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Circular solar: Evaluating the profitability of a photovoltaic panel recycling plant

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Abstract

Photovoltaic (PV) panels have a crucial role in coping with the global warming mitigation and the energetic crisis currently affecting the European Community. However, from the circular perspective of end-of-life (EoL) management, there are still big issues to be solved in order to recover materials from this kind of e-wastes. Because of several reasons (e.g. type of embedded materials, illegal shipments, location of manufacturers) EoL businesses do not have the interest in approaching them. This poses a significant environmental concern in terms of their management. This work wants to assess the profitability of a specific PV module recycling plant, by evaluating several market contexts in which multiple scenarios of material price, investment and process costs will be considered. The results for a 3000 tonnes plant show that profitability is not verified in the absence of an avoided landfill cost. Instead, when a value of 200 €/tonnes is applied, the net present value is positive in 35.2% of the scenarios and at 87.6% when a value of 350 €/tonnes is considered. The policy choice of this value requires linking the PV module disposal fee to the circular benefits associated with its recovery.

Keywords

Circular economy, economic analysis, photovoltaic, policy implications, recycling, sustainability

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Introduction

The development of sustainable manufacturing models is necessarily linked to energy production (European Commission, 2020a). An increasing power generation from renewable resources like sun, biomasses and water certainly contributes to the transition from a fossil fuel economy to a renewable energy economy (Giannetti et al., 2020). Global warming is the most severe threat that humankind has to face shortly (Biermann et al., 2022), and the reduction of fossil fuels that generate greenhouse emissions cannot be postponed anymore (Adedoyin et al., 2022; Caferra et al., 2021; Calabrese et al., 2021). Stakeholders' engagement (Hristov and Appolloni, 2022) and environmental education (Eliades et al., 2022) are enabling factors for this transition. The European Green Deal is a response to these challenges. It is a new growth strategy that aims to transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use (European Commission, 2019). The goal is to foster a plan for the development of the circular economy (European Commission, 2020b).

Photovoltaic (PV) energy plays a crucial role in this regard (D'Adamo et al., 2022a). PV plants are the main example of distributed production, a concept that will revolutionize the way in which energy is generated and used in the territory. The utilization of large and flat industrial areas and building roofs can certainly drive this expansion process (Aronescu and Appelbaum, 2017).

Such an industrial model, coupled with the promotion of a circular economy approach, shall also be fostered and sustained in developing countries in order not to repeat the errors of the western countries (Abbasi et al., 2022). PV small plants to power mini-grids is an efficient way to bring electricity access to people living far from power transmission networks, particularly in developing countries with excellent solar irradiation (IRENA, 2020). Hence, accumulators are required to store the energy that can be used when solar light is unavailable; for this purpose, Li-ion accumulators can undoubtedly be used, even those replaced for heavy-duty applications, before the final recovery of the metals contained therein (Abo Atia et al., 2020; Granata et al., 2012; Pagnanelli et al., 2014).

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A record-breaking 175 GW of newly installed PV capacity was added in 2021, bringing the total historical value up to 942 GW. With 54.9 GW, China dominated the world in newly installed PV capacity in 2021, followed by the United States (26.9 GW) and the European Union (26.8 GW) – (International Energy Agency, 2022).

PVs are electronic devices that convert sunlight directly into electricity. The production of PV panels strictly depends on the availability of particular chemical elements such as silicon (Si), silver (Ag), gallium (Ga), indium (In) and germanium (Ge). Furthermore, we have other elements as aluminium (Al), copper (Cu), lead (Pb) and zinc (Zn) – (Azeumo et al., 2019; D'Adamo et al., 2017). PV plants are inserted within waste from electrical and electronic equipment (WEEE) (Włodarczyk, 2022). The amount of WEEEs is indeed expected to grow exponentially in the following years, and this poses a significant environmental concern (Khoshand et al., 2022). Wrong recycling procedures, illegal disposal and non-authorized transportation to third-world countries represent the most important concerns (Awasthi et al., 2016; Fthenakis, 2000). Besides that, another threat will also affect the PV panel market in the future: the availability of the raw materials and the location of most of the PV panel manufacturing factories. China indeed hosts the majority of such plants. Considering the geopolitical instability, developing the required production chains and infrastructures is necessary to lower the foreign dependence.

There are different PV modules according to the solar cell and, once exhausted, they are classified as WEEE in the European Union. End-of-life (EoL) PV panels are usually labelled with code 160214 or 160213* if containing hazardous heavy metals such as the cadmium-telluride cells that also contain copper and tin, according to the European Waste Catalogue (Marwede and Reller, 2014; Sinha, 2013). PV modules based on mono-crystalline and poly-crystalline silicon cells do not contain hazardous heavy metals and represent 90% of the market share, whereas the remaining 10% accounts for thin film technology cells based on cadmium telluride (CdTe), copper-indium-gallium-selenide, and amorphous silicon (Azeumo et al., 2019).

Some estimates predict that more than 78 million tonnes of EoL photovoltaic modules will be reached by 2050 (Tan et al., 2022). The issue of PV module recycling is increasingly urgent. If they are not properly managed, they have the potential to: (i) damage our terrestrial ecology; (ii) inadvertently stimulate further resource extraction and mining and (iii) reduce the net environmental benefit of solar energy harvesting (Tan et al., 2022). In this picture, the growth of PV systems has a significant increasing trend and will play a decisive role within energy models based on renewables and sustainable communities (D'Adamo et al., 2022a). The full view of sustainability requires assessing what will happen at the end of the life cycle of these products, and therefore this work focuses on the recycling of PV modules. In fact, EoL PV must be framed within a comprehensive waste management perspective (Papamichael et al., 2022a; Zorpas et al., 2021). The development scenario should include optimization of the transportation of these wastes (Molano et al., 2022; Oteng et al., 2022). This highlights the need for small and medium-sized plants as well.

