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Title: End-of-Life of used photovoltaic modules: a financial analysis

Article Type: Review Article

Keywords: Photovoltaic, End-of Life PV, Recycling, WEEE

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Order of Authors: Federica Cucchiella, Ph.D.; Idiano D'Adamo; Paolo Rosa

Abstract: The photovoltaic (PV) industry has a relevant role in terms of energy systems sustainability. The economic and environmental benefits related to its application brought the PV sector to an overall installed power of about 138 Giga Watt in 2013 (+24% compared to 2012).The recent update of the European Waste Electrical and Electronic Equipment (WEEE) Directive classifies End-of-Life (EoL) PV panels as an electrical/electronic waste. Hence, it became mandatory to define alternative strategies to landfill [1]. The scientific literature presents different interesting technological solutions, together with related environmental benefits coming from the PV modules recycling. However, there is a clear fragmentation from an economic point of view [2]. The aim of this paper is to apply a financial methodology, like the Discounted Cash Flow (DCF) analysis, for the assessment of PV modules recycling process profitability. This method goes to evaluate two main indexes, as the Net Present Value (NPV) and the Discounted Payback Period (DPBT). The Italian context is selected as a reference case study for the definition of an optimal plant capacity size related to current and expected national market volumes. To this aim, two types (pilot and industrial) of plants are proposed by the authors. The obtained financial results are useful to support future strategic decisions about the PV recycling management.

Response to Reviewers: REVIEWER 1

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first of all thank you for your informed comments which have helped improve this paper to the standard considered fit for publication. We appreciate the time that you have spent doing this. We have tried to address them all.
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Table 3: Economic analysis of PV recycling

Type of cells	Plant size	Indexes	Reference
c-Si	185 t	Monthly Profit: -10,100 \$/month	[46]
x-Si	1,876 t	Monthly Profit: -7,509 \$/month	[46]
mixed	20,000 t	Monthly Profit: 624,755 \$/month	[46]
CIGS	Not specified	Unitary Profit: 22.25 \$/module	[45]
CdTe	Not specified	Unitary Profit: -0.24 \$/module	[45]
c-Si	Not specified	Unitary Profit: -23.96 \$/module	[45]
p-Si	Not specified	Unitary Profit: -23.99 \$/module	[45]
Thin film	2,688 t	Monthly Profit: -151,000 \$/month	[55]

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Organic PV	Not specified	Target of Recycling Cost: 0.44 \$/m^2	[61]
CZTSSe	Not specified	Recycling Cost: 77 \$/t	[61]
Thin film	Not specified	Recycling Cost: 3-4 €/module	[36]

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Table 3: Economic analysis of PV recycling

Type of cells	Plant size	Indexes	Reference
c-Si	185 t	Monthly Profit: -10,100 \$/month	[46]
x-Si	1,876 t	Monthly Profit: -7,509 \$/month	[46]
mixed	20,000 t	Monthly Profit: 624,755 \$/month	[46]
CIGS	Not specified	Unitary Profit: 22.25 \$/module	[45]
CdTe	Not specified	Unitary Profit: -0.24 \$/module	[45]
c-Si	Not specified	Unitary Profit: -23.96 \$/module	[45]
p-Si	Not specified	Unitary Profit: -23.99 \$/module	[45]
Thin film	2,688 t	Monthly Profit: -151,000 \$/month	[55]
Thin film	2,688 t	Monthly Profit: 107,000 \$/month	[55]
Organic PV	Not specified	Target of Recycling Cost: 0.44 \$/m^2	[61]
CZTSSe	Not specified	Recycling Cost: 77 \$/t	[61]
Thin film	Not specified	Recycling Cost: 3-4 €/module	[36]

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End-of-Life of used photovoltaic modules: a financial analysis

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Abstract

The photovoltaic (PV) industry has a relevant role in terms of energy systems sustainability. The economic and environmental benefits related to its application brought the PV sector to an overall installed power of about 138 Giga Watt in 2013 (+24% compared to 2012).

The recent update of the European Waste Electrical and Electronic Equipment (WEEE) Directive classifies End-of-Life (EoL) PV panels as an electrical/electronic waste. Hence, it became mandatory to define alternative strategies to landfill [1]. The scientific literature presents different interesting technological solutions, together with related environmental benefits coming from the PV modules recycling. However, there is a clear fragmentation from an economic point of view [2].

The aim of this paper is to apply a financial methodology, like the Discounted Cash Flow (DCF) analysis, for the assessment of PV modules recycling process profitability. This method goes to evaluate two main indexes, as the Net Present Value (NPV) and the Discounted Payback Period (DPBT). The Italian context is selected as a reference case study for the definition of an optimal plant capacity size related to current and expected national market volumes. To this aim, two types (pilot and industrial) of plants are proposed by the authors. The obtained financial results are useful to support future strategic decisions about the PV recycling management.

Keywords: Financial analysis, Photovoltaic, End of Life PV, Recycling, WEEE

1. Introduction

PV power is currently one of the fastest growing power-generation technologies in the world, mainly driven by technological improvements that reduced costs, and government policies supporting renewable energy sources [3, 4]. At the end of 2013, the cumulative PV capacity around the world reached more than 138 Giga watts (GW). Over the past four years, 83% of the overall available power has been installed [5].

A financial analysis of the renewable energy sector has demonstrated that investments have reliable and healthy long-term financial returns with low levels of risk [6, 7]. There are numerous factors contributing to the definition of the economic performance of renewable energy investments, such as subsidies, sale price of energy, investment cost, equivalent operating hours and the size of the plants. PV technologies can reach the aim to decarbonise the power generation system [8] and a literature review has highlighted that one of the greatest challenge of the PV system is its cost effectiveness [9]. The incentive scheme has encouraged and accelerated the deployment of energy produced from PV sources in several countries and it represents the preferable tool in new markets [10]. Instead, in absence of support mechanisms, the harmonisation of the consumption and production of electricity (self-consumption) determines the profitability of PV facilities [11]. Furthermore it is opportune highlighted that the combination between solar systems, heat pumps and heat use can add additional profits and can reduce environmental pollution. Several papers have shown that the heat pump offers economic advantages [12-14].

