Environmental and Climate Technologies
2024, vol. 28, no. 1, pp. 243–257
https://doi.org/10.2478/rtuect-2024-0020
https://content.sciendo.com

A Predictive Framework for Photovoltaic Waste Quantities and Recovery Values: Insights and Application to the Italian Context

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Received 01.04.2024; accepted 13.05.2024

***Abstract* – The global surge in photovoltaic (PV) panel deployment since the 2000s has contributed to advancing the renewable energy sector. However, this proliferation raises concerns about the increasing number of PV modules that will end their operational life in the coming years, necessitating effective planning for their decommissioning and recovery. This paper addresses this imminent challenge by presenting a predictive model to estimate the volume of decommissioned PV modules from existing installations. To consider the variability associated with the operational life duration of PV panels, two different scenarios were considered: early loss and regular loss, both modelled through the Weibull function. Furthermore, the article proposes a methodology for the economic valorization of materials recovered from decommissioned PV modules, according to the different technologies employed. This approach encourages sustainable practices by assigning an economic value to recovered materials and promoting a circular economy in the renewable energy sector. The economic valuation methodology adds practicality to dismantling, emphasising responsible waste management's potential economic benefits. To illustrate the applicability of the model, the study focuses on the Italian case, providing a detailed regional breakdown. The regional analysis not only improves the accuracy of the predictive model but also offers insights into localised PV module disposal patterns. By adapting the methodology to the individual Italian regions, the article serves as a concrete and valuable resource during the programming and planning phases, facilitating the implementation of a strategy to efficiently recover PV modules and minimising the environmental impact associated with decommissioning activities.**

***Keywords* – Circular economy; economic assessment; end of life; modules; recovery; sustainability.**

1. INTRODUCTION

Since the 2000s, there has been a significant global spread of photovoltaic (PV) energy as a source of electricity in various regions. This technology is adaptable, widely produced, and has affordable installation costs, making it highly popular among individuals and companies. Furthermore, solar energy is anticipated to emerge as one of the most prominent forms of renewable energy [1], [2]. The global installed capacity increased from 224 215 MW in 2015 to 1 055 030 MW in 2022, marking a growth of almost 350 % in a span of 7 years [3].

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As a result of these installations, there will be a substantial worldwide increase in the quantity of waste in the coming years. Furthermore, despite the ongoing attempts to create new technologies related to renewable energy sources, there is still a void in the literature concerning relevant solutions for the management of PV modules when they have reached the end of their life cycle [4], [5]. Many studies attempted to forecast the waste stream that will be generated by PV panels in the European and non-European countries [6], [7], [8], and more in general waste electrical and electronic equipment (WEEE) generation [9]. Several studies that have already addressed this issue will now be presented.

[4] shows an interesting application of the Weibull function to make the prediction of the waste load in Australia till the year 2059. The life cycle of PV cells was also taken into consideration. It was necessary to estimate the degree to which PV technology has penetrated the market. The authors also recommended the computation of the individual materials that comprise PV modules. Furthermore, by evaluating the rate of reuse of individual components, they forecasted savings from the recovery of these components for the creation of new modules. This was done from the perspective of a circular economy. Reference [10] shows a similar study for Italy; however, the author assumes a fixed period of 25 years as the span of the lifecycle, and the forecast is carried out up until the year 2050. In addition, different PV panel technologies are taken into consideration. Calculations were also made to determine the waste produced and then separated into the various components. Using the Weibull function and considering not only the photovoltaic module but also the Balance of System, which is the collection of all components that are necessary for the proper functioning of PV modules, other studies carried out a calculation that was comparable in Mexico and the United States [11], [12]. The authors of these studies took into consideration a life cycle that is thirty years long. Reference [1], when applying the Weibull function and taking into consideration an average life of thirty years, predicted the quantity of panels that will be available at the end of the life cycle by the year 2045 and compared them with the estimates by IRENA Report [3]. In reference [13] authors presented not only the waste prediction modelled by the Weibull function, but a defined usable life duration of 25 and 30 years in two different scenarios. Reference [6] not only shows a prediction for the quantity of PV panels that will reach the end of their useful life in India, but it also investigates the issues of reuse, recovery, and disposal, as well as the implementation of policies and strategies that encourage more sustainable waste management, topics widely covered in the renewable energy sector [14], [15].