Several works highlights the relevance of the topic (Chatziparaskeva et al., 2022; Papamichael et al., 2022a) and the need to conduct economic analyses (Rathore and Panwar, 2021) aiming to reach circular economy goals (Papamichael and Zorpas, 2022b). The approach to be used is to propose technical evaluations (Dobra et al., 2021) to be applied to established economic models of analysis (D'Adamo et al., 2017). This work will assess the profitability of a polycrystalline PV module recycling plant by evaluating different market contexts in which multiple scenarios of material price, investment and process costs will be considered and finally the analysis will also address the relevance of the avoided landfill cost.

Literature analysis

Few research groups have been studying more efficient ways to recycle PV panels since 2000, in particular, to recover metals contained therein (Dias et al., 2016; Tao and Yu, 2015). Life cycle assessment of recycling was also investigated, demonstrating that such a process generates 370 kgCO_2eq and requires 2780 MJ for recycling 1000 kg of PV waste. The main impacts are due to the incineration of the panel's encapsulation layers, followed by the treatments to recover silicon, copper, silver and aluminium (Latunussa et al., 2016). Entrapment of solar cells in cementitious matrices like concrete guard rails was proposed, but the mechanical properties were not satisfactory (Fernández et al., 2011). Hence, there are two main routes to treat EoL PV modules so far, and they are the hydrometallurgical and thermal ones (Rocchetti and Beolchini, 2015).

Well-established businesses already recycle spent PV panels at the industrial level. Ethylene-vinyl acetate (EVA) is a very adhesive glue that must be removed to disassemble the different layers of the panels. For this reason, a thermal treatment is usually proposed up to 600°C (Azeumo et al., 2019). The aluminium frame, glass and solar cells undergo specific treatments that are proprietary and are unknown due to undisclosed business proprietary data. The main recycling stages foreseen by the current industrial processes are well described in S, in which economic considerations also are addressed regarding the profitability of the recycling. The organic solvent leaching is a stage used in most of the recycling processes currently established (Doi et al., 2001), eventually assisted by ultrasonic irradiation that makes the dissolution of EVA greater and faster (Kim and Lee, 2012).

Pagnanelli et al. (2017) tested a recycling process applied to Si-based and CdTe panels. It involves a three-stage crushing, followed by thermal treatment and thus the final chemical process. Three fractions are obtained from crushing: a coarse fraction ($>$1 mm) requiring thermal treatment to remove EVA-glued layers in the glass scraps, an intermediate fraction (0.4–1 mm) of good quality glass (17% wt), and a fine fraction ($<$0.4 mm) that is leached to dissolve metals and thus to obtain another valuable glass fraction. The 0.08–0.4 mm fraction mainly contains Fe, Al, and Zn, while precious and hazardous metals (Ag, Ti, Te, Cu and Cd) are concentrated in fractions <0.08 mm. Acid leaching of 0.08–0.4 mm fractions allowed them to get a third recoverable glass fraction (22%w/w). The process route can get an overall recycling rate of 91%.

Another proposed process for Si-based panels includes the typical mechanical dismantling and pretreatments; thus, the cells are leached with a hot 30% wt KOH aqueous solution for removing the aluminium coating and the $HNO_3/HF/CH_3COOH/Br_2$ mixture for removing the silver layer (Radziemska et al., 2009). One integrated process based on flotation stages to concentrate the metals of interest was proposed by Berger et al. (2010).

Other authors focused on the recovery of pure silicon; Kang et al. (2012) recovered silicon with a 99.9% grade with a yield of 86% of the initial mass. This process includes leaching with an organic solvent, a thermal treatment at 600°C, and a final leaching stage with acids. Silver is the most precious metal contained in Si-based PV modules. After milling, sieving, pyrolysis at 500°C was applied and the resulting material leached in HNO3/NaCl: the silver extraction yield was 92% (Dias et al., 2016).

Other authors proposed the recycling of the cells for producing new solar cells instead of recovering the different materials and metals. For instance, Lee et al. (2017) proposed a recycling process to produce crystalline silicon (c-Si) solar cells using a Si wafer reclaimed from exhausted cells. The efficiency of the new cell was encouraging, being 17.6%. Another remanufacturing process was studied to recover silicon wafers from EoL solar panels and produce secondary cells with a conversion efficiency between 15% and 16.0% (Shin et al., 2017).

The literature places strong emphasis on the mix among the boards to be treated (Rosa and Terzi, 2016) in order to identify the correct technological process to improve performance (Zueva et al., 2021) and denotes the relevance of economic aspects in EoL management (D'Adamo and Rosa, 2019). This goal requires optimizing the disassembly process (Sassanelli et al., 2021), improving the decision-making process (Luglietti et al., 2016) and the circularity of resources within manufacturing context (Acerbi et al., 2022), in order to increase green supply chain management (Sathiya et al., 2021) minimizing the level of emissions (Cucchiella et al., 2017), and maximizing gold recovery (Ippolito et al., 2021). The literature highlights how the circular approach is essential to sustainability goals (Qazi and Appolloni, 2022), also within solar projects (Van Opstal and Smeets, 2023). Circular management of solar resources in all countries is called to have a perspective that looks at the long term and not the short term (Chowdhury et al., 2020; Tasnim et al., 2022).

