison between different impact category indicators (PRé, 2014). Normalization is calculated by dividing the scores calculated by a reference value, already established for the ReCiPe impact assessment methodology, at each impact category to obtain "normalized" data. The normalization factors used in this research are available on the ReCiPe website (ReCiPe normalization factors, 2010). Here, the normalized impact assessment corresponds to the annual impact of a single European in each category (Sleeswijk et al., 2008). Figure 3 shows the normalized im-

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[2] The data used in this article are representative of the averaged EU electricity mix from 2013 available in Ecoinvent 3.1. According to data from Eurostat, the shares of fossil fuels and nuclear in the EU electricity mix dropped from 63% in 2013 to 58% in 2017, which means a difference of only 5%. Consequently, the averaged electricity mix in the EU at 2017 is still dominated by fossil fuels, therefore, in principle we think that, in terms of order of magnitude, our results are still representative for the EoL Open-Energy scenario. Data available here: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Maximum_electrical_capacity,_EU-28,_2000-2017_(MW).png

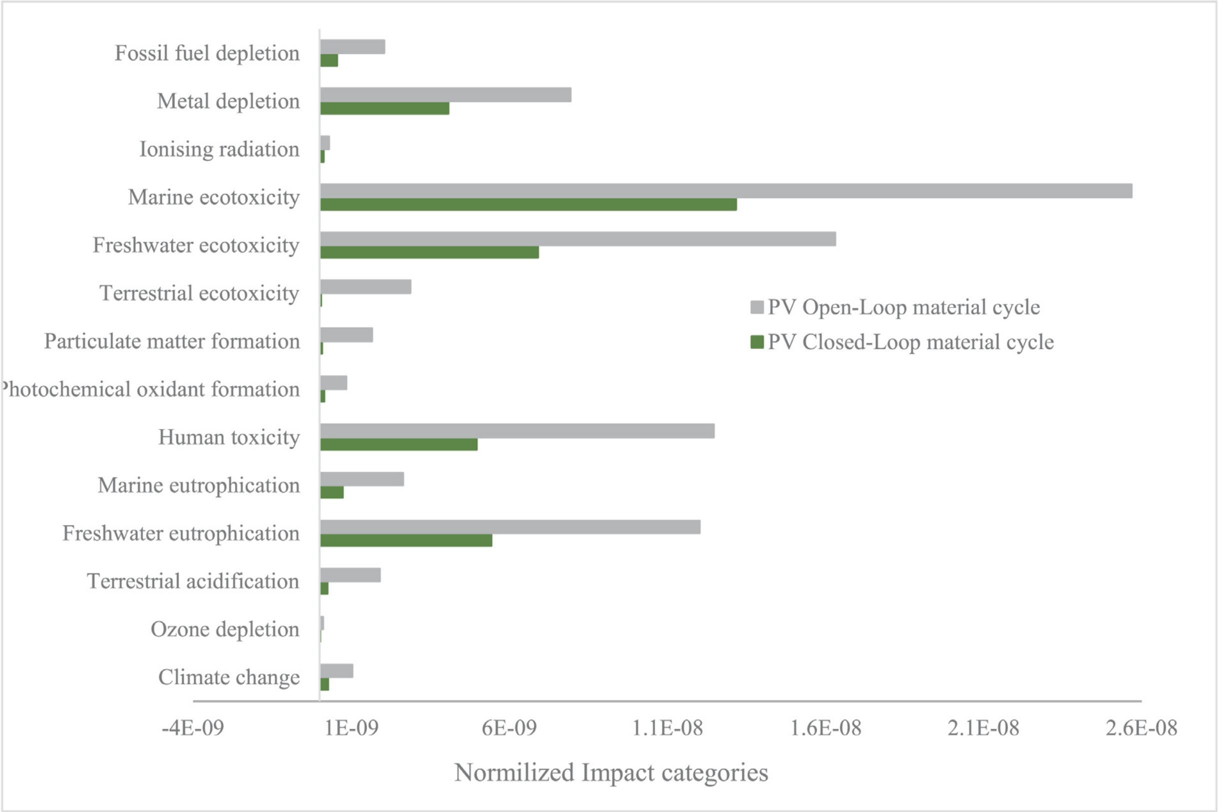

Figure 3. Comparison of normalized impacts per each category for the two scenarios

Table 6
Environmental impacts results: PV Open-Loop scenario and PV Closed-Loop scenarios

ReCiPe midpoint impact categories	Abbreviation	Unit	PV OLMC scenario	PV CLMC scenario
Climate change	CC	kg CO2 eq	5.39E+03	1.38E+03
Ozone depletion	OD	kg CFC-11 eq	1.16E-03	2.31E-04
Terrestrial acidification	TA	kg SO2 eq	3.04E+01	4.00E+00
Freshwater eutrophication	FE	kg P eq	2.32E+00	1.05E+00
Marine eutrophication	MEP	kg N eq	1.24E+01	3.44E+00
Human toxicity	HT	kg 1,4-DB eq	3.63E+03	1.45E+03
Photochemical oxidant formation	POF	kg NMVOC	2.24E+01	3.89E+00
Particulate matter formation	PMF	kg PM10 eq	1.15E+01	5.33E-01
Terrestrial ecotoxicity	TET	kg 1,4-DB eq	1.10E+01	1.93E-01
Freshwater ecotoxicity	FET	kg 1,4-DB eq	8.34E+01	3.53E+01
Marine ecotoxicity	MET	kg 1,4-DB eq	1.04E+02	5.34E+01
Ionizing radiation	IR	kg U235 eq	8.88E+02	3.73E+02
Metal depletion	MD	kg Fe eq	2.63E+03	1.35E+03
Fossil fuel depletion	FFD	kg oil eq	1.48E+03	4.01E+02

pact assessment comparison for the selected impact categories for the two scenarios.

As expected, the evaluation of the absolute values for each impact categories for the *Open* and *Closed loop* material cycle scenarios show that the *Closed-Loop* material cycle scenario has the highest environmental benefits (see Table 6). However, the normalized results (see Figure 3) show that some categories from the *Open-Loop* scenario have significantly reduced their impact's magnitude. According to the results, for the *Open-Loop* material cycle scenario the major impacts are observed in fossil fuel depletion, metal depletion, freshwater ecotoxicity, marine ecotoxicity, human toxicity, marine and freshwater eutrophication, and climate change categories. The impacts of these categories mentioned above are mainly due to the transportation, incineration of plastics, PV residual materials disposed in the landfill, and the energy consumed during the EoL processes.