The aim of this research, applied to the Italian case, is to provide a regional method that can address the developing difficulty connected to the management of waste resulting from the increasing use of PV panels. Since PV modules have a limited lifespan, it is expected that there will be a significant increase in the amount of generated waste. As a result, the primary purpose of this research is to develop a method that is both efficient and accurate in determining the quantity and nature of waste that will be generated, as well as the locations where this waste will be generated.

By developing the research for each Italian region, the study serves as a helpful instrument for businesses operating within the sector to evaluate and plan for the management of solar waste in a sustainable manner. Our strategy aims to minimize the environmental impact of PV waste production by estimating the recoverable amount, taking into account how recovery is environmentally desirable in the sector [16]. Additionally, it aims to promote the advancement of recycling and material treatment through research and development of innovative solutions. This will help to ensure that waste management is sustainable over the long term, with the goal of achieving a circular economy. To give data and practical tools that can be used to guide waste management decisions and policies in the solar energy industry, our developed approach is applied by taking into consideration PV panel installations in Italian regions and in different technologies from 2000 to 2022.

2. METHODS AND METHODOLOGY

There are many different PV modules technologies in use today, however we consider only four types of these, which represent almost the entirety of the Italian national market, and consist of monocrystalline silicon, polycrystalline silicon, amorphous silicon and thin film [17]–[31]. These technologies dominate the photovoltaic market in both Europe and the rest of the world [4], [32], [33]. There are many kinds of solar cells, but crystalline silicon cells make up more than 80 % of the number of solar cells that are now being manufactured all over the world [10]. Due to its ability to facilitate the fabrication of thin-film cells, cadmium telluride is the semiconductor material that is utilized the second most frequently [10]. Monocrystalline silicon and polycrystalline silicon are first generation panels while amorphous silicon and thin film are second generation panels.

First generation technologies rely on the utilization of two distinct forms of silicon. The first type is monocrystalline silicon, which is the purest form of silicon and is produced through a sophisticated manufacturing process [10]. Therefore, the monocrystalline PV panel is pricier than the polycrystalline one but also significantly more efficient, with an efficiency range of 13–19 % [34]. Within monocrystalline silicon, the structure consists of a uniform crystalline framework. The crystal lattice spans the entire sample without interruption, resulting in the absence of grain boundaries [10]. Polycrystalline silicon solar cells consist of several smaller crystals and can be identified by their visible grain. Currently, they are the most prevalent photovoltaic technology, making up 65 % of the Italian market [20]. This is due to their lower cost compared to monocrystalline panels, although having a lower efficiency ranging between 11–18 % [34].

For second-generation panels, we considered thin film and amorphous silicon. Thin film solar cells consist of one or more thin layers (1–10 μm) of semiconductor materials placed on a solid and inexpensive substrate, such as stainless steel, glass, or plastic [35]. Thin films significantly reduce the amount of semiconductor material needed per cell, resulting in lower prices compared to silicon cells, as mentioned above. Because of their flexibility, thin film solar cells can be used for multiple purposes, such as roof tiles and roofing, building facades, or skylight glass [10]. One particular type of thin film that we analyzed as a separate category following the GSE is amorphous silicon. Amorphous silicon, known as a-Si, is a silicon material that lacks a crystalline structure and instead has an amorphous arrangement. The arrangement of atomic positions is restricted to a limited distance [10]. This thin film uses less abundant resources and achieves a cell efficiency of about 4–8 % [34].

After identifying the four types of photovoltaic panels to provide all of the tools needed to comprehend the study, we proceed to describe the methodology (e.g., Fig. 1). The methodology is applied to the Italian case, but it has been designed to be applied in any geographical context, if the appropriate input data is available.

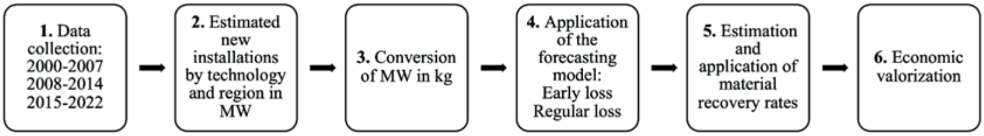

Fig. 1. Methodology to estimate photovoltaic waste.