Description of the recycling process

The technical analysis is based on a recycling process studied at the Sapienza University of Rome whose main results are reported in (Azeumo et al., 2019). EoL polycrystalline-silicon PV panels were treated by applying a physic mechanical and chemical treatment. The module was manually dismantled to remove the aluminium frame; cables and junction boxes were also detached. The panel was cut into 130 × 130 mm plates undergoing mechanical treatments.

First, the plates were crushed with a knife mill until reaching the cut-off of the grid installed beneath, that is, 2, 1 and 0.4 cm, according to the different trials carried out (Azeumo, 2020). The resulting material was composed of glass and metals. This fraction underwent dense medium separation, a typical technique of the mining industry, using aqueous solutions with additives like sodium chloride and sodium polytungstate.

The two fractions were thus separated, that is, the float (silicon fine powder and EVA) and the sink (metals, glass and a small amount of EVA and silicon). The latter was washed with water, dried in the oven, ground by a ring mill, and sieved. The fractions obtained were quantified and characterized by Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) after acid digestion with aqua regia.

The chemical treatment aims to remove EVA by dissolving it in a suitable solvent. The PV pieces underwent a thermal pretreatment at 190°C for 2 h. Thus, different boiling solvents were tested in the leaching step, enhanced by ultrasounds, for 2 h. This stage is crucial for the detachment of the different layers and, thus, their separation and recovery. The overall mass composition of the recovered materials for a polycrystalline PV panel is distributed as follows: plastic 9.93 (% wt), metals 1.37 (% wt), glass 84.02 (% wt) and other metals 0.71 (% wt) – (Azeumo, 2020).

The metal fraction was mainly composed of ribbons that connect the various cells. The fraction 'others' includes especially EVA and silicon. Furthermore, the material balance does not close to 100%: this is due to the inevitable losses during each phase, in particular crushing and milling/sieving. The total loss accounts for nearly 3.97% wt of the total mass. The most concentrated metals detected in the metallic fraction were Cu 77.11% wt, Ag 0.54%, Pb 3.14% and Zn 0.19%. Metallic ribbons consist mainly of copper coatings with a thin layer of silver. There are also lead and zinc in smaller quantities. After the experimental campaign, a recycling process, whose block diagram is shown in Figure 1, was thus designed.

Materials and methods

The size of the PV module recycling plant significantly influences its profitability. Some works show that for 10,000 tonnes/year plants it is not verified (Mahmoudi et al., 2020) and other works set the minimum value at 20,000 tonnes/year (Choi and Fthenakis, 2014; Deng et al., 2019). In these scenarios, it is evident how the revenues obtained from the materials do not offset the related investment and operating costs, in the absence of an environmental contribution associated with the recovery of these wastes. However, considering this variable, the scenario may change: some works propose verified profitability for plants smaller than 4000 tonnes/year (Dias et al., 2022), others point out that it is not verified for 2000 tonnes/year (D'Adamo et al., 2017). This work considers the scenario in which 3000 tonnes/year are recovered. It is worth specifying that typically 1 MW of PV systems produce