With the growing installation of PV systems and limited availability of resources, the end-of-life (EoL) management of these products is becoming very urgent [2]. In fact, these scraps represent a potential source of environmental pollution because they can contain hazardous materials, such as Pb, Cd, Cr and Bi, that cause serious illnesses in humans because of their toxicity [15, 16]. Furthermore, the expected volumes estimated by some experts (e.g. [17] speak about 50,000 tons of scrap PV panels generated all over the world since 2015) give some idea of the issue.

The recent decision taken by the EU commission to include PV panels into the new WEEE directive follows these expectations, trying to limit in some way the negative impacts. In fact, being now PV panels a WEEE category, implicitly imposes the Extended Producer Responsibility (EPR) principle also to PV panel manufacturers. Basing on this principle, they have to ensure the right collection and recovery of EoL products within European borders. In the United States the Environmental Protection Agency has regulated EoL disposal of solar products under the Federal Resource Conservation and Recovery Act (RCRA). However, issues about the management of scrap PV panels goes to be added to the more general issue about the management of WEEEs.

Globally, about 30 to 50 million tons of WEEEs are disposed each year and the estimated annual growth rate is equal to 3-5% [18]. For example, Asian and EU countries together dispose an estimated amount of 12 and 6.5 million tons/year of WEEE, respectively [19]. These numbers makes the management of WEEEs is an interesting challenge toward sustainability [20] and its positive impact on GHG mitigation was already analyzed by the literature [21] also in terms of Sustainable Supply Chain Management (SSCM) [22].

From an environmental side, even if the sustainability of PV panels in terms of decommissioning, disposal or energy requirements is well-stressed by the literature, these analyses are underestimated, by negatively influencing also the related energy and emissions analyses based on Energy Payback Time (EPBT) and Greenhouse Gas Payback Time (GPBT) indicators [23]. For example, in Italy EPBT and GPBT are equal to 1.8-2.9 years and 2.5-3.3 years, respectively [24]. However these date could be decreased of about 1.7% if recycling would be considered in the analysis [25].

From the technological side, previous works suggested that the recycling of silicon based and thin-film PVs is technically possible [26, 27]. Unfortunately, they are not yet fully implemented because of the current lack of collection networks in many countries (e.g. Europe implemented a dedicated infrastructure only in 2007). However, thanks to new governmental, economic, environmental and human health policies, this trend seems to begin its inversion [28].

Finally, from the economic side, what emerges from the literature is that the profitability of investments related to the construction of PV recycling facilities seems to be guaranteed only by the management of great amounts of wastes. The authors decided to analyse the Italian context with the aim to assess if the presence of current low volumes and the expectation of great volumes in the next future can support (or not) the development of a national PV panels recycling chain.

The paper is organised as follows. Section 2 presents a literature analysis about PV panels recycling with a technological, environmental and economic perspective. Section 3 focuses on the Italian market, by calculating the amount of wastes to be recovered under a high uncertainty. This way, it is possible to define the number of plants to be constructed in function of the selected optimal size. Section 4 presents an economic model developed and used to evaluate four case studies investments assumed with respect to two different installation sizes (185 tons and 1,480 tons) and two different scenarios (PV manufacturer coincides or not with the PV recycler). Results are presented and discussed in Section 5. Additionally, a sensitivity analysis on some critical variables is conducted. Section 6 presents concluding remarks and future perspectives.

2. State of the art on PV panels recycling

The topic “PV modules recycling” is current, relevant and multidisciplinary. The development of the PV market over recent years emphasized the need for a sustainable method for their disposal at the end of their life.

2.1 Technological view

The recycling of PV modules involves both silicon-based (mono crystalline (c-Si), poly crystalline (p-Si), amorphous (a-Si)) and thin film (CIGS and CdTe) solar cells. However, authors do not exclude that, to these PV panels categories currently available in the market, other technologies (e.g. Concentrator photovoltaic (CPV), Dye-sensitized solar cells, Organic solar cells, Hybrid cells, Passivated emitter and rear cell (PERC) and Passivated emitter and rear locally diffused (PERL) [29]) will be considered as new scrap PV panes in the next future. These categories were not included in the present analysis because of their absence in terms of current installed volumes. In general terms, the PV panels recycling process can be divided into three macro-steps: i) mechanical, chemical or thermal de-lamination, ii) chemical de-coating and iii) chemical extraction/refining [30, 31]. However, these phases can differ basing on the constructive technology of PV panels. In particular:

- the recycling of mono and poli crystalline (x-Si) solar cells involves pyrolysis, for the recovery of crystalline silicon wafers [32];
- the recycling of CIGS solar cells involves a thermal or chemical process to recover critical metals (e.g. Se, In and Ga) and glass [33];
- the recycling of CdTe solar cells involves a chemical process to strip metals and Ethylene and Vinyl Acetate copolymer (EVA) and additional steps of chemical treatments to separate and recover critical metals (e.g. Cd and Te) - [34];
- the recycling of a-Si solar cells involves a mechanical process [35].

In addition, innovative PV panels recycling processes able to improve the purity level of recovered materials are under investigation by the experts. Among them, one of the most promising recycling technology seems to be represented by the so called “wet etching process” described by [17]. This process differs from the previous ones because de-lamination and de-coating phases are substituted by two different etching phases (the first one using nitric and hydrofluoric acids mixed with potassium hydroxide, the second one using a mixture of phosphoric, nitric and hydrofluoric acids) to recover Si wafers from degraded Si solar cells.

Many laboratory-scale or pilot industrial processes have been developed globally during the years by private companies and public research institutes to demonstrate the real potential offered by the recycling of PV panels [16, 36]. They can be classified in: 8 laboratory processes, 2 industrial pilot plants, 1 industrial plant and 1 patent. Nowadays, only three of these treatment and recycling methods reached the industrial scale and all of them are focused on thin film panels [37]: the First Solar’s process and two EU funded pilots (the SENSE project plant and the RESOLVED plant).