The incinerated PV panels residues that ended up landfilled has direct ecotoxicity impacts that are related to the emission of toxic pollutants and the discharge of wastewater into the environment. Most of these pollutants are discharged to the environment through leaching from the PV waste incineration ash, which can contain toxic metals such as lead.

This EoL scenario reduces the recovering alternatives of materials, while recycling and subsequent recovery of materials in a *Closed-Loop* material cycle scenario dramatically reduces waste generation and environmental impacts, compared to the *Open-Loop* material cycle scenario. Our results correlate fairly well with earlier findings (Vellini et al., 2017), corroborating that closing the material flow by recycling means has overall a highly positive impact, reducing environmental burdens in virtually all categories evaluated in this study. In fact, we found that the Climate Change impact factor (kg CO2 eq) is reduced 74%, whereas Vellini et. al.

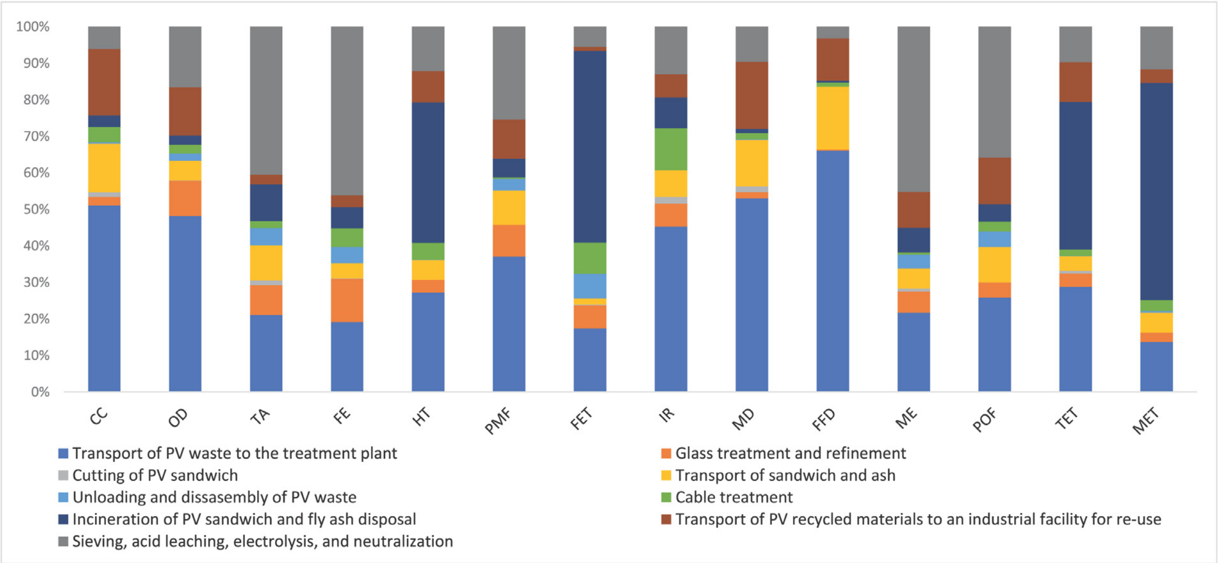

Figure 4. Contribution of different processes to the selected categories for the *Closed-Loop* scenario

(Vellini et al., 2017) found an impact reduction of 24% for the Global Warming Potential impact factor (kg CO2 eq), which however referred to a different impact indicator and methodology. A direct comparison of the impact assessment results was not possible because the data was presented only as percentages.

It can be concluded that the PV Open-Loop scenario has higher environmental impacts than the PV Closed-Loop scenario. The PV Open-Loop scenario is responsible for greenhouse gas emissions, pollutants and toxic waste throughout the PV EoL phase, while the PV Closed-Loop scenario shows significant reductions in all of the impact categories evaluated in this article. Therefore, a PV Closed-Loop system based on C2C principles may support the shifting towards a reduction of waste generation and promote up-cycling at the PV EoL phase.

Even so, the *Closed-Loop* material cycle scenario still has relevant environmental impacts. The transportation, incineration of plastics and PV sandwich, disposal of the sludge and fly ashes on a landfill from the thermochemical process used during recycling of the PV panels are the major contributors in the potential impacts observed in the following categories: particulate material formation, fossil fuel depletion, freshwater ecotoxicity, climate change, metal depletion, and photochemical oxidant formation. It is notable in this study how transport contributes the most to potential impacts in every category analyzed in both EoL phases.

Yet, the initial comparison between the two scenarios (see Figure 3) begs further questions. When compared to the *Open-Loop* scenario, the impacts attributed to the *Closed-Loop* scenario merit thorough analysis to identify key waste challenges that still need to be addressed. Understanding how new emerging PV recycling technologies are impacting the environment and human health is essential to provide direction for research, investments, and policies to make PV panels a fully sustainable technology.

To identify these challenges, we assessed the relative environmental impact contribution for each of the sub-unit processes involved in the *Closed-Loop* material scenario (see Figure 4). The identified challenges will be valuable information that will develop some key messages for policy makers and private PV sector.

Figure 4 shows that most of the impacts are linked to different transportation phases included in the *Closed-Loop* scenario. According to the results, the most relevant impacts are registered in the following categories:

Table 7
Total contribution of transportation to the impact categories for the *Closed-Loop* material cycle scenario

Impact categories	Abbreviation	Percentage (%)
Climate change	CC	82.58%
Ozone depletion	OZ	66.81%
Human toxicity	HT	41.19%
Particulate matter formation	PMF	57.04%
Ionizing radiation	IR	58.85%
Metal depletion	MD	84.08%
Fossil fuel depletion	FFD	94.86%
Photochemical oxidant formation	POF	48.27%
Terrestrial ecotoxicity	TET	43.67%

Table 8
Contribution estimated on some of the highest impact categories for the *Closed-Loop* material cycle scenario from: a) incineration of PV sandwich and fly ash disposal and b) Sieving, acid leaching, electrolysis, and neutralization

Impact categories	Abbreviation	Percentage (%)
Human toxicity	HT	38.47%
Freshwater ecotoxicity	FET	52.52%
Terrestrial ecotoxicity	TET	40.40%
Marine ecotoxicity	MET	59.39%
Impact categories	**Abbreviation**	**Percentage (%)**
Terrestrial acidification	TA	40.58%
Freshwater eutrophication	FE	46.15%
Particulate matter formation	PMF	25.47%
Marine eutrophication	ME	45.21%
Photochemical oxidant formation	POF	35.86%