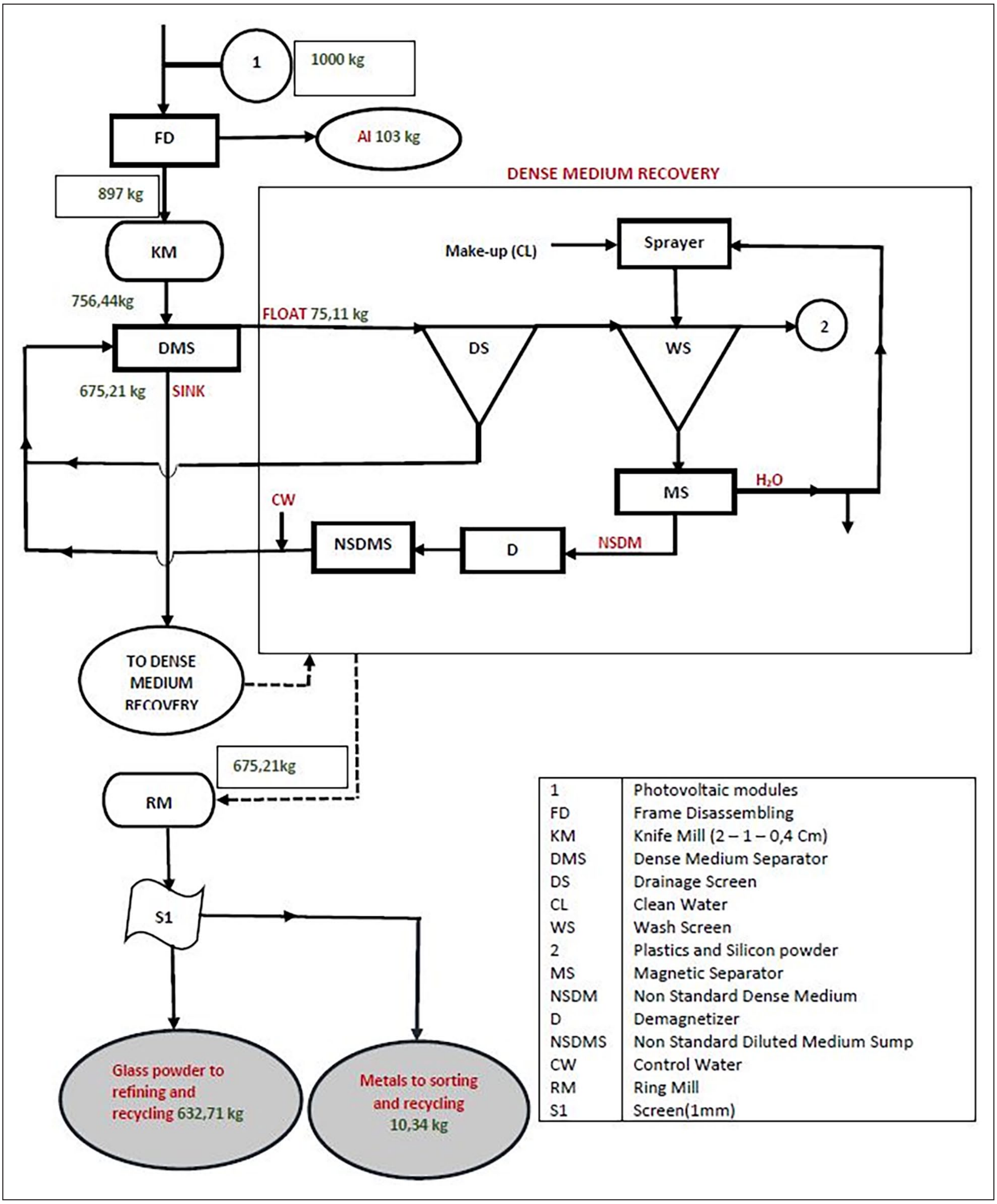


Figure 1. Block-diagram and mass balance of the recycling process.

about 75 tonnes of waste (Choi and Fthenakis, 2014). Thus, the plant considered in this work can recover 40 MW.

The discounted cash flow (DCF) method is used to evaluate the economic profitability of a recycling plant. Specifically, net present value (NPV) is the chosen indicator that can consider both the time value of money and include the various estimated cash flows (Woo and Whale, 2022). It is a prediction of what might happen in the future but is still important as it highlights whether a market has economic potential or not. The following economic model is used in this work (D'Adamo et al., 2017):

$$\mathrm{NPV} = \mathrm{DCI} - \mathrm{DCO} \tag{1}$$

$$\mathrm{DCI}=\sum_{t=1}^{N}\frac{\left(\begin{array}{c} m_{\mathrm{Al}}^{\mathrm{m}}*y_{\mathrm{Al}}*\mathrm{pl}_{\mathrm{Al}}*\mathrm{pr}_{\mathrm{Al,t}}*S+m_{\mathrm{glass}}^{\mathrm{m}}*y_{\mathrm{glass}}*\mathrm{pl}_{\mathrm{glass}}*\mathrm{pr}_{\mathrm{glass,t}}*S+m_{\mathrm{Si}}^{\mathrm{m}}*y_{\mathrm{Si}}*\mathrm{pl}_{\mathrm{Si}}*\mathrm{pr}_{\mathrm{Si,t}}*S+\\ m_{\mathrm{Cu}}^{\mathrm{m}}*y_{\mathrm{Cu}}*\mathrm{pl}_{\mathrm{Cu}}*\mathrm{pr}_{\mathrm{Cu,t}}*S+m_{\mathrm{Ag}}^{\mathrm{m}}*y_{\mathrm{Ag}}*\mathrm{pl}_{\mathrm{Ag}}*\mathrm{pr}_{\mathrm{Al,t}}*S+m_{\mathrm{Zn}}^{\mathrm{m}}*y_{\mathrm{Zn}}*\mathrm{pl}_{\mathrm{Zn}}*\mathrm{pr}_{\mathrm{Zn,t}}*S \end{array}\right)}{(1+r)^{\mathrm{t}}}+\sum_{t=1}^{N}\frac{(\mathrm{AC}_{\mathrm{PM,t}}*S)}{(1+r)^{\mathrm{t}}} \quad (2)$$

$$\mathrm{DCO}=\sum_{t=0}^{N_{\mathrm{debt}}-1}\frac{\left(\left(\mathrm{C}_{\mathrm{inv}}^{\mathrm{u}}*S\right)/N_{\mathrm{debt}}+\left(\mathrm{C}_{\mathrm{inv}}^{\mathrm{u}}*S-C_{\mathrm{lcs,t}}\right)*r_{\mathrm{d}}\right)}{\left(1+r\right)^{\mathrm{t}}}+\sum_{t=1}^{N}\left(\frac{C_{\mathrm{p}}^{\mathrm{u}}*S+C_{\mathrm{c}}^{\mathrm{u}}*S+m_{\mathrm{m}}^{\mathrm{m}}*C_{\mathrm{CM,t}}^{\mathrm{u}}*S+\mathrm{ebt}_{\mathrm{t}}*C_{\mathrm{tax}}^{\mathrm{u}}}{\left(1+r\right)^{\mathrm{t}}}\right) \quad (3)$$

On the discounted cash inflows side, an important role is related to the recycling of materials contained in the products being processed. Therefore, the amount of materials recovered is multiplied with some variables such as the market price of these materials but also their recycling rate and degree of purity (Choi and Fthenakis, 2014). About the prices of recycled materials, the main websites devoted to these topics were considered (Heraeus, Kme, Investing). Therefore, from the market analysis, it is found that among the materials that can be recovered from the recycling of PV modules, silver is the most valuable component. Its average value is quantified as 650 €/kg, while the lowest value is associated with glass (0.125 €/kg). Furthermore, we identify 2.3 €/kg for Al, 2.1 €/kg for Si, 8.5 €/kg for Cu and 3.1 €/kg for Zn. These values are higher than in previous analyses, but the result was expected given the current surge in the raw materials market (D'Adamo et al., 2017). Regarding the level of purity an optimistic scenario is considered, set equal to 100% although this condition is not always verified (Choi and Fthenakis, 2014). Regarding, yield of recycled material, values emerged in the literature were considered, where again a very satisfactory recovery perspective emerges (Deng et al., 2019).