For the application of the proposed methodology, Italy proves to be an excellent case study. This country has a particular territorial conformation, consequently the spread of photovoltaic panels on the territory, as presented below, diverges widely between different regions. Furthermore, Italy at European level is one of the countries with the largest number of photovoltaic installations. The total installed capacity in Italy has significantly expanded since 2008 and continues to grow rapidly (e.g., Fig. 2). In particular, the installed capacity increased by 20.6 % during the year 2022, rising from 22 594 MW to 25 094 MW [17]–[31].

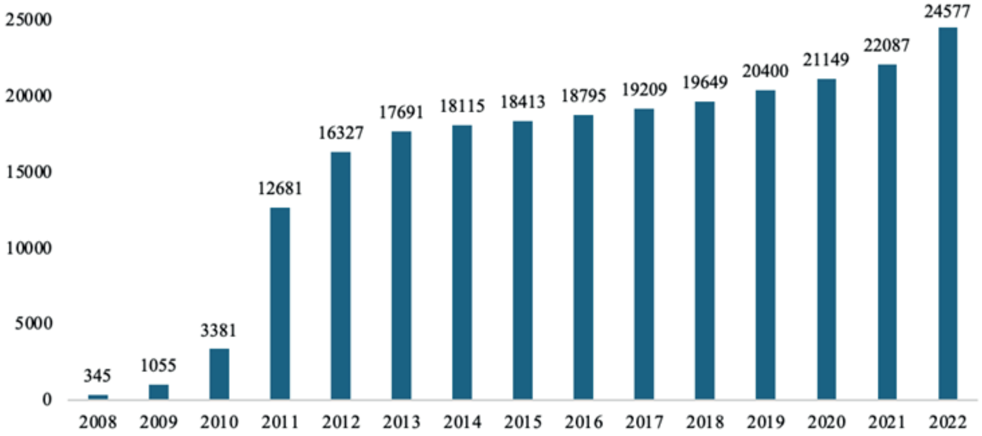

Fig. 2. Cumulative PV power installed in Italy (MW).

2.1. Data collection

The first critical data to be obtained to proceed with the analysis are the total new installations for each year for each technology in each Italian region from 2000 to 2022 (measured in terms of installed power - MW), the process for obtaining the data is specified in section 2.2. The source data (i.e., the new installations for each year broken down by technology and for each region) were obtained from the GSE (Gestore dei Servizi Energetici) reports and from a personal reworking of the data by the Terna database. In the subsequent section, we present an approach that can be implemented even in situations where the required data is partially unavailable, based on different assumptions.

2.2. Estimated new installations by technology and region in MW

Due to lack of obtainable data, we made assumptions depending on the period considered. From 2000 to 2007 new installations of PV modules by region and technology are not available, the only available data for this period are the total installations in Italy at the conclusion of period t.

It was therefore necessary to consider the breakdowns of PV modules as zero over this short period. We took this assumption due to the limited number of PV modules in Italy till 2007.

We have therefore considered new installations for each region as shown in Eq. (1):

$$\text{New installations } (t, i) = \text{Total installations } (t, i) - \text{Total installations } (t-1, i), \tag{1}$$

where:
New installation (t, i) represents the total new installations during year t in region i;
Total installation (t, i) represents the total installations in year t in region i;
Total installation ($t-1$, i) represents the total installation in year $t-1$ in region i.

In addition, the percentage distribution of different PV module technologies within Italian regions was considered constant.

From 2008 to 2014 data on new installations in Italy are available for each year, however, the breakdown into the different technologies used in each region is not provided. To obtain the data on new installations per region and technology, the percentages of installations per technology in the different regions were considered constant, taking 2015 as the reference year.

From 2015 to 2022 data on new installations are available for each region and for different technologies. New installed capacity by Italian region for different years are reported in Annex 2.

2.3. Conversion of MW in tons

The conversion from MW to tons was developed according to the methodologies proposed in literature [4], [10]–[12], using values as in Table 1. In particular, the kg/Wp ratio was taken from the literature for thin film and amorphous silicon technologies, calculated as an average between different studies [10], [11].

In contrast, for the first-generation technologies that occupy almost the entirety of the Italian photovoltaic market, we decided to investigate the data sheets directly from the largest manufacturers on the Italian panorama according to the National Survey Report of PV Power Application in Italy [36] (Table 2).