Based on the results presented in Table 7, climate change and fossil fuel and metal depletion are the most impacted categories. Additionally, for the other impact categories, the contribution ranges between 41.19% (human toxicity) to 66.81% (ozone depletion), suggesting an important impact on those categories too. Considering new transportation technologies and planning the location of future recycling plants will be crucial to reduce the overall environmental impacts generated by the *Closed-Loop* scenario. On the other hand, incineration of the PV sandwich, fly ash disposal, Sieving, acid leaching, electrolysis, and neutralization are also responsible for significant environmental impacts on many of the categories included in this study. Based on the results, the highest contribution estimates are for the following impact categories:

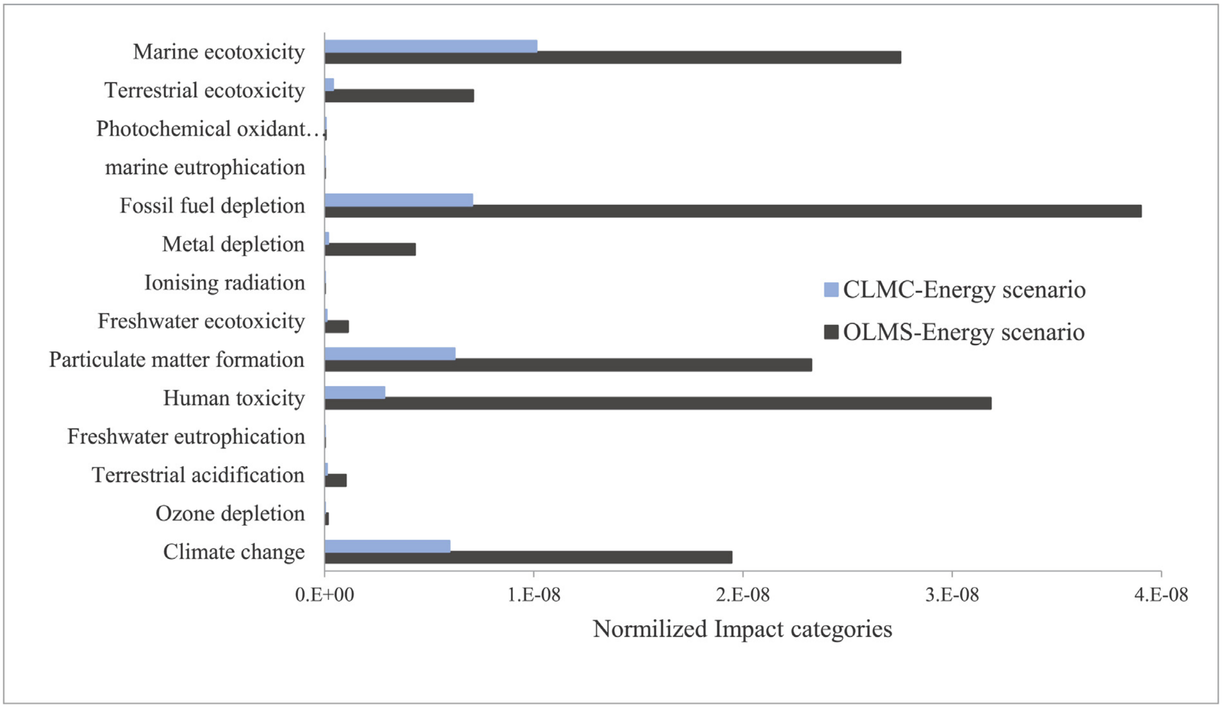

Figure 5. Comparison of normalized impact categories results for the CLMC-Energy scenario and the OLMS -Energy scenario

Table 8 shows that the major drawback of the recycling method assessed here (FRELP method) is responsible many for environmental impacts being the second most important after transportation. Thus, the use of chemicals and incineration of the PV sandwich should be carefully studied to reduce further environmental impacts.

An alternative pathway to remove EVA from PV panels could be the use of an ultrasonic method involving organic solvents (Kim and Lee, 2012). This method offers a viable and well-known alternative. Additionally, the organic liquid residues can be treated in a wet oxidation conversion process to carbon dioxide and water, avoiding the use of high-thermal processes (Ojovan and Lee, 2014), and/or use other alternative recycling methods (García et al., 2013; Lau and Koenig, 2001). Here, considering the role of C2C principles for PV panel design is essential in the search for alternative encapsulation materials for EVA, allowing more favorable environmental impacts and a high-energy intensive incineration process used in the FRELP recycling process.

Finally, it is expected that transport sectors will restrict legal emission limits in the future and the sustainable transformation of the electricity matrix will facilitate the reduction of most environmental impacts coming from the *EoL* of PV panels.

5.1.1. Comparison: OLMS and CLMC Energy scenarios

As it was described at Section 4, since a *CLMC* system based on *C2C* principles should be powered by renewable energy sources, we have developed a scenario where the recycling facility in the CLMC scenario is powered by PV panels (i.e. only electricity requirements). In order to learn about the differences and similarities in environmental impacts coming from the *CLMC* and *OLMS* systems to process a FU, a comparison of normalized impacts based on the Europe ReCiPe Midpoint H methodology was performed for both scenarios.

As expected, the CLMC-Energy scenario powered by renewables is responsible for small environmental impacts (see Figure 5). While the use of thermal power plants (~64% of total install capacity in Ecoinvent 3.1) in the EU electricity mix is one of the main responsible for the environmental impacts observed in the *OLMS-Energy* scenario. Here, the thermal power plants are responsible for environmental impacts in the following categories: fossil fuel depletion, human toxicity, particle matter formation, maritime and terrestrial ecotoxicity, and climate change. Overall, the burning of diesel fuel releases carbon monoxide-CO, hydrocarbons-HC, particulate matter-PM and nitrogen oxides-NOx, components responsible for several human health issues. In the future, EU electricity mix impacts due to fossil fuel generation will be virtually eradicated due to the predominance of renewable generation in the electricity mix.

In the CLMC-Energy scenario, the normalized impact scores are reduced compared with the OLMS-Energy scenario. However, since there are no emissions into the environment associated with the conversion of solar radiation into electricity from a PV power plant, the only impacts linked with the CLMC-Energy scenario are given by the use of diesel-based incineration and forklift. They are the main contributors to environmental impacts in the following impact categories: maritime ecotoxicity, fossil fuel depletion, particulate matter formation, human toxicity, climate change and terrestrial ecotoxicity.

Despite the benefits of using PV panels to power the recycling facility, based on the normalized impacts in the *CLMC-Energy* scenario, there is no doubt that the use of incineration to recover metals from the PV sandwich it is not the appropriate pathway to follow. The incineration phase in the FRELP recycling technology not only releases harmful gases into the atmosphere, but also produce fly-ashes that are disposed as toxic waste. This alternative is especially inappropriate if the main goal is to develop a *CLMC* based on *C2C* principles, where toxics elements must be avoided.