To this item can be added a cost that is not incurred. Within a business plan, this item can be considered as revenue if the PV producers are also recyclers (McDonald and Pearce, 2010). Alternatively, recycling centres receive such a fee for disposing of PV modules appropriately. The literature proposes several values: 112 $/tonnes (Gautam et al., 2022), 500 $/tonnes (Rubino et al., 2020) and 225–425 $/tonnes (Granata et al., 2022).

The analysis of discounted cash outflows turns out to be characterized by high variability. As for investment costs, they are influenced by the size of the plant and some work shows that they can play a significant role on the profitability of the investment (Mahmoudi et al., 2020). Turning to an analysis of operating costs, several components emerge. Production process costs turn out to be the value that per unit tonnes represents the greatest value (Cucchiella et al., 2015), however there is a significant increase in the cost of collection/transportation when analysing a large target area (Choi and Fthenakis, 2014; Gautam et al., 2022). In addition, some materials that cannot be recycled (plastics) must be properly disposed of in suitable locations. In order to identify comparable values in the literature the following data are proposed related to unitary collection cost ($\mathrm{C}_{\mathrm{c}}^{\mathrm{u}}$), unitary conferred materials cost ($\mathrm{C}_{\mathrm{cm}}^{\mathrm{u}}$), unitary process cost ($\mathrm{C}_{\mathrm{p}}^{\mathrm{u}}$) and unitary investment cost ($\mathrm{C}_{\mathrm{inv}}^{\mathrm{u}}$): $C_{\mathrm{c}}^{\mathrm{u}} = 210€ / \mathrm{tonnes}$; $C_{\mathrm{cm}}^{\mathrm{u}} = 90€ / \mathrm{tonnes}$; $C_{\mathrm{p}}^{\mathrm{u}} = 320€ / \mathrm{tonnes}$ and $\mathrm{C}_{\mathrm{inv}}^{\mathrm{u}} = 270€ / \mathrm{tonnes}$ (D'Adamo et al., 2017) and $\mathrm{C}_{\mathrm{c}}^{\mathrm{u}} = 288€ / \mathrm{tonnes}$; $\mathrm{C}_{\mathrm{p}}^{\mathrm{u}} = 351\$ / \mathrm{tonnes}$ and $\mathrm{C}_{\mathrm{inv}}^{\mathrm{u}} = 400\$ / \mathrm{tonnes}$ (Gautam et al., 2022).

In addition, some assumptions should be specified: (i) recovered Lead can be valued by other centres and therefore is considered to have zero value in the market exchange; (ii) other metals are not included as potential revenues and (iii) lost dust is also not included in the economic analysis. Finally, a conservative assumption is made in which material prices do not increase.

The two-macro variables that typically characterize a DCF are the opportunity cost of capital set at 5% and the useful life of the project set at 10 years (D'Adamo et al., 2017). In addition, 2022 is taken as year zero of the project, such that in 2023, the project goes into operation and the entire initial investment is covered by third-party funds. The choice of input values was therefore made in accordance with the literature and experts in the field working in recycling centres. Table 1 proposes the list of acronyms and values of input data.

In order to have a suitable model in multiple case studies, the map of several scenarios as a function of the baseline inputs is proposed (Figure 2):

- Regarding the price of sales materials, both a pessimistic and an optimistic scenario was added in which the average value is decreased/increased by its standard deviation than baseline scenario.
- Inherently the avoided landfill cost, two values were identified that are consistent with, but not equal to, what has been proposed in the literature. The 500 €/tonnes value was not considered, but values of 200 €/tonnes and 350 €/tonnes were favoured. In addition, the scenario in which this value is zero was considered. A useful scenario for policy implications.
- Finally, about costs, the two extremes were taken for all cost variables such that two related scenarios were identified. An intermediate scenario was then added.