TABLE 1. CONVERSION COEFFICIENTS FROM MW TO KG

	Mono-crystalline, kg/Wp	Poly-crystalline, kg/Wp	Thin-film, kg/Wp	Amorphous- silicon, kg/Wp
Values	0.06996	0.07459	0.1933	0.21568
Source	Table 2	Table 2	Paiano and Dominguez	Paiano and Dominguez

We selected several models on the market and then calculated the average kg/Wp ratio, so that we obtain values that were closer to reality. This phase of the study was developed precisely for the Italian case, selecting the largest producers in Italy, however it is a methodology easily applicable to any geographical context.

TABLE 2. SOURCES AND CONVERSION COEFFICIENTS FROM MW TO KG FOR MONO-CRYSTALLINE AND POLY-CRYSTALLINE PANELS

Technology	**Producer**	**Model**	**Kg**	**Wp**	**kg/Wp**
Mono-crystalline	Eclipse Italia	156M60	19.5	300	0.06500
Mono-crystalline	Eclipse Italia	156M72	24	350	0.06857
Poly-crystalline	Eclipse Italia	156P60	19	270	0.07037
Poly-crystalline	Eclipse Italia	156P72	24	320	0.07500
Mono-crystalline	Exe s.r.l.	A-HCM415/108	21	312	0.06731
Mono-crystalline	Exe s.r.l.	A-HCM470/120-TC/M10	24.5	353	0.06941
Mono-crystalline	Exe s.r.l.	A-HCM670/132-TC/M12	33.9	508	0.06673
Mono-crystalline	Exe s.r.l.	A-HCM430/108-TC/M10-DG	24	323	0.07430
Mono-crystalline	Futura Sun	FU 410 M	20.8	308	0.06753
Mono-crystalline	Futura Sun	FU 420 M	26	316	0.08228
Mono-crystalline	Futura Sun	FU 420 MV	25.4	316	0.08038
Poly-crystalline	Futura Sun	FU 280 M	17.7	205	0.08634
Poly-crystalline	Gruppo STG	VE160PV	18	270	0.06667
Mono-crystalline	Gruppo STG	VE360PV	18	310	0.05806

2.4. Application of the forecasting model

The predictive modelling applied in this study considers two different forecasting schemes: Early-loss and Regular-loss, both modelled using Weibull function, as shown in Eq. (2):

$$\mathrm{F}(t) = 1 - e^{-\left(\frac{t}{T}\right)^{\alpha}}, \tag{2}$$

where

F(t) represents Weibull function;

t represents panel life in years;

T represents the average lifetime of photovoltaic panels;

α represents the shape factor and it is responsible for the typical shape of Weibull curve.

An α value of 2.4928 was considered for the Early-loss scenario, and a value of 5.3759 for the Regular-loss scenario [4], [6], [33]. A 99.99 % probability of module loss after 40 years of use is assumed for both scenarios [33]. Furthermore, for the Early-loss scenario, a probability of loss in the first year of 0.5 % is assumed due to damage during transport and installation, and an additional probability of failure in the first two years of life of 0.5 % [33]. Probability of loss based on Weibull function for each scenario are reported (e.g., Fig. 3). A literature analysis was also conducted to find out the value to use as the average life of photovoltaic modules (Table 3). As a result, a value of 25 years was selected.

The Weibull function was then used repeatedly for each year, each region and each technology considered. In this way, it was possible to work out by when new PV module installations would come to the end of their life cycle.