One of the most important hurdles in the *CLMC*-Energy scenario is the use of incineration (FRELP method) by thermal processing in the absence of air or oxygen (pyrolysis) used in other recovering materials processes to separate EVA from solar cells. Based on our results, PV panel manufacturers must focus on using alternative materials to promote low-energy intensive disassembly of PV panels at EoL. Considering that the amount of work needed to separate a random mix of materials, like EVA and glues used in a PV panel, is given by equation (1), where W is the work, R is the universal gas constant and T is temperature, and X represent the mixture at a constant mole concentration (Gutowski, 2008).

$$W = RT\left[Ln\frac{1}{x}\right] \tag{1}$$

Consequently, the more randomly mixed the materials are, the amount of energy needed to separate them will increase infinitely. C2C principles can help to reduce randomness in mixture of materials by providing clear guidelines in the design of future PV panels, improving disassembly, the recyclability of the materials used, and replacing toxic components with non-toxic ones.

Appropriate policies will help to promote and, identify market opportunities, to reduce environmental impacts from the recycling industry and overcome resistance to change, and raise awareness about better recycling methods for crystalline PV panels.

6. Environmental assessment of photovoltaic technologies in an EoL closed material system: PV vs CdTe

An LCA study of this nature would not be complete without an EoL comparison with other photovoltaic technology. In 2017, the cadmium-telluride (CdTe) thin film panels technology represented 4.5% of the global market, the second largest after silicon technology (mono and polycrystalline), which accounted for more than 93% of the global market (Fraunhofer Institute, 2019). Furthermore, First Solar, the world's largest CdTe panels manufacturer, established the first global CdTe panel recycling program in 2005 (First Solar, 2017). The recycling program addresses the issue of cadmium (Cd) toxicity contained in CdTe panels, which can potentially leak from them and pollute the environment. Based on the above, the present study used the publicly available LCI data from the recycling technology developed by First Solar (Fthenakis et al., 2011; Jungbluth and Stucki, 2012; Stolz and Frischknecht, 2017) to assess the environmental impacts at the EoL for PV and CdTe technologies at a *quasi-CLMC*. Since the previous sections describe in detail the LCI and EL of the PV technology, a brief description of the EoL and LCI of the CdTe technology will follow, focusing on First Solar's recycling methodology.

The First Solar recycling process is a combination of mechanical and chemical treatments. This recycling technology has a recovery rate of more than 90% and 95% for the semiconductor materials and glass (First Solar, 2017, 2010). The following is a brief description of the processes involved in the recycling methodology of CdTe panels developed by First Solar:

a *Shredding and hammer-milling*: To reduce the size of the panels, a shredder is used to break the panels, and those are later crushed by a hammer mill into approximately 4-5mm pieces to shatter the lamination bond.

b *Semiconductor film removal*: Both sulfuric acid and hydrogen peroxide are added in a slowly rotating leach drum, aiding the removal of the film by this chemical process. The process lasts up to 4-6 hours.

c *Solid-Liquid separation*: Once the semiconductor film is dissolved, the leach drum is drained, and the glass is separated from the liquids.

d *Glass- Laminate material separation and glass rinsing*: A vibrating screen separates the crushed materials, separating the glass and the EVA. Subsequently, the glass is deposited on a conveyor belt, and it is rinsed while it is transported on the belt. Once rinsed and free of residual semiconductor material, the glass is packaged for recycling.

e *Precipitation and dewatering*: As a result of the solid-liquid separation process, the remaining liquid, with a high concentration of metals, is placed into a precipitation unit, where the metal compounds follow a three-step process with increasing values of pH, using sodium hydroxide. Subsequently, the sludge of precipitated metal materials is concentrated in a thickening tank, separating the solids, which settle at the bottom, from the water. As a result, a high concentration of unrefined semiconductor material, which is composed of cadmium sludge and copper telluride cement, is recovered.

Table 9
Summary of LCI in both scenarios

CdTe Closed Scenario Input	Quantity	Unit
CdTe panel Waste	1000	kg
Sulfuric acid	5.063	kg
Electricity[a]	247.03	kWh
Deionized water	329.4	kg
H_2O_2 (50% in water)	34.77	kg
$NaOH$ (50% in water)	6.10	kg
Emissions		
Outputs	**Quantity**	**Unit**
Cd air emissions	3.59×10^{-7}	kg
Cd water emissions	5.44×10^{-6}	kg
Recycling waste to landfill/incineration		
Outputs	**Quantity**	**Unit**
Plastic waste (municipal incineration)	37.20	kg
Inert glass waste (inert landfill)	7.80	kg
Wastewater for treatment	100	kg

[a] Updated data for the following processes: Shredding: 448.20 MJ; Hammer-milling: 29.88 MJ; Semiconductor film removal: 2.99 MJ; Solid liquid separation: 2.99 MJ; Glass laminate and rising: 403.45 MJ; Precipitation and dewatering: 1.80 MJ. (excluding data from Ecoinvent database)

Table 10
Summary of the mass breakdown of a FU obtained during the recycling of the decommissioned CdTe panels

Material	Mass (kg)
Glass	953.50
EVA	36.17
CdTe	2.42
CdS	0.069
Cooper	4.74
Others (i.e. *Cr*, *Pb*, *Sn*, *Ti*, *Zn*, steel, rubber and solder)	3.10
Total	~1000 kg

As a result of the process described above, and according to First Solar, up to 95% of semiconductor material is recovered (First Solar, 2010), while the EVA and all laminate material residues are collected for later incineration as municipal waste, and then the residue from incineration is disposed in a landfill (Held, 2009). It is estimated that the recycling yield of unrefined CdTe semiconductor of the First Solar methodology is about 0.0037 kg/kg (Stolz and Frischknecht, 2017). In this study, given the lack of reliable data, the further processing and refinement of the recovered CdTe by an external partner of First Solar is not considered.

Since the original electric power requirements reported in the literature (Held, 2009) are outdated with respect to the equipment used during the pre-treatment phase, we have updated these data-inputs based on more accurate available data (see Table 9 and 10) (Giacchetta et al., 2013). The LCI data and inputs used for the CdTe technology are shown in Table 9 and 10. The functional unit (FU) considered here is 1000 kg of unframed CdTe panel and crystalline silicon (PV) panel materials.