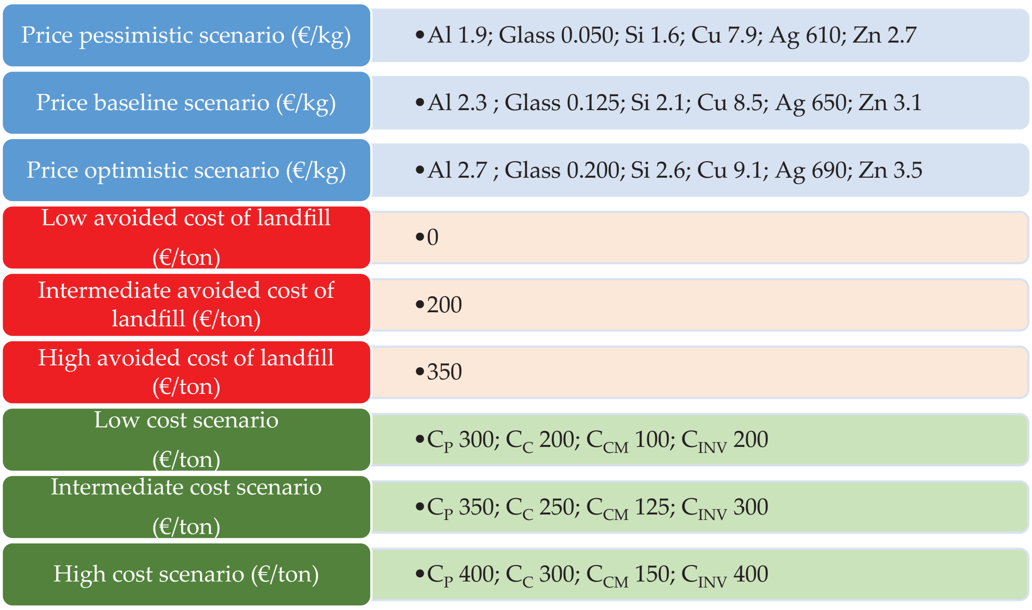
Results

The economic model used in this work is based on a set of input data that allowed the evaluation of the variability related to the main critical economic variables. The number of scenarios analysed in this work amounted to 27. It is obtained from the combination of three scenarios related to costs with three scenarios

Table 1. Input values.

Acronym	Variable	Value
AC_{PM}	Avoided cost of landfill (PV modules)	0–350 €/tonnes
C_c^u	Unitary collection cost	200–300 €/tonnes
C_{cm}^u	Unitary conferred materials cost	100–150 €/tonnes
C_{inv}^u	Unitary investment cost	200–400 €/tonnes
C_{lcs}	Loan capital share	$f\,(C_{inv}^u\,;\,N_{debt};\,r_d)$
C_p^u	Unitary process cost	300–400 €/tonnes
C_{tax}^u	Unitary taxes cost	40%
ebt	Earnings before taxes	*f* (revenues; costs)
inf	Rate of inflation	2%
m_m^m	Mass/module of conferred material[a]	89.10 kg/tonnes plastics
m_{rm}^m	Mass/module of recycled material[a]	103.00 kg/tonnes Al; 753.60 kg/tonnes glass; 6.40 kg/tonnes Si; 9.50 kg/tonnes Cu; 0.07 kg/tonnes Ag; 0.02 kg/tonnes Zn
N	Lifetime of investment	10 year
N_{debt}	Period of loan	5 year
pl_{rm}	Purity level of recycled material	100%
pr_{rm}	Price of recycled material	1.9–2.7 €/kg Al; 0.050–0.200 €/kg glass; 1.6–2.6 €/kg Si; 7.9–9.1 €/kg Cu; 610–690 €/kg Ag; 2.7–3.5 €/kg Zn
r	Opportunity cost of capital	5%
r_d	Interest rate on a loan	3%
S	Size	3000 tonnes
t	Period	Year
y_{rm}	Yield of recycled material	100% Al; 100% glass; 95% Si; 99% Cu; 94% Ag; 95% Zn

[a] Other materials composition in 1 tonnes of crystalline Si PV modules: 0.40 kg/tonnes Pb; 2.31 kg/tonnes other metals and 35.60 kg/tonnes dust.



Price pessimistic scenario (€/kg)	• Al 1.9; Glass 0.050; Si 1.6; Cu 7.9; Ag 610; Zn 2.7
Price baseline scenario (€/kg)	• Al 2.3 ; Glass 0.125; Si 2.1; Cu 8.5; Ag 650; Zn 3.1
Price optimistic scenario (€/kg)	• Al 2.7 ; Glass 0.200; Si 2.6; Cu 9.1; Ag 690; Zn 3.5
Low avoided cost of landfill (€/ton)	• 0
Intermediate avoided cost of landfill (€/ton)	• 200
High avoided cost of landfill (€/ton)	• 350
Low cost scenario (€/ton)	• C_P 300; C_C 200; C_{CM} 100; C_{INV} 200
Intermediate cost scenario (€/ton)	• C_P 350; C_C 250; C_{CM} 125; C_{INV} 300
High cost scenario (€/ton)	• C_P 400; C_C 300; C_{CM} 150; C_{INV} 400

Figure 2. Map of scenarios.

associated with changes in revenues through material prices. The nine scenarios obtained from the combination of costs and revenues are then repeated for each of the three scenarios related to the potential avoided landfill cost (Table 2).

The results show that profitability is not verified in all scenarios and, there are 17 (about 63% of the total) scenarios in which NPV is negative. The considerations that emerge are as follows. The first sharply defines that in the absence of an economic contribution that enhances the environmental damage avoided through the receipt of a fee to dispose of PV modules appropriately, the NPV is always negative. This result influences the policy maker because the use of renewables has a clear support for combating climate change, quantifiable as 620 gCO_2eq/kWh (D'Adamo et al., 2021); however, sustainability requires the evaluation of a product throughout its life cycle. Energy payback time for silicon panels is quantified as 2.6 years, which can be reduced to 1.6 years by including the recycling process (Vellini et al., 2017). The second consideration is inherent to a scenario in which the variables present a high value of costs, since in such a situation only in one scenario the NPV is positive and equal to

Table 2. NPV of PV modules recycling (thousand €).