These methods differ in the phases composing the recycling process. The First Solar process sees a mechanical phase for the recovery of glass, followed by a series of chemical treatments for the recovery of precious and hazardous materials, like Te and Cd [38]. The SENSE project presents different recycling strategies to recover valuable metals from different types of thin film PV panels. A mechanical and chemical process is used to treat CIGS panels, a thermal and chemical process is used to treat CIGS and CdTe panels and a fully mechanical process is used to treat a-Si panels [35]. Finally, the RESOLVED project exploits mechanical treatments with a minimum use of chemicals for the recovery of both undamaged and damaged PV modules [39]. The first ones are subjected to thermal and mechanical processes. The others only to mechanical processes. The resulting material is, then, treated by a chemical attack in order to recover the semiconductor materials. First Solar's process is the only private plant currently operational (in the US, Germany and Malaysia) on the base of which are established all the more recent studies on economic evaluations about PV panels recycling processes. However, this plant is currently employed to treat, mainly, production scraps. From the industrial point of view, PV Cycle (the most important industrial association focused on PV panels recycling) is involved, together with other partners, into three different projects targeted on the improvement of the PV panels recycling sector [40]: Full Recovery End-of-Life Photovoltaic (FRELP), Photovoltaic Panels MObile REcycling Device (PV MOREDE), Cradle to cradle sustainable PV modules (CU-PV). The first one is focused on the study of innovative recycling technologies able to improve the current PV panels' average recycling rate up to 100%, by reducing also the overall energy consumption rate of a common PV panel. The second one wants to develop a mobile EoL PV panels treatment plant supporting the recycling of small quantities of scraps. Finally, the last one wants to reduce the use of Ag and Pb inside PV panels, by contemporarily develop a more sustainable PV panels design process and improve the value of EoL phases. A summary of the current recycling methods distinguished by constructive technologies is reported in Table 1 [41].

2.2 Environmental view

After having assessed the technological view of PV panels recycling, it is of outmost importance to analyze the environmental benefit of recycling. In fact, recycling can ensure the supply chain (SC) sustainability in the long-term [42] by enhancing, from one hand, the recovery of energy and materials embedded in PV modules and, from the other hand, by reducing CO_2 emissions, EPBT and GPBT related to the PV modules manufacturing industry [1]. The transition towards a more sustainable SC will be critical because promising clean technologies, like the ones embedded in PV modules, are based on materials with inherent risks in their supply; these risks include scarcity, price volatility, criticality, and other potential SC disruptions [42]. Only an improvement in byproduct yields, end-use recycling rates, and end-use materials intensity will allow to minimize these sources of risk. From an energy market view, recycling could contribute in: i) mitigation of price fluctuations, both for material inputs and new PV modules, ii) limiting political instability effects, iii) increasing energy security and diversification, iv) augmenting green and high-tech jobs, v) improving access to electricity and full account of electricity costs [2]. From a social point of view, basing on the human health risk estimates generated for PV panel disposal, there are no problems at current production volumes, but could become critical in the near future if not appropriated EoL strategies will be implemented [28]. All these problems clearly indicate the need to introduce the Extended Producer Responsibility (EPR) concept also in the PV modules recycling sector, so to ensure the environmental and economic sustainability of recycling for all the types of PV modules. The recent update of the European WEEE directive and the advances in recycling technologies goes in this direction [31], with a positive effect in almost all the damage categories defined in the Life Cycle Assessment (LCA) and significantly contributing to the reduction of global warming and carbon footprint of the PV technology estimated in almost 16 kg CO_2-equivalent (CO_2eq) of primary energy from non-renewable resources. In other words, recycling 1 ton of silicon-based PV modules can save approximately 800 kg CO_2eq and up to 1,200 kg CO_2eq in the case that the module was 100% manufactured from primary materials [43]. This could provide the environmental facelift needed to restore the sustainable image of PV production [44] and PV investments are characterized by a savings of 8.5 t CO_2eq per kW installed [3].

2.3 Economic view

The recycling of the available types of PV modules is not only an environmental and technological question. Crystalline silicon modules have traditionally dominated the PV panels production market (over 80% of market share) because it was the first technology to be installed at the beginning of the '90s and, hence, it is now the most present in EoL volumes to be treated. However, as it can be previously drawn, the attention of researchers and companies is even more focused on thin film modules recycling. In fact, silicon-based panels (c-Si, p-Si and a-Si) are poor of valuable materials and their recycling cost is always higher than the landfilling one, making recycling an unfavorable economic option [2]. From the opposite side, thin film panels (CIGS and CdTe) guarantee to recyclers a higher profit because of the content in valuable materials [45]. The characterization of current PV modules technologies available in the market are reported in Table 2 in terms of materials concentration, recycling rate [27, 46, 47] and raw materials market prices (LME prices - April 2014). However, these prices are referred to a 100% purity level [46], not always reachable with current recycling technologies. To this aim, in the following section a proper sensitivity analysis on materials market prices will be implemented, to demonstrate the influence of purity levels.

From a pure economic view (Table 3), many authors tried to estimate the profitability of different recycling processes and PV modules mixes. Some interesting models are presented by [45] and by [46]. The first one is a detailed mathematical model where the recycling profitability is analyzed only basing on PV modules technology. The second one adds to the previous view the plant capacity variable. So, it permits to support tactical decisions on optimizing the locations of new PV take-back centres (PVTBC) given the geographic concentration of goods and manufacturers for both silicon-based and thin film systems. What emerges from this last model is that: i) profitability is guaranteed only for industrial plants ii) treating thin film PV modules and iii) with a capacity of at least 20,000 tons/year. These plants could hypothetically reach a monthly revenue of 899,740$ (strongly dependent by materials market prices) out of 274,985$ of monthly costs. However, they are subjected to higher capital, operational and logistic costs than smaller plants. In facts, taking into account a smaller plant (for example with a capacity of about 185 tons/year), monthly revenues decrease to 8,953$ and overall costs decrease to 19,053$.