As described in section 4.2.1, panels (PV and CdTe) are collected and transported to a facility for disassembly. The diesel consumed by the truck (Lorry 7.5-16t/EURO 5) is modeled based on the Ecoinvent database. In order to keep consistency across scenarios, we have assumed an average distance of 200 km from the collection site to the recycling facility. The forklift used to transfer materials

Table 11
Environmental impacts results per categories: CLMC scenarios for PV and CdTe

ReCiPe midpoint impact categories	Abbreviation	Unit	PV CLMC scenario	CdTe CLMC scenario
Climate change	CC	kg CO2 eq	1.38E+03	5.73E+02
Ozone depletion	OD	kg CFC-11 eq	2.31E-04	1.04E-04
Terrestrial acidification	TA	kg SO2 eq	4.00E+00	1.41E+00
Freshwater eutrophication	FE	kg P eq	1.05E+00	4.87E-01
Marine eutrophication	MEP	kg N eq	3.44E+00	3.03E+00
Human toxicity	HT	kg 1,4-DB eq	1.45E+03	1.84E+03
Photochemical oxidant formation	POF	kg NMVOC	3.89E+00	1.08E-01
Particulate matter formation	PMF	kg PM10 eq	5.33E-01	4.16E-01
Terrestrial ecotoxicity	TET	kg 1,4-DB eq	1.93E-01	1.28E-01
Freshwater ecotoxicity	FET	kg 1,4-DB eq	3.53E+01	4.07E+01
Marine ecotoxicity	MET	kg 1,4-DB eq	5.34E+01	5.72E+01
Ionizing radiation	IR	kg U235 eq	3.73E+02	2.67E+02
Metal depletion	MD	kg Fe eq	1.35E+03	2.05E+02
Fossil fuel depletion	FFD	kg oil eq	4.01E+02	1.80E+02

in these scenarios is powered by diesel fuel, as in the Open-Power scenario described in section 4.2.1.

The residues from the recycling process (for PV) are: contaminated glass; fly ash (hazardous waste); liquid waste; and sludge (hazardous waste). For CdTe they are: plastic waste (municipal incineration); inert glass waste (inert landfill); and wastewater (for treatment). These are transported to the municipal landfill in a truck (Lorry 7.5-16t/EURO 5), with an average distance of 50 km. In addition, the transportation method from the incineration facility to the municipal landfill of the PV and CdTe residues is modeled as a truck (Lorry 7.5-16t/EURO 5), with an average distance of 50 km. Once the recycling process for both PV and CdTe is completed, all the recovered materials are transported from the recycling facility to an industrial facility for reuse. In this study, an average distance of 50 km from the recycling facility to the industrial material recovery facility is assumed as reasonable.

Finally, under the framework of the C2C principles, the entire CdTe recycling facility is powered by PV solar energy (excluding the incineration facility). This facility aims to improve the benefits of the *Closed-Loop material cycle* system and maximize efforts to emulate C2C principles. The electric power was modeled as a CdTe power plant, as the system represents a set of panels ground mounted and standard BOS components, able to generate the 247.03 kWh required to satisfy the recycling facility electricity needs to process a FU.

6.1. Results and discussion

To preserve consistency, in this LCA we have used the ReCiPe methodology. The impact categories assessed are: climate change; ozone depletion; terrestrial acidification; freshwater eutrophication; human toxicity; particulate matter formation; freshwater ecotoxicity; ionizing radiation; metal depletion; fossil fuel depletion; marine eutrophication; photochemical oxidant formation; terrestrial ecotoxicity; and marine ecotoxicity (see Table 5). As indicated in section 5, due to the lack of consistent LCI data, the following impact categories were not considered: urban land occupation; natural land transformation; water depletion; and agricultural land occupation. The impact assessment results of processing 1000 kg of PV and CdTe waste are shown in Table 11.

On the other hand, as described in section 5.1, the results for the FU in both scenarios (Table 11) were normalized based on the Europe ReCiPe midpoint H methodology, and correspond to the annual impact of a single European person in each category. Figure 6 shows the normalized impact assessment comparison for the selected impact categories for PV and CdTe EoL scenarios.

The evaluation of the impact categories for the *PV* and *CdTe* EoL scenarios shows that the CdTe *Closed-Loop* material cycle scenario has overall the lower environmental impacts (see Figure 6 and Figure 7). Based on the results, the major environmental impacts for the PV scenario are observed in the Fossil fuel depletion (FFD), Metal depletion (MD), Freshwater Eutrophication (FE), Terrestrial acidification (TA), and Photochemical oxidant formation (POF) categories. These environmental burdens are mainly due to the use of thermal processes and transportation based on fossil fuel during the recycling process of a FU in the PV scenario. Though both recycling technologies employed for PV (~95% of *Si* for FRELP) and CdTe (~95% of *Cd* and *Te* for First Solar) have a high metal recovery rate, the PV technology has a higher metal content compared to CdTe, and it is not possible to fully recover all the metals during its recycling process, deepening the environmental impacts in the Metal depletion category. In addition, the low recovery rate of aluminum waste from bottom ashes, which is only ~50% for PV (FRELP Project, 2018), together with the loss of other metals (such as Copper, Silicon, Tin, Lead, and others) due to thermal degradation, ultimately increases the impact on the MD category.

On the other hand, both the PV and CdTe *Closed-Loop* material cycle scenarios show the same higher environmental impacts in the toxicity related categories: Marine ecotoxicity (MET), Freshwater ecotoxicity (FET) and Human toxicity (HT) categories. These environmental impacts are mainly due to the toxic emissions released during the recycling process, the use of hazardous chemicals to recover *Si* and *Cd* (described in the LCI), and the incineration of the EVA and plastics, which results in higher toxic impacts. In addition, the transportation system used in both scenarios is fully dependent on fossil fuels, responsible for the emission of air pollution causing human health negative effects. This situation is confirmed by the high magnitude of the FFD indicator, which is nevertheless lower in the CdTe scenario (see Figure 7).

On the other hand, the normalized environmental impact results for the categories with small magnitude (i.e., FFD, IR, TET, PMF, POF, ME, TA, OD, and CC), which are worthy of consideration due to potential ecological and Climate Change impacts on both PV and CdTe scenarios.

Based on the evaluation of the impact categories for the PV and CdTe scenarios, the CdTe scenario has the lowest environmental impacts (see Figure 7). According to our results, PV scenario accounts for the main environmental impacts in the following categories: FFD, ME, TA, PMF, POF, and CC. These environmental impacts are due to the use of pyrolysis, fossil fuel-based transport system, incineration of plastics, disposal of PV material residues in the landfill, and energy-intensive fossil-based thermal processes used at the EoL. The CdTe scenario also has environmental impacts, particularly ME. The *Cd* emissions into air and water during recycling of the CdTe panels are the major contributors in the potential impacts observed in the ME category.