Low avoided cost of landfill

	Price pessimistic scenario	Price baseline scenario	Price optimistic scenario
Low-cost scenario	−3115	−1600	−84
Intermediate-cost scenario	−4860	−3344	−1828
High-cost scenario	−6604	−5088	−3573

Intermediate avoided cost of landfill

	Price pessimistic scenario	Price baseline scenario	Price optimistic scenario
Low-cost scenario	−335	1180	2696
Intermediate-cost scenario	−2080	−564	951
High-cost scenario	−3824	−2308	−793

High avoided cost of landfill

	Price pessimistic scenario	Price baseline scenario	Price optimistic scenario
Low-cost scenario	1749	3265	4781
Intermediate-cost scenario	5	1521	3036
High-cost scenario	−1739	−224	1292

1292 k€ (when considering a Price optimistic scenario and a High avoided cost of landfill). This inevitably drives the consideration that costs must follow innovation processes that lead them to have high performance values by recovering all possible materials from a waste, giving them the opportunity to be a benefit but at the same time, technological development must also lead to cost reduction. Some analyses confirm the unprofitability of the recycling plants, but the cost to recycle could be as little as 0.03 $/kg (Faircloth et al., 2019).

Potential synergies emerge from combining PV within other products for recycling (Islam et al., 2020). In addition, there is greater interest in thin film modules consider the presence of higher value-added critical materials (Choi and Fthenakis, 2010; Cucchiella et al., 2015). When considering the intermediate cost scenario if it is true that in the presence of a High avoided cost of landfill the NPV is always positive, on the other hand it is noted that this performance remains only verified in the Price optimistic scenario if the avoided cost of landfill is reduced from 350 to 200 €/tonnes. The third consideration relates to prices since while it is true that in an economic situation in which the raw materials market is affected by strong fluctuations, the comparison among contexts shows that depending on the pessimistic, baseline and optimistic scenario there are two, three and five scenarios in which NPV is positive, respectively. The most striking finding, however, is the change in the profits that can be realized (about a 1515 k€ increase between the different scenarios). This value is motivated by the low presence of valuable materials that are recorded within the polycrystalline modules. The positive NPV ranges from 5 to 4781 k€. Such significant values are also recorded in other analyses, where the payback period is quantified as 1 year (Lim et al., 2022). Moreover, the profitability conditions of these recycling plants require not high levels of taxation (Liu et al., 2018), as does the level of risk with which these projects may be associated (Lim et al., 2022).

However, if the future market environment predicts continued growth in material prices, businesses can be competitive if they create partnerships or industrial symbiosis (Colpo et al., 2022) such that they have a short supply chain with access to contained raw materials. Furthermore, agreements between various stakeholders about recycling fees will further boost the overall economic viability of PV recycling (Daniela-Abigail et al., 2022). Cooperation between government and private entities is also needed, utilizing the advantages associated with adequate infrastructure and research and development programmes (Yu et al., 2022).

Finally, it is necessary to promote the development of small and medium-sized plants because decentralized models involve PV plants installed within different territories (D'Adamo et al., 2017). This favours the autonomy of individual territories, and within the concept of sustainable communities these territories must be able to produce energy but also manage the waste they have produced. Where only large plants are developed, it results in transportation needed to transfer this waste, which inevitably reduces the environmental benefits associated with the use of renewables. Furthermore, particular attention is given to the recovery of valuable materials (especially Ag) which although present in smaller quantities has a much larger selling price than other materials as pointed out earlier (Granata et al., 2022). At the same time, large quantities of some materials can bring great benefits, particularly if the market for these products (e.g. glass) is heading toward growing trends (Dias et al., 2022).

In order to give robustness to the results obtained, a risk analysis was conducted, in which all critical variables analysed previously (including cost components and material selling prices) are varied by means of the Monte Carlo model. One thousand iterations of the NPV are considered and the value of the intermediate scenario is taken as the mean value, while the standard deviation is calculated based on the alternative scenarios (Figure 3). The analyses then refer to the joint Intermediate cost and Price baseline scenario according to the three distinct avoided landfill costs.