The technological and environmental issues are themes mainly treated by studies on PV modules recycling. Future research, as evidenced by other papers, should be oriented to analyze EoL strategies also by an economic perspective. In particular, for this analysis the DCF methodology can be used and in this direction a case study is proposed in section 5.

3. The Italian situation

Only by considering the recycled materials linked to the PV sector, PV Cycle quantified the amount of treated wastes from 2010 to 2014 (1^{st} quarter) in 9,225 tons [48], representing the 0.11% of all European WEEEs. Germany and Italy (as confirmed by data in Table 4) are characterized, respectively, by:

- installed power of 45% and 22%;
- PV panels dismantling of 57% and 27%;
- treated waste level per installed unit of power of 0.15 g/W and 0.08 g/W.

To better comprehend this last data, the average value of treated wastes per installed unit of power in Europe is about 0.12 g/W. It is, also, to enhance the Poland data, characterized by a high amount of treated wastes (584 tons).

The estimations on installed power, often, do not register an univocal data, because of the strong variability of reference data sources. Consequently, also the estimations of the recovered wastes are characterized by a high uncertainty both in overall EoL volumes and in percentages of production scraps at the Beginning-of-Life. The proper scientific literature focuses on the following hypotheses [46, 49]:

- the useful life of a PV plant is estimated in 20 years;
- manufacturing scrap is estimated to be about the 2%;
- the proportion between installed power and corresponding mass of produced wastes is fixed in 1 MW = 75 tons.

Starting from data about the Italian installed power since 1992 onward, volumes of EoL PV panels to treat from 2010 up to 2035 (Table 5) were estimated. It was hypothesized that from 2014 up to 2020 the annual installed power will be about 1 GW and from 2021 up to 2035 this value will decrease to 500 MW.

The total amount of waste PV modules to treat from 2014 up to 2035 results to be about 1.5 million tons, with a peak (83%) concentrated within the 2030-2033 period. Instead, by comparing data about potentially PV wastes generated and currently treated, there is an evident distinction in values during the 2010-2013 period (1,449 tons treated, as reported in Table 4, out of 26 kilotons potentially generated, as reported in Table 5). It exists, hence, a reduced propensity to recycle, typical of new products considered within the WEEE list [50]. However, this effect is not determined by a scarce awareness toward environmental issues, but it is due to a lack in regulations and an additional uncertainty on PV panels recycling profitability, caused by the available reduced volumes to treat and the low amount of recoverable key materials.

The description of this case study is useful to define the potential embedded in waste PV panels to treat, with the double aims to estimate the optimal dimension of PV panels recycling plants and, subsequently, the number of plants to construct [51]. The following section will describe the proposed economic methodology able to establish these important data.

4. Model assumptions

Given the relevance of EoL phases in the evaluation of PV investments, it is of outmost importance to focus the attention on the economic profitability of a PV modules recovery centre, by analyzing this aspect through the DCF method. The reference financial indexes are represented by NPV and DPBT [52, 53]. The economic model implemented for this scope is described below:

$$\mathrm{NPV} = \sum_{t=0}^{N} \frac{C_t}{(1+\mathrm{WACC})^t} = \sum_{t=0}^{N} \frac{I_t - O_t}{(1+\mathrm{WACC})^t} \quad (1)$$

$$\sum_{t=0}^{\mathrm{DPBT}} \frac{C_t}{(1+\mathrm{WACC})^t} = 0 \quad (2)$$

$$I_t = m_{rm}^{m} * y_{rm} * p_{rm} * R_{t,rm} * S + AC_{l,t} * S \qquad \forall rm \quad (3)$$

$$0_t = C_{e,t} + C_{lcs,t} + C_{lis,t} + C_{p,t} + C_{c,t} + C_{w,t} + C_{cm,t} + C_{tax,t} \tag{4}$$

$$R_{rm,t} = R_{rm,t-1} * (1 + inf) \qquad \forall t = 1 \dots N \quad \forall rm \tag{5}$$

$$AC_{l,t} = AC_{l,t-1} * (1 + inf) \qquad \forall t = 1 \dots N \tag{6}$$

$$C_{inv} = C^{u}_{inv} * S \tag{7}$$

$$C_d = \omega_d * C_{inv} \,;\, C_e = \omega_e * C_{inv} \qquad \text{with } \omega_d + \omega_e = 1 \tag{8}$$

$$C_{e,t} = C_e \qquad t = 0 \tag{9}$$

$$C_{lcs,t} = \frac{C_d}{N_{debt}} \qquad \forall t = 1 \dots N_{debt} \tag{10}$$

$$C_{lis,t} = \left(C_{inv} - C_{lcs,t}\right) * r_d \qquad \forall t = 1 \dots N_{debt} \tag{11}$$

$$C_p = C^{u}_{p} * S \tag{12}$$

$$C_{p,t} = C_{p,t-1} * (1 + inf) \qquad \forall t = 1 \dots N \tag{13}$$

$$C_c = C^{u}_{c} * S \tag{14}$$

$$C_{c,t} = C_{c,t-1} * (1 + inf) \qquad \forall t = 1 \dots N \tag{15}$$

$$C_{w,t} = m^{m}_{w} * f_{w,t} * S \tag{16}$$

$$f_{w,t} = f_{w,t-1} * (1 + inf) \qquad \forall t = 1 \dots N \tag{17}$$

$$C_{cm,t} = m^{m}_{m} * C_{ocm,t} * S \qquad \forall t = 1 \dots N \quad \forall ocm \tag{18}$$

$$C_{ocm,t} = C_{ocm,t-1} * (1 + inf) \qquad \forall t = 1 \dots N \quad \forall ocm \tag{19}$$

$$C_{tax,t} = Ebit_t * 3.9\% + Ebt_t * 27.5\% \qquad \forall t = 1 \dots N \tag{20}$$

$$WACC = \omega_e * r_e + \omega_d * r_d * (1 - t_f) \tag{21}$$

with:

Nomenclature

AC_l:	avoided cost of landfill	inf:	rate of inflation
C_c:	total collection cost	m^{m}_{m}:	mass/module of conferred material
C^{u}_{c}:	unitary collection cost	m^{m}_{rm}:	mass/module of recycled material
C_{cm}:	total conferred material cost	m^{m}_{w}:	mass/module of waste
C_d:	total debt cost	N:	lifetime of investment
C_e:	total shareholder's equity cost	N_{debt}:	period of loan
C_{inv}:	total investment cost	NPV:	net present value
C^{u}_{inv}:	unitary investment cost	O_t:	discounted cash outflows
C_{lcs}:	loan capital share cost	ocm:	other conferred material
C_{lis}:	loan interest share cost	p_{rm}:	purity level of recycled material
C_{ocm}:	unitary other conferred material cost	R_{rm}:	revenue of recycled material
C_p:	total process cost	r_d:	interest rate on loan
C^{u}_{p}:	unitary process cost	r_e:	opportunity cost
C_t:	discounted cash flow	rm:	recycled material
C_{tax}:	taxes cost	S:	plant size
C_w:	total waste cost	t:	time of the cash flow
DPBT:	discounted payback period	t_f:	tax rate
Ebt:	earnings before taxes	WACC:	weighted average cost of capital
Ebit:	earnings before interests and taxes	ω_d:	debt percentage

$f_{w,t}$:	waste fee	ω_e:	equity percentage
I_t:	discounted cash inflows	y_{rm}:	yield of recycled material

Since the profitability results are influenced by the plant capacity, (also evidenced in section 2) two distinct scenarios are analysed overcome this limitation:

- a pilot plant (185 tons/year), acting at local level and treating "only" crystalline modules;
- an industrial plant (1,480 tons/year) acting at national level and treating "all" types of PV modules. Basing on market data, it was assumed the following mix of products in input: 80% of crystalline PV modules and 20% of thin film PV modules (7% CdTe, 13% CIGS and CIS).

The optimal capacity of a PV module recycling plant is defined by the scientific literature [46]. Given that the installed PV plants distribution differs enormously from one region to another in Italy (for example, in Puglia, Lombardy and Emilia-Romagna is installed the 14%, 11% and 10% of the national solar power respectively), the "local" term means a geographical area more or less similar to the regional dimension. Instead, for what it concerns the industrial plant, a specific dimension equal to the amount of PV modules recovered during the period 2014-2024 was considered as reference volume (**Error! Reference source not found.**).

The pilot plant investment cost is evaluated in almost 105 k€, while the industrial plant is assumed to be almost 337 k€. This difference evidences the presence of an economy of scale of about 51% [46]. Other relevant costs are the ones originated by the PV modules production and collection processes, showing a reduction of 57% and an increase of 37% respectively, by switching the investment project from a pilot plant toward an industrial one [46, 54, 55]. Other materials that cannot be directly recycled or recovered are supposed to be adequately managed, with related conferred costs: plastics and junction boxes are sent to specialized recycling centres, while process scraps (wastes) are sent to landfills.

Revenues are obtained from: i) the amount of recovered materials ii) the corresponding recycling rate and iii) the material's market price and iv) the material's purity level obtained by the recycling process listed in Table 2[46]; furthermore, an additional benefit is related to the amount of avoided conferred costs (McDonald and Pearce, 2010). Given that this last benefit has to be allocated to the PV manufacturer, not necessarily it has to be allocated to the PV take-back centre (PVTBC) economic analysis. Hence, the following analysis will consider two distinct scenarios (S1 and S2) characterized by the presence (or not) of these benefits.

The DCF analysis needs other parameters, as: i) 2014 is taken as year zero of the project, ii) the plant useful life is estimated in 10 years, as established by European Commission methodological guideline for the cost-benefits analysis and iii) the entire investment cost is covered by third party funds (Table 6).

After having defined the economic model structure (and related input values), all the financial indexes useful for the assessment of the project will be estimated in the following section 5.

5. Results

The recycling of PV modules, developed to respect the principles of environmental protection, can allow to recover materials in an economic way. Several papers in literature guarantee about the success of PV recycling processes (e.g. [27, 56]) from an environmental view. Given that the realization of a new plant requires to accrue investment and operating costs, financial indexes (e.g. NPV and DPBT) allow to define the profitability related to a generic PV modules recovery centre.

5.1 Environmental impact

Before proceeding with the financial analysis, the environmental benefits were quantified [3, 43]. These are:

- the recycling of 185 tons of PV modules (pilot plant), instead of placing them in a landfill, saves about 1,480-2,220 tCO_2eq. To this amount of waste is associated the installed power equal to 2.46 MW, that saves about 21,000 tCO_2eq during the lifetime (20 years) compared to non-renewable resources (see Section 2.2);
- the recycling of 1,480 tons of PV modules (industrial plant), instead of placing them in a landfill, saves about 11,840-17,760 tCO_2eq. To this amount of waste is associated the installed power equal to 19.73 MW, that saves about 168,000 tCO_2eq during the lifetime (20 years) compared to non-renewable resources (see Section 2.2).

5.2 Baseline scenario – Financial analysis

The literature analysis results highlight as the plant size plays a key role in economic performances. The pilot plant is able to adjust the specific parameters of operation and to evaluate the deviations than theoretical assumptions. In the transition from the pilot plant to industrial one it is evaluated the economy of scale and this is a critical step in assessing the feasibility of new technologies or new recovery processes [46, 57]. The application of the model described in section 4 allowed the estimation of NPV and DPBT indexes related to investments for a pilot and an industrial plant for the EoL PV panels management. Figure 1 results show that the profitability level is never verified.

In the first scenario (S1) the loss is equal to 4.3 €/kg and 2.1 €/kg of treated volumes for pilot and industrial plants, respectively. Instead, in the second scenario (S2), where related benefits to avoided cost of landfill are considered, there is a slight reduction (4.2 €/kg and 1.9 €/kg of treated volumes). Furthermore, it was evidenced that the 1,480 tons plant has a significant economic improvement in the order of 50% than the 185 tons plant.