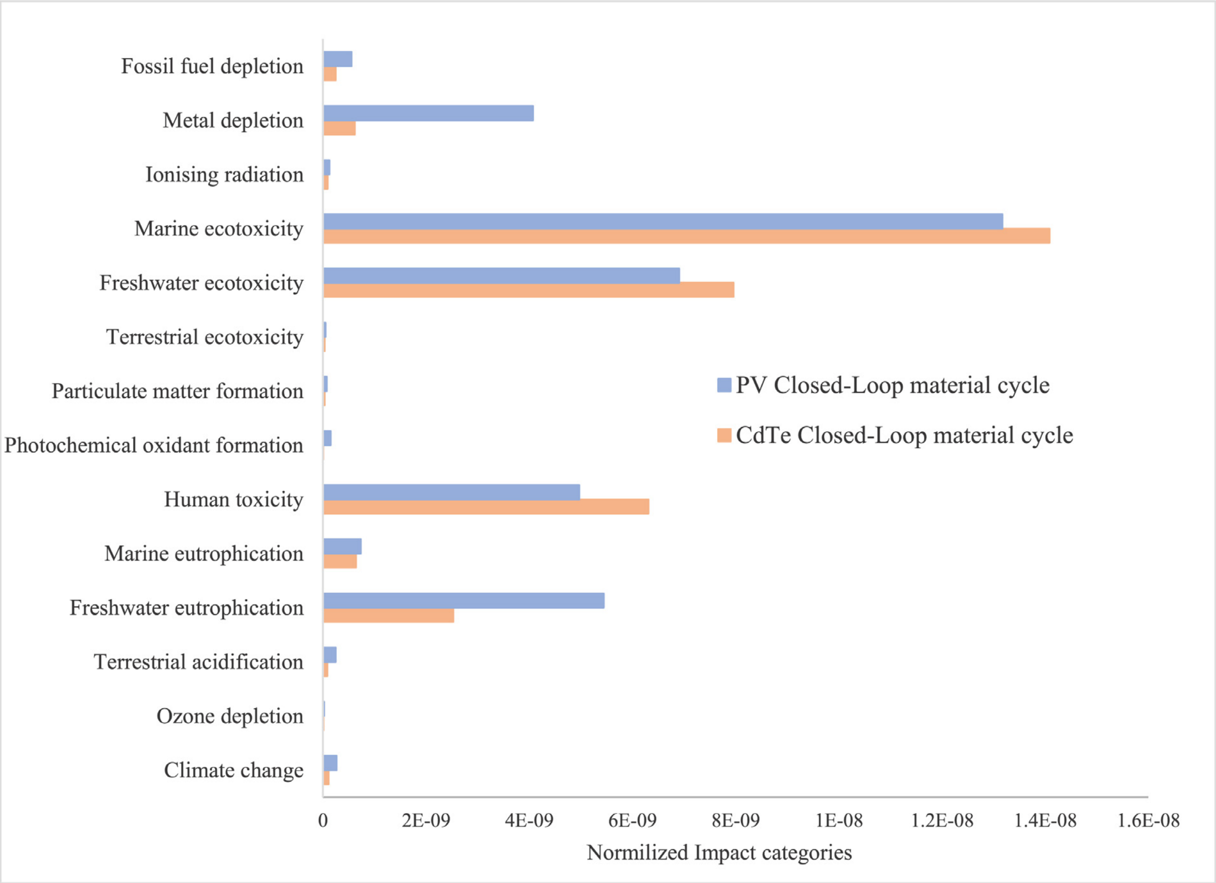

Figure 6. Comparison of normalized impacts per each category for the PV and CdTe scenarios

As results of the LCA implemented for the PV scenarios in section 5 demonstrate, transportation is once again the largest impact contributor at the EoL phase, regardless of the type of photovoltaic technology that is being assessed. In the case of the CdTe scenario, transportation has the biggest relative environmental impact contribution, averaging around 65% for all the categories assessed in this study. The shredding and hammer-milling processes are responsible for significant environmental burdens for the ME, FET, and HT categories, mainly due to the toxic emissions that are released into the air and water (fly ashes and wastewater respectively). Even so, the encouraging environmental performance results obtained by the CdTe scenario in most of the categories considered in our study, we suggest to further minimize *Cd* emissions during the recycling phase by improving the management of hazardous chemicals at the EoL. Therefore, in order to minimize the impacts from *Cd* emissions during the EoL, we propose the use of new alternatives for the treatment of fly ashes and wastewater. An alternative way to remove *Cd* from the wastewater of the recycling process could be the use of membrane filtration, electrodialysis, and photocatalysis, thus avoiding the use of energy-intensive thermal treatments (Barakat, 2011). Additionally, bagasse fly ash (solid waste of the sugar industry) can be used for the removal of cadmium and nickel from wastewater, with a *Cd* removal rate of ~90% (Gupta et al., 2003).

In the case of fly ashes, the use of bioleaching using microbes is a natural alternative solution (Meer and Nazir, 2018). The use of electrodialytic remediation offers a low energy intensity alternative with experimental efficiencies of ~97% (Hansen et al., 2004). Alternatively, it is possible to use a combination of both technologies, known as electrodialytic bioleaching. The use of this alternative has shown promising performances in the recovery of metals such as Cd, Co, Li, Pb, and Zn (Gomes et al., 2020).

Concerning the comparison of our results with similar studies, we found that there is limited access to literature about other EoL environmental LCA of PV vs CdTe recycling technologies. Furthermore, a quantitative comparison with comparable studies is not possible due to the use of different FU, results are aggregated, and different boundaries and impact categories . Although, in qualitative terms, our results concur overall fairly well with Vellini et al.[3] (Vellini et al., 2017), confirming that the recycling process of CdTe panels outperforms PV panel recycling technology, having smaller environmental burdens in almost all the impact categories assessed here. Even though our results are in line with some studies already mentioned above, they differ considerably from those previous findings regarding the low environmental performance of the CdTe recycling technology (Li et al., 2018). In addition to outperforming PV recycling technology in almost every indicator assessed in this article, we found that at the EoL, CdTe recycling technology is overall less energy-intensive compared with PV. Our results show that the recycling of 1000 kg of CdTe panel waste would require 2748 MJ, which is lower than 3264 MJ needed for the recycling of 1000 kg of PV panel waste.