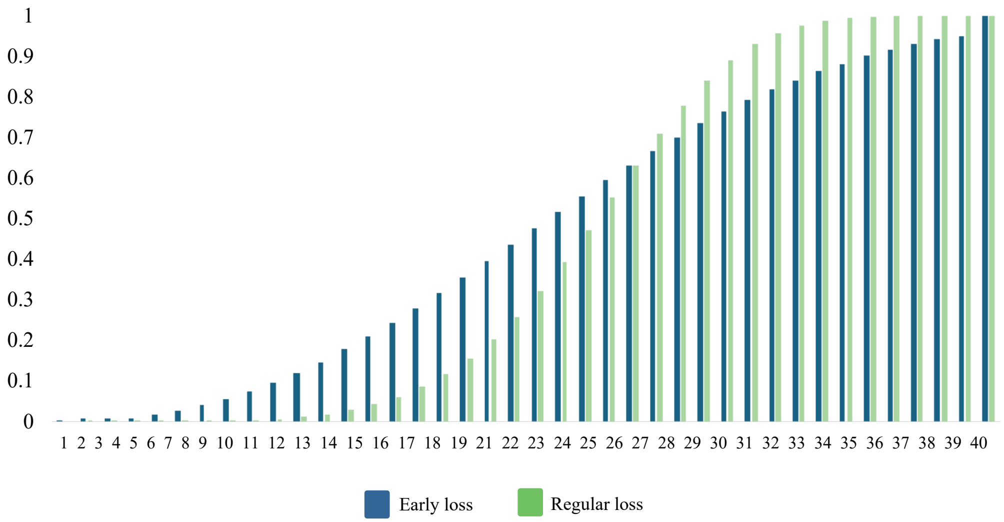

Fig. 3. Probability of loss based on Weibull function.

TABLE 3. VALUES OF AVERAGE LIFETIME FROM LITERATURE

Region and Source	**Global [33]**	**Mexico [11]**	**Australia [4]**	**Italy [10]**	**Europe [37]**	**India [6]**
Average lifetime (years)	30	30	30	25	25	25

2.5. Estimation and application of material recovery rates

The percentage quantities of materials contained within the PV modules are presented in Table 4 [10]. The composition of mono-crystalline and poly-crystalline silicon modules is almost identical, as the only variable between the two technologies lies in the crystallization phase of the material. For this reason, they have been considered equal, namely c-Si [10]. A further study of the literature was conducted to define the percentage recovery rates of each recoverable component (Table 5).

TABLE 4. COMPOSITION OF PV TECHNOLOGIES [10]

Material	**Symbol**	**c-Si**	**a-Si**	**Thin film**
Glass		74.16	86	95
Aluminium	Al	10.3	0.035	0.035
Polymers (e.g., EVA)		6.55		3.5
Backing film (Tedlar)		3.6		
Adhesive (e.g., silicone)	Si	1.16	0.02	
Methylene diphenyl diisocyanate			12	
Copper	Cu	0.57	0.9	1
Silver	Ag	0.004-0.006		
Tin	Sn	0.12	0.043	
Zinc	Zn	0.12		0.01
Silicon	Si	3.35	0.0064	

Lead	Pb	0.06		
Cadmium	Cd			0.07
Tellurium	Te			0.07
Indium	In		0.5	
Selenium	Se			
Gallium	Ga			
Germanium	Ge		0.5	

TABLE 5. MATERIALS RECOVERY RATE

Material	**Recovery rate**	**Source**
Glass	95 %	[10]
Aluminium	99.7–100 %	[10]. [38]
Adhesive (e.g., silicone)	86 %	[10]
Copper	100 %	[39]
Silver	95–98 %	[39], [40]
Tin	32 %	[41]
Zinc	27 %	[4]
Silicon	99.90–99.50 %	[40], [42]
Lead	96 %	[41]
Cadmium	95 %	[43]
Tellurium	95 %	[10]
Indium	90 %	[44]
Germanium	40 %	[10]

2.6. Economic valorization

The last phase of the methodology presented in this study involves the economic valorization of recoverable materials from waste PV modules, as already proposed by in Mexico and United States [11], [12]. However, this remains a delicate phase due to the variability of commodity prices. particularly in the current historical period. The economic valorization considers the unit price of individual materials [11], [12] and the quantities of materials that can be recovered from the waste stream generated. See Annex 1 for more details.

3. RESULTS

3.1. Conversion of MW in tons

Using the described methodology. we calculated the amount of kg for each type of module in each of the Italian regions. Given the impossibility of presenting results over time for each region. we chose to show the case of the Lombardy region as an example (more details in Annex 2). It can be seen that over the years, the kg of panels giving rise to waste will increase until 2045 to 177 097 tons in the case of Early-loss, while in the case of Regular-loss it will reach 222 232 tons (e.g., Fig. 4, Fig. 5). The worst-case scenario that will see the presence of more waste will be the Regular-loss one.