The indexes proposed in this paper are not directly comparable to ones that are been defined in Table 3. In literature are not present papers in which the DCF analysis is used to evaluate the profitability of PV recycling facilities. This methodology is typically used in financial analysis [11, 52, 53] and permits to consider two important variables: i. the time value of money and ii. the useful life of the plant.

NPV measures the returns generated by the investment project, while the DPBT represents the number of required years so that the cumulative discounted cash flows equate the initial investment. The DPBT, like the NPV index, defines the non-profitability of the investment. In fact, DPBT is greater than 10 years (pessimistic solution, where the cut off period is equal to the recycling plant's useful life) and in all the observed case studies it will not be possible to balance revenues and costs. The non-profitability of PV recycling facilities is been demonstrated also in [46].

Financial performances are heavily determined by process costs. In fact, they are equal to 77% and 57% of pilot and industrial plants total cost respectively. This is the case, therefore, of projects in which the investment cost has not a decisive role. Furthermore, it is possible to highlight that the collection cost increases its importance (from 15% to 36%) due to the greater value associated to the unitary cost (with a national level of collection) - Figure 2. In another paper [46] the collection cost seems to be the most relevant component when considering a European level of collection. In this scenario is possible to opt for an automated plant and the profitability is verified when the amount of incoming PV waste per year is at least equal to 19,000 ton.

From the revenues side, the hypothesized mix of industrial plants provides that 80% of treated modules are crystalline, and so the fine materials used in thin-film modules are present in very low percentages (0.01% in volume, but representing the 3% of the value). Additional revenues derive from glass (with a very low market value, but present in large quantities) and aluminum (that in crystalline modules is the second component for amount and it is characterized by a market value greater than glass). In the following section 5.2, a sensitivity analysis on critical variables is performed in order to define in which scenarios plants could have a positive financial performance.

5.3 Sensitivity analysis

NPV results are based on assumptions of a set of input variables. However, compared to the baseline scenario, the critical variables can record changes with respect to initial estimations. The sensitivity analysis reveals the influence of these changes on the financial index values on which the investment evaluations are based [49].

Cost components decrease by 20% in the optimistic scenario and increase by 20% in the pessimistic one. For example, unitary investment cost in the pilot plant is equal to 677 €/t with an increase of 20% of this variable. Regarding revenue components the variation of +/- 20% in optimistic/pessimistic scenario is always proposed. For example, the aluminum's market price is equal to 1.04 €/kg with a decrease of 20% of this variable. It should be highlighted that the revenue of recycled material is always equal to 1.04 €/kg when there is a reduction of 20% of aluminum's purity level obtained by the recycling process than to total purity.

The following tables show NPV obtained for each analyzed facility size: 185 tons (Table 7) and 1,480 tons (Table 8). Furthermore, with respect to financing options (defined by debt and/or owned capital), the WACC value is modified in the range 3-8% and corresponding NPV values are proposed in Table 9. Sensitivity analysis estimations confirm the non-profitability of the investment in any of the selected scenarios, both for the pilot and the industrial plants. Results indicate that, even by considerably increasing the materials economic value, it is not possible to obtain any improvement in the overall economic result able to justify the implementation of the analyzed investment. In fact, the negative result is linked to the impossibility to reach the critical mass of key materials embedded in PV modules.

In this analysis some variables are not considered:

- the module lifetime does not affect the profitability of PV recycling facilities, but only the one of PV systems [49]. Its variation determines a temporal shift of the amount of waste PV modules to be treated. For example, if the module lifetime is equal to 25 years the peak of the waste is achieved in 2036 and not in 2031;
- Table 3 defines that the recycling of thin film PV modules is more profitable than crystalline ones. However, the mix of products in input is not changed because, basing on market data, there is only a little reduction of c-Si and p-Si modules. Furthermore, in literature it is not well defined the relationship between the mix of waste PV modules and related treatment costs;
- the parameters on losses produce several effects. The loss of efficiency of the generator determines a lower electrical power, which affects only the profitability of PV systems [49]. The loss of efficiency of recycling processes is not considered, because it is supposed the operation at full load, determined by effective maintenance (obviously characterized by costs). The manufacturing scrap is estimated in this paper (section 3), but it does not change the profitability of recycling PV modules. Its variation determines a shift of the amount of wastes to be treated [46].

5.4 Discussion

The ideal approach for end-of-life PV modules disposal is recycling [17, 58]. The current analysis demonstrated that the investment generates a better environmental solution, but not an economical one. In order to stimulate the interest toward this type of investments, a way is to link the creation of economies of scale and learning. By considering bigger plants it is possible to obtain a series of benefits, first of all an overall cost reduction with particular focus on processing costs related to automated sorting systems. Furthermore, larger dimensions determine a better efficiency in thermal processes and, also, more innovative chemical treatments.

However, currently this way doesn't represent a good solution for the Italian market, where the construction of a wider recycling plant, rather than the hypothesized one, could not represent a real solution. In fact, for this type of plant the critical quantitative levels in input materials able to reach the saturation point could not be guaranteed. At the same time, even the hypothesis to treat materials coming from other EU countries it doesn't represent a real alternative. First of all, the PV panels transfer could have a great negative environmental impact. Secondly, Germany and Italy sees the 70% of the EU installed PV power. Hence, even by considering the construction of a recycling plant able to manage trans-national volumes, it should be impossible to saturate it.

The analysis conducted in this work is strictly based on cash flows and, hence, has a strong financial nature. One of the future research objectives is to proceed with the investments profitability evaluation by adopting an economic perspective based on accounting prices that allow to modify market distortions of prices and, also, permit to consider externalities able to generate social costs and benefits [59]. Furthermore, there is a need of some chemical analyses to evaluate the output materials purity level [46]. Another objective of future researches will be finalized to investigate the possibility to construct flexible plants where products characterized by compatible recycling processes will be treated together (e.g. NiCd batteries, CRT televisions, LCD monitors, etc.) allowing to define new recycling business models [31, 36] characterized, also, by an innovative product-service vision [60].