Finally, it is important to mention that the use of renewable energy (CdTe panels) to power the CdTe recycling facility has helped to significantly reduce environmental impacts in almost all the categories evaluated in this article. However, the

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[3] Study set up as: FU: 1m^2 of PV and CdTe panels; CML 2001 impact assessment methodology; aggregated results; and Gabi software (version 5.0)

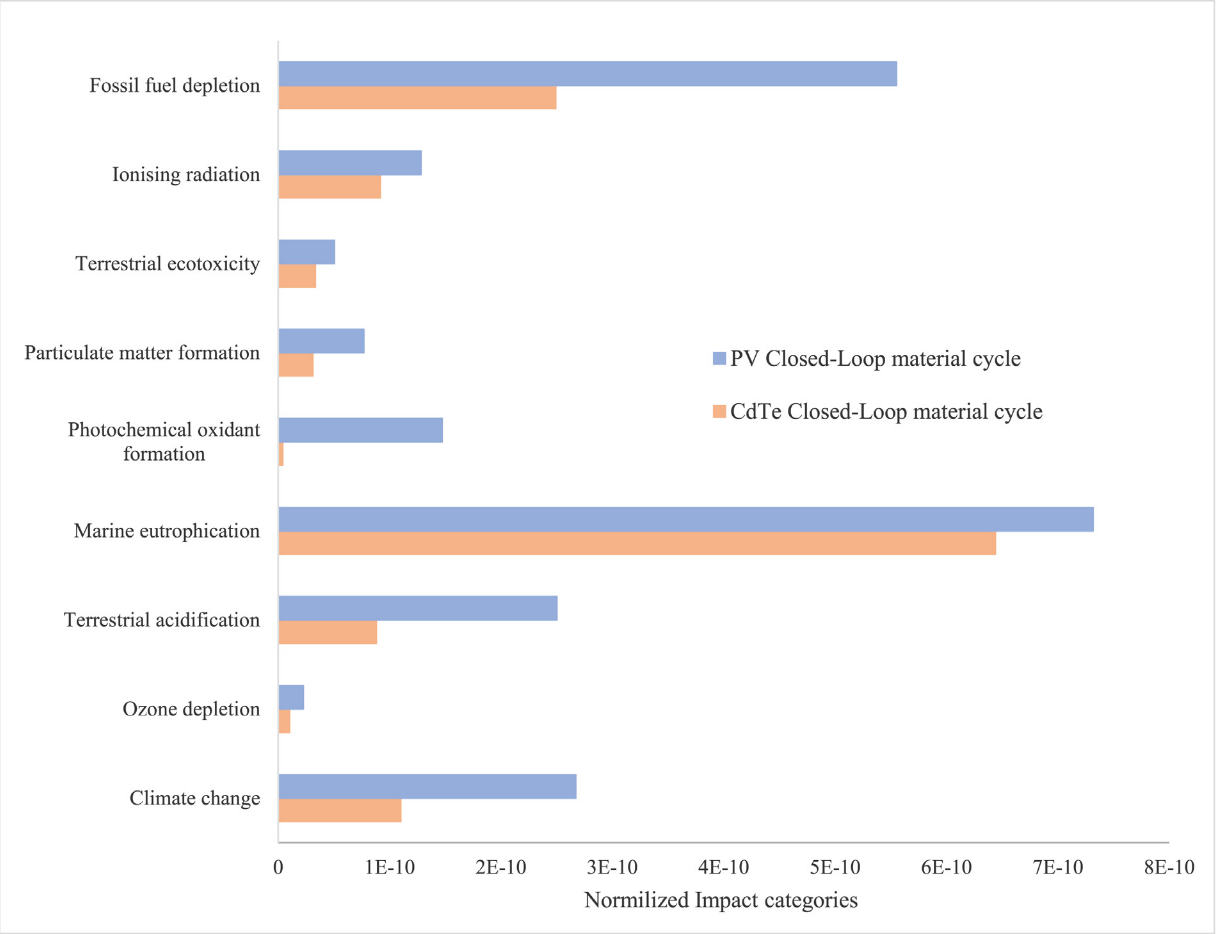

Figure 7. Comparison of normalized impacts - categories that have a low order of magnitude- per each category for the PV and CdTe scenarios

design issue still needs to be further improved in order to improve material recovery in the future. To this end, we encourage the PV industry to adopt a framework that supports the implementation of a closed materials cycle, like the promising C2C principles.

7. Suggestions and limitations

The findings of this study confirm that the solar panel EoL phase is undoubtedly emerging as a new environmental challenge. Even the new recycling technologies that are available on the market still need to reduce their environmental footprint. In this section, some views are presented in the form of suggestions. Finally, the limitations of the study are presented.

Results provide the following outline of key take-aways:

- These results reveal the urgency of accelerating the deployment of recycling facilities for solar photovoltaic technology if we want to decrease the environmental impacts of disposal and burned waste at the EoL phase. This is especially true for countries where PV panels are already a highly-used technology, and recycling is not an existing alternative in the form of legislation or available technology.
- There is no doubt that recycling at the EoL phase has positive environmental impacts, in terms of reducing emissions and the waste of valuable materials. However, PV recycling and silicon recovery are still new scientific processes. Already well-established CdTe recycling process outperforms the PV recycling process in almost all categories. Hence, more R&D is needed to improve current PV recycling technologies and methodologies to avoid negative environmental impacts coming from today's recycling processes.
- At the EoL phase, high-intensity thermal processes and the toxic and inflammable substances used during the recycling of PV materials should be avoided in future recycling technologies. All recycled materials are essentially downgraded in quality after the thermochemical processes using current recycling technology. Thus, even after the recycling process, some materials still end up in a landfill, creating a negative impact on the environment and human health. Therefore, a design that facilitates the disassembly of panels at EoL, along with a more environmentally-friendly recycling process, are key to developing and deploying a truly closed-loop material cycle system (up-cycling) in the future.
- The transportation of the decommissioned panels to the recycling facilities is responsible for the most significant environmental burdens and has a high relative impact in many of the 14 impact categories assessed in this study. However, it is almost impossible a priori to identify the distance between a recycling plant and the panels to be decommissioned, due to the high uncertainty involved. Hence, a sensitivity analysis on the transportation of materials from the decommissioned PV power plant to the PV recycling facility is conducted, to validate the influence of distance on the levels of impacts. In our study we have assumed a 200 km (base scenario) average distance between the recycling plant and the panels to be decommissioned, therefore, the sensitivity analysis components decrease