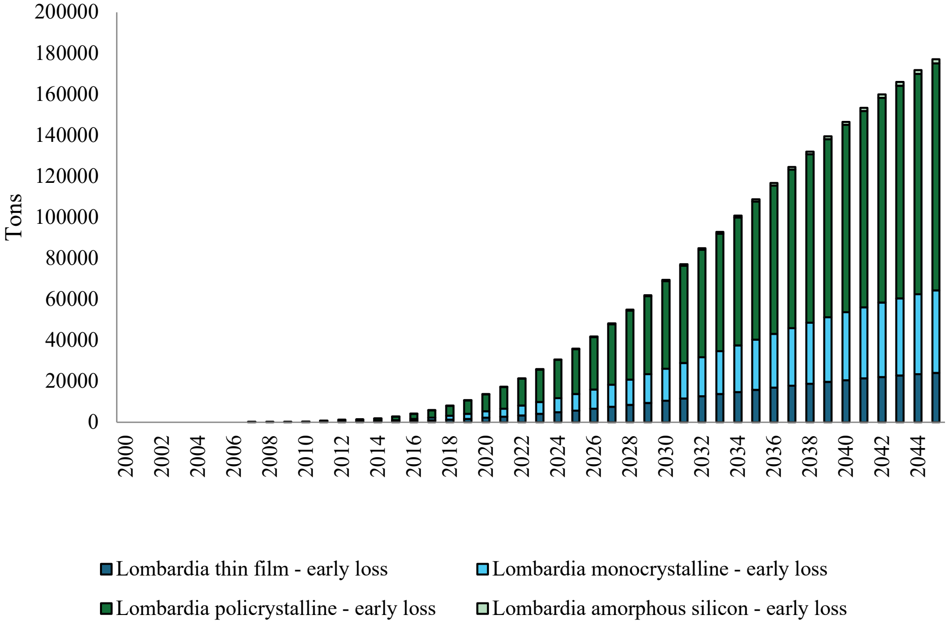

Fig. 4. Tons of PV in Lombardia – Early loss scenario.

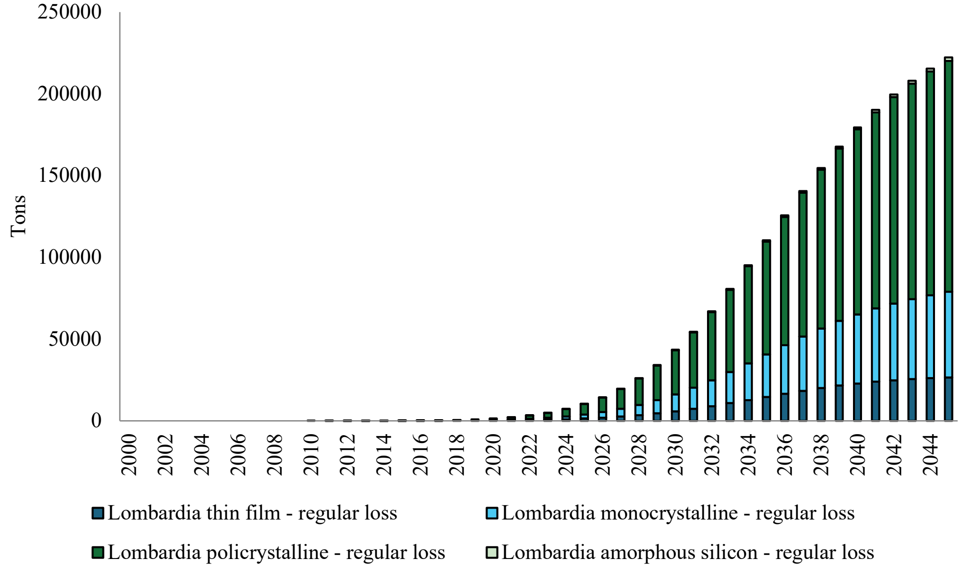

Fig. 5. Tons of PV in Lombardia - Regular loss scenario

3.2. *Amount of waste produced*

We report the results for the year 2045, which is one of the most representative years according to the data collected (more details in Annex 3). Using the proposed methodology, the amount of materials that will need to be disposed or recovered broken down by the categories of materials that make up a photovoltaic panel was calculated for each region. The Early loss and the Regular loss scenario are presented (e.g., Fig. 6). In both scenarios, the most critical regions are Puglia, Lombardia, Emilia Romagna and Veneto. In these regions it is important to start setting up a system for the disposal and recovery of panel materials. The total waste generated in these regions amounts to 239 052 tons, 177 015 tons, 147 382 tons and 150 582 tons in the Early loss case and 302 041 tons, 222 141 tons, 189 022 tons and 186 019 in the Regular loss case. respectively.