6. Conclusions

The results coming from this paper evidence that the construction of a PV modules recycling plant allow, from one side, to reduce CO_2eq emissions released into the atmosphere, but the investment presents strong economic losses. Again, by considering the future treatable volumes, their level will become interesting only from 2028 onwards. However it is unthinkable and unsustainable the non-adoption of some recycling strategies for this type of WEEEs.

In Germany, despite the PV installed power level is higher than the Italian one, experts are studying alternative scenarios where it is contemplated the hypothesis to treat PV modules coming from other countries than the only Germany. The scope is to reach the optimal level of input materials to treat able to saturate the PV modules recycling plants. By taking into consideration this hypothesis, it is of outmost importance to evidence the low sustainability level of this choice because of the level of pollution generated by transport flows. An interesting way to solve this trade-off is represented by the construction of multi-product recycling centres able to treat a wide mix of wastes (PV modules included) adequately supported by risk assessment methodologies able to manage a dynamic environment as the PV modules recycling sector.

This solution, in the brief/medium period, could support the treatment of a reduced number of PV modules reaching their end of life, responding to current market needs. At the same time this could permit to the experts to study optimal solutions to manage future needs where the volume of wastes to recycle will reach a critical level, especially if solar energy will continue to represent an important role in the Italian energy mix. A proper EoL PV modules management will offer a sustainable solution in terms of available resources, economic feasibility and environmental risks.

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TABLES

Table 1: Current PV modules recycling methods

Type of technology	Type of solar cell	Recycling process
Cyrstalline	c-Si p-Si	Pyrolysis at about 500ºC for the recovery of crystalline silicon wafers from the modules and chemical etching for the removal of metal coatings, anti-reflective coatings (ARC) and diffusion layers;
Thin film	a-Si	Currently no literature explaining the recycling process of amorphous silicon solar cells.
	CIGS	A smeltering process or acid baths to recover the metals, including selenium (Se), indium (In) and gallium (Ga); the glass is processed through thermal decomposition, solvent or acid dissolution to remove any remaining PV layers.
	CdTe	Chemical stripping of the metals and EVA and subsequent steps of electro-deposition, precipitation and evaporation to separate and recover the metals cadmium and tellurium; EVA is skimmed from the chemical solution for potential reuse and the glass and frame are recovered.

Table 2: Materials in current PV modules

	Materials composition												
	Al	Cd	Cu	Ga	In	Mo	Plastics	Se	Si	Sn	Te	Glass	Zn
x-Si (%)	17.5		1.0				12.8		2.9			65.8	
CdTe (%)		0.08	0.03				3.0			0.02	0.07	96.8	
CIGS (%)			0.01	0.01	0.01	0.12	3.0	0.01				96.9	0.04
	Recycling rates												
(%)	100	98	78	99	75	99	-	80	85	99	80	97	90
	Market prices												
(€/kg)	1.3	1.24	4.8	199	543	19	0.09	42	1.52	16.5	77	0.1	1.45
Al: Aluminum, Cd: Cadmium, Cu: Copper, Ga: Gallium, In: Indium, Mo: Molybdenum, Se: Selenium, Si: Silicon, Te: Tellurium, Zn: Zinc													

Table 3: Economic analysis of PV recycling

Type of cells	Plant size	Indexes	Reference
c-Si	185 t	Monthly Profit: -10,100 $/month	[46]
x-Si	1,876 t	Monthly Profit: -7,509 $/month	[46]
mixed	20,000 t	Monthly Profit: 624,755 $/month	[46]
CIGS	Not specified	Unitary Profit: 22.25 $/module	[45]
CdTe	Not specified	Unitary Profit: -0.24 $/module	[45]
c-Si	Not specified	Unitary Profit: -23.96 $/module	[45]
p-Si	Not specified	Unitary Profit: -23.99 $/module	[45]
Thin film	2,688 t	Monthly Profit: -151,000 $/month	[55]
Thin film	2,688 t	Monthly Profit: 107,000 $/month	[55]
Organic PV	Not specified	Target of Recycling Cost: 0.44 $/m^2	[61]
CZTSSe	Not specified	Recycling Cost: 77 $/t	[61]
Thin film	Not specified	Recycling Cost: 3-4 €/module	[36]

Table 4: Top 9 European PV panels recycling leaders

Country	Treated waste (t)	Installed power (MW)	Country	Treated waste (t)	Installed power (MW)
Germany	5,273	35,700	Belgium	242	2,865
Italy	1,449	17,900	the Netherlands	145	650
Spain	812	5,306	Slovenia	101	280
Poland	584	24	UK	68	3,100
France	376	4,300	EU	9,225	79,952

Table 5: Projections about the amount of waste PV modules to treat (data in kt)

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Scraps	3.49	14.18	5.22	2.16	1.50	1.50	1.50	1.50	1.50	1.50	1.50	0.75	0.75
EoL	0.00	0.00	0.64	0.27	0.15	0.13	0.02	0.05	0.07	0.06	0.04	0.08	0.15
Total	**3.49**	**14.18**	**5.86**	**2.43**	**1.65**	**1.63**	**1.52**	**1.55**	**1.57**	**1.56**	**1.54**	**0.83**	**0.90**
	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Scraps	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
EoL	0.30	0.35	0.51	0.94	5.27	25.36	54.23	174.45	709.05	261.00	108.00	75.00	75.00
Total	**1.05**	**1.10**	**1.26**	**1.69**	**6.02**	**26.11**	**54.98**	**175.20**	**709.80**	**261.75**	**108.75**	**75.75**	**75.75**

Table 6: Model input values

AC_l(€/module):	0.432	N_{debt} (y):	10
C_c^u (€/t):	150[i]; 205.5[ii]	R_{rm} (€/kg):	Table 1
C_{inv}^u(€/t):	564[i]; 285[ii]	r_d(%):	8
C_{ocm}(€/kg):	0.09	r_e(%):	5
C_p^u(€/t):	760[i]; 326[ii]	S (t):	i, ii
$f_{w,t}$(€/t):	7	t_f (%):	27.5
inf (%):	2	WACC(%):	5.8
m_m^m:	Table 1	ω_d (%):	100
m_{rm}^m(kg/module):	Table 1	ω_e(%):	0
m_w^m(kg/module):	0.43[i]; 0.469[ii]	y_{rm}:	Table 1
N (y):	10	i = 185t; ii = 1480t	