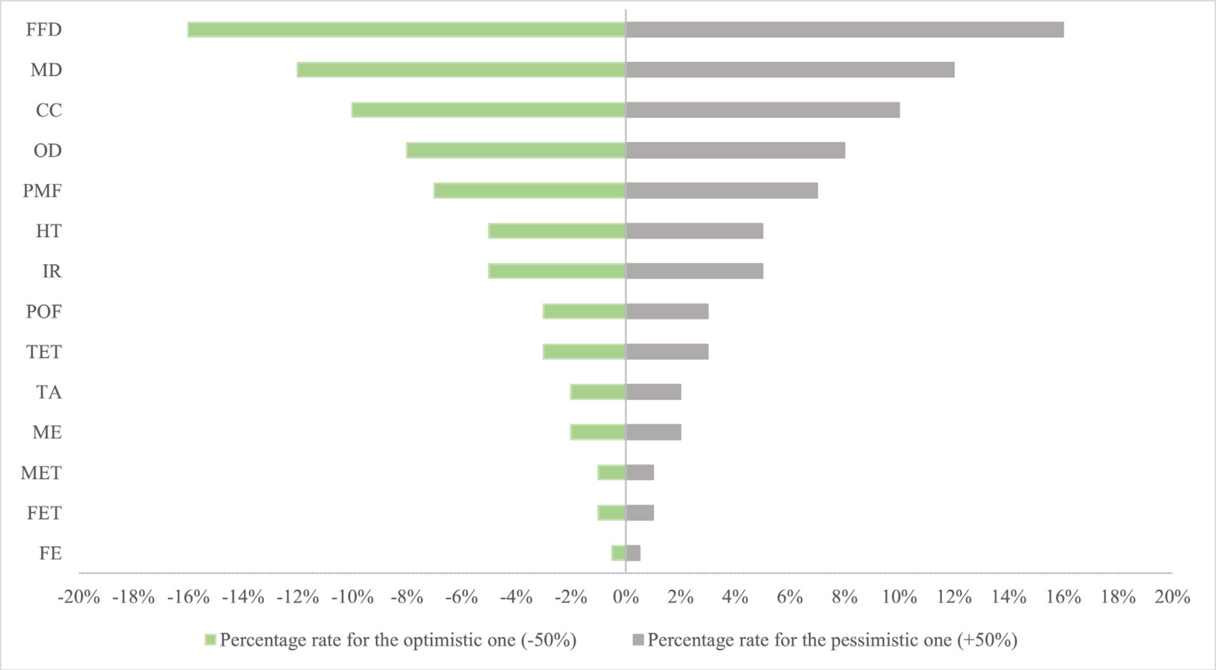

Figure 8. Sensitivity of transportation system used in this study. The optimistic and pessimistic scenarios have a variation of ±50% of the base case (200 km).

by 50% in the optimistic scenario (100 km) and increase by 50% in the pessimistic one (300 km).

As expected, the uncertainty analysis results (see Figure 8) show that as the distance between the decommissioned PV power plant to the PV recycling facility increases, all outputs increase. The higher the distance, the higher the fuel consumption and vice versa. The Fossil Fuel Depletion (FFD) impact category has higher variation up to ±16%, whereas in real conditions variation may also be impacted by aging of the truck engine and efficiency reduction. While the categories of Metal Depletion (MD), Climate Change (CC), Ozone Depletion (OD) and Particulate Matter Formation (PMF) show a variation of ±12%, ±10%, ±8% and ±7% respectively, all other impact categories have a variation between 5% and 1%. Thus, from this result it is possible to conclude that distance is a decisive factor in the EoL PV panel when using an unsustainable transportation system for long distance freight.

Our findings suggest that future research should focus on a more realistic approach, where the CO_2 emissions are a function that accounts not just for the distance, but also for the vehicle speed. An eco-friendly transport system based on renewables is the only alternative to eliminate the harmful effects on the environment caused by the current transportation system used at the PV EoL phase. Planning the location for future recycling plants or implementing a multi-recycling facility to increase the effectiveness of the overall recycling process will be key to facilitate the implementation of a true *Closed-Loop material cycle* and must be studied in detail.

It is important to highlight that this study has some main limitations. First, there are many recycling technologies and supply chains of PV system manufacturers apart from the FRELP case analyzed here. We chose the FRELP case mainly due to the limited access to data and inventories from other PV recycling proprietary technologies. More R&D and data verification are needed along with more transparent data from all recycling technologies. These limitations produce some opportunities for future research, and we urge researchers and developers to create open and transparent databases for all the technologies available concerning the EoL phase of PV panels.

8. Conclusions

In this article, we have presented a comparison of a PV panel at its EoL phase in both *Open-System* (*OLMS*) and a novel *Closed-Loop* material cycle (*CLMC*) scenario using the LCA methodology. As expected, the amount of decommissioned PV panels will increase dramatically in future decades. The deployment of new PV panels and the disposal of PV panels in a landfill on an *OLMS* system at the EoL phase is currently not a solid solution because of the environmental impacts observed in the results of this study.

The results confirm the role of recycling to reduce the environmental footprint of the PV industry. However, in a CLMC system, the results confirm that the recycling process has significant environmental impacts due to the incineration of the solar cells. Furthermore, closing the material flow is only possible by transporting back the recovered materials to a manufacturing facility, stressing out the impact on the environment in almost all categories analyzed.

Based on our results, wafer recovery should be the optimal method of recycling PV panels at the EoL, and thermochemical processes must be avoided during the delamination process. The use of organic solvents can be considered as an alternative pathway to reduce emission of toxic gases, and generation of fly-ashes and sludge, and to avoid damaging solar cell materials in the delamination phase. Consequently, if we want to make PV technology fully sustainable, we should avoid the use of incineration and pyrolysis and toxic acids that are generating harmful environmental impacts.

These energy scenario comparisons confirm that the use of solar energy to power recycling facilities offers several environmental advantages in comparison to using the current electricity mix available on the grid. However, in countries/regions with a highly renewable electricity mix, the environmental impacts may already be significantly reduced. Nevertheless, the use of high-energy intensity thermal process powered by fossil fuels limits the benefits of PV recycling.

On the other hand, when compared the EoL PV and CdTe scenarios, we find out that overall CdTe has a better performance in most impact categories evaluated, resulting in lower environmental impacts and energy consumption. Therefore, it is imperative to overcome limitations of current PV recycling technologies, which only considers PV panels that were never designed to be recycled, much less reused.

We conclude that a *CLMC* system offers important benefits that can be maximized if PV panels are *designed* based on C2C principles with the EOL phase in mind from the beginning. More concretely, we argue that lack of a design that facilitate disassembly and selection of insulation materials in current PV technology limits the implementation of a cleaner recycling process. It is imperative to develop a fully recyclable and reusable PV panel. C2C principles can help by facilitating the disassembling phase, help to reduce negative environmental impacts caused by recycling (e.g., replacing EVA, current plastics used on PV panels for bioplastics and improving the design of the PV sandwich to facilitate recycling), helping to move towards a truly sustainable CE in the PV industry. Future research could assess the environmental impacts of the EoL for innovative new photovoltaic panels designs, full electric transportation system and alternative recycling methodologies.

Declaration of Competing Interest

None.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.spc.2020.05.008.

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