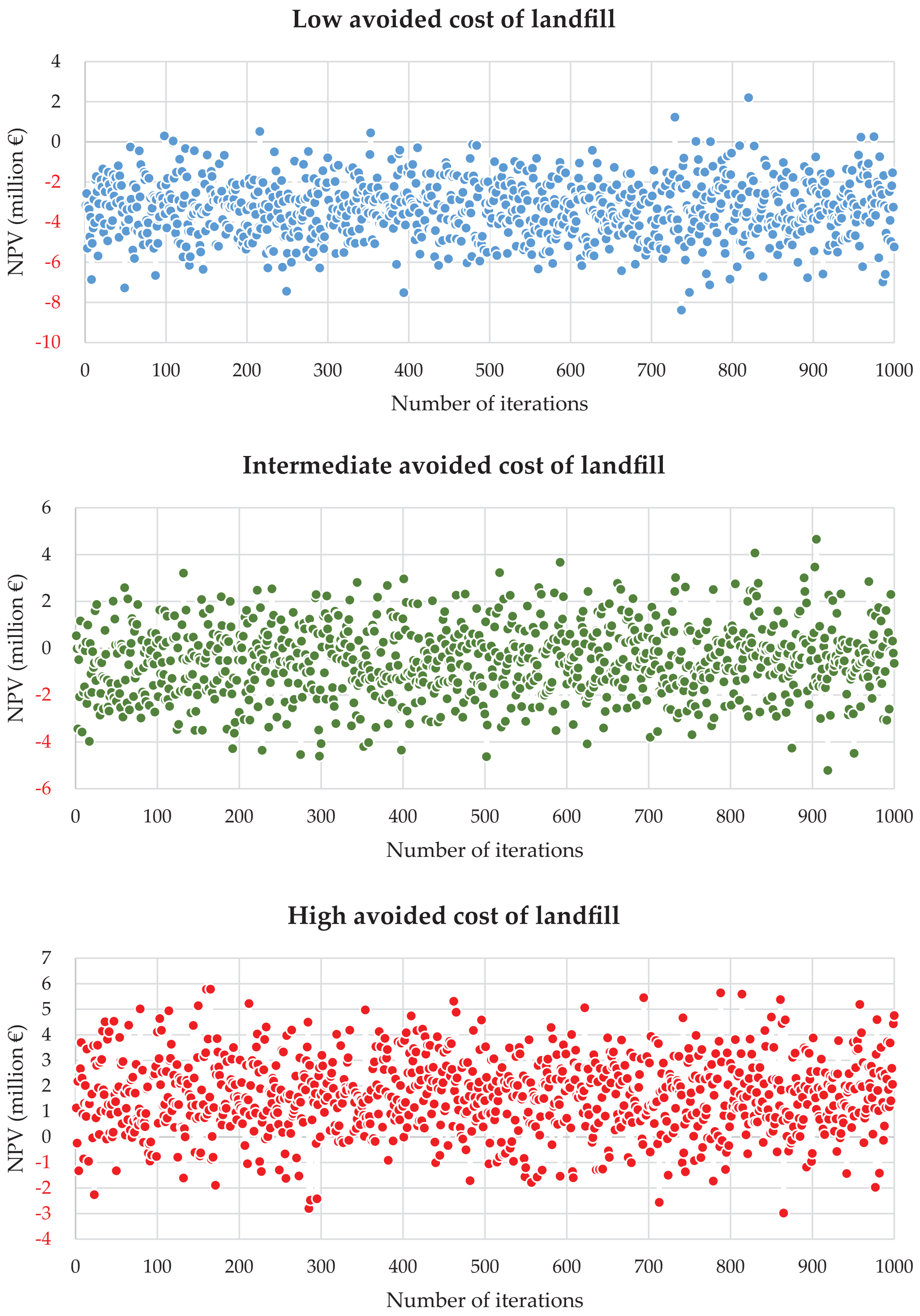


Figure 3. Risk analysis.

Table 3. BEP of avoided cost of landfill (€/ton).

	Price pessimistic scenario	Price baseline scenario	Price optimistic scenario
Low-cost scenario	224	115	6
Intermediate-cost scenario	350	241	132
High-cost scenario	475	366	257

The results emerging from these analyses confirm previous results. In the market context in which an avoided cost of landfill of 0 €/tonnes is applied, there are about 1.1% scenarios in which the NPV is positive. Thus, we can point out that investors have no advantage to invest in a recycling plant that only processes 3000 tonnes of polycrystalline PV modules. The situation becomes diametrically different when considering an avoided cost of landfill of 350 €/tonnes since in about 87.6% of iterations, the NPV is positive. This work has the limitation of not associating the correct value of the PV module disposal fee with the relative net benefit associated with its sparing environmental management. Such a value requires environmental analyses that quantify the exact value of emission reductions, but it is also contextually linked to the economic value associated with CO_2. Thus, economic analyses aim to support the policy maker in order to highlight how the profitability of a recycling plant varies according to this scenario. If an intermediate scenario between the previous two is chosen, with an avoided cost of landfill of 200 €/tonnes, the NPV turns out to be positive in about 35.2% of the scenarios. Some authors have calculated the unitary subsidy, which is 1.95 USD/kW (Liu et al., 2018), to have a benefit-cost ratio of 1.1 (Liu et al., 2020). This value is considered a reference value for material recycling businesses.

Finally in order to give support to the policy maker, the avoided cost landfill values that make the project profitable are identified. In fact, the Break-Even Point (BEP) analysis identifies the value of this critical variable when NPV = 0 (Table 3).

The results confirm what is shown in Table 2. In fact, even in the most favourable market scenario (low cost scenario and optimistic revenue scenario) a new cost of landfill of 6 €/tonnes needs to be applied. There are only three of the nine market scenarios that have a value below 200 €/ton, which becomes seven if the value of 350 €/tonnes is used as a comparison parameter. In the least favourable market scenario (high cost scenario and pessimistic revenue scenario) a new cost of landfill equal to 475 €/tonnes should be considered.

Conclusions

PV panels have a crucial role in coping with the global warming mitigation and the energetic crisis currently affecting the European Community. However, from the perspective of EoL management, there are still big issues to be solved in order to recover materials from this kind of e-wastes. Because of several reasons (e.g. type of embedded materials, illegal shipments, location of manufacturers) EoL businesses do not have the interest in approaching them. This poses a significant environmental concern in terms of their management. This work assessed the profitability of a specific PV module recycling plant, by evaluating different market contexts in which multiple scenarios of material price, investment and process costs are considered. The results emerging from these analyses confirm what has been evidenced by other works available in the literature. Specifically, stakeholders have no advantage to invest in a recycling plant processing just 3000 tonnes of polycrystalline PV modules. The situation becomes diametrically different when landfill costs are avoided. NPV ranges from 5 to 4781 thousand € with a disposal fee of 300 €/tonnes in function of price scenario considering a low/intermediate cost scenario. Instead, NPV varies from 951 to 2696 thousand € with a disposal fee of 350 €/tonnes only for an optimistic price scenario considering low/intermediate cost scenario. The limit of this work lies in not associating the correct value of the PV module disposal fee with the relative net benefit associated with its sparing environmental management. Thus, further economic analyses should be done in order to better understand the influence of certain policy measures on the recovery of PV panels.

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