Table 7: Sensitivity analysis - 185 tons plant

	NPV (€) – S1		NPV (€) – S2	
Δ Change	-20%	20%	-20%	20%
Aluminum price	-825,890	-769,852	-796,425	-740,386
Glass price	-805,718	-790,024	-776,252	-760,559
Silicon price	-802,453	-793,289	-772,988	-763,823
Copper price	-802,468	-793,274	-773,002	-763,809
Avoided cost of landfill	-	-	-774,299	-762,513
Δ Change	20%	-20%	20%	-20%
Investment cost	-814,227	-781,515	-784,762	-752,049
Process cost	-953,383	-642,359	-923,917	-612,894
Collection cost	-828,564	-767,178	-799,099	-737,713

Table 8: Sensitivity analysis - 1,480 tons plant

	NPV (€) – S1		NPV (€) – S2	
Δ Change	-20%	20%	-20%	20%
Aluminum price	-3,242,643	-2,853,911	-3,006,920	-2,618,188
Glass price	-3,121,476	-2,975,079	-2,885,753	-2,739,355
Silicon price	-3,080,065	-3,016,490	-2,844,342	-2,780,767
Copper price	-3,080,283	-3,016,271	-2,844,560	-2,780,548
Cadmium price	-3,048,331	-3,048,223	-2,812,608	-2,812,500
Indium price	-3,053,562	-3,042,992	-2,817,839	-2,807,269
Molybdenum price	-3,048,876	-3,047,678	-2,813,153	-2,811,955
Selenium price	-3,048,714	-3,047,840	-2,812,991	-2,812,117
Tin price	-3,048,484	-3,048,070	-2,812,761	-2,812,347
Tellurium price	-3,051,017	-3,045,538	-2,815,293	-2,809,815
Zinc price	-3,048,334	-3,048,220	-2,812,611	-2,812,497
Gallium price	-3,050,834	-3,045,720	-2,815,111	-2,809,997
Avoided cost of landfill	-	-	-2,859,699	-2,765,409
Δ Change	20%	-20%	20%	-20%
Investment cost	-3,114,398	-2,982,156	-2,878,675	-2,746,433
Process cost	-3,581,928	-2,514,626	-3,346,205	-2,278,903
Collection cost	-3,384,674	-2,711,881	-3,148,950	-2,476,158

Table 9: Sensitivity analysis – Weighted Average Cost of Capital

	NPV (€) – S1		NPV (€) – S2	
%	185 t	1,480 t	185 t	1,480 t
3	-914,904	-3,494,279	-880,930	-3,222,481
4	-870,275	-3,324,209	-838,021	-3,066,179
5	-828,868	-3,166,409	-798,209	-2,921,140
6	-790,400	-3,019,804	-761,222	-2,786,381
7	-754,619	-2,883,430	-726,817	-2,661,016
8	-721,295	-2,756,417	-694,774	-2,544,246

Figure

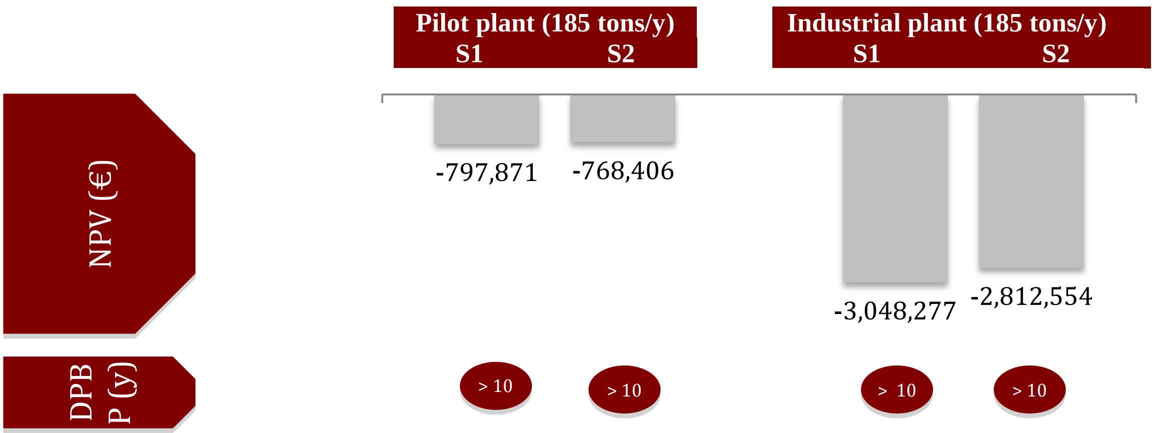

Figure 1: Profitability of a PV modules recovery center

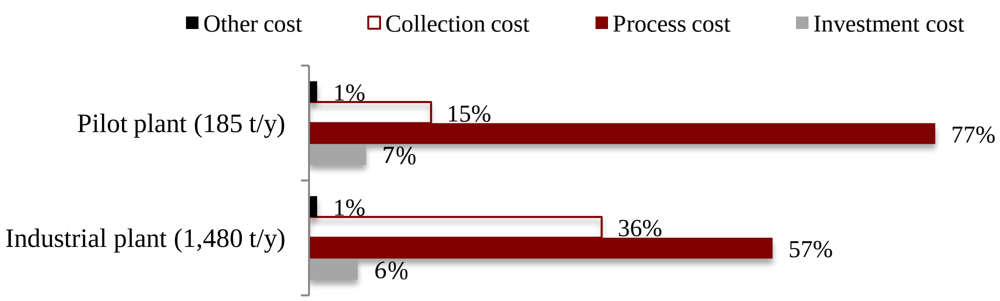

Figure 2: Cost distribution for each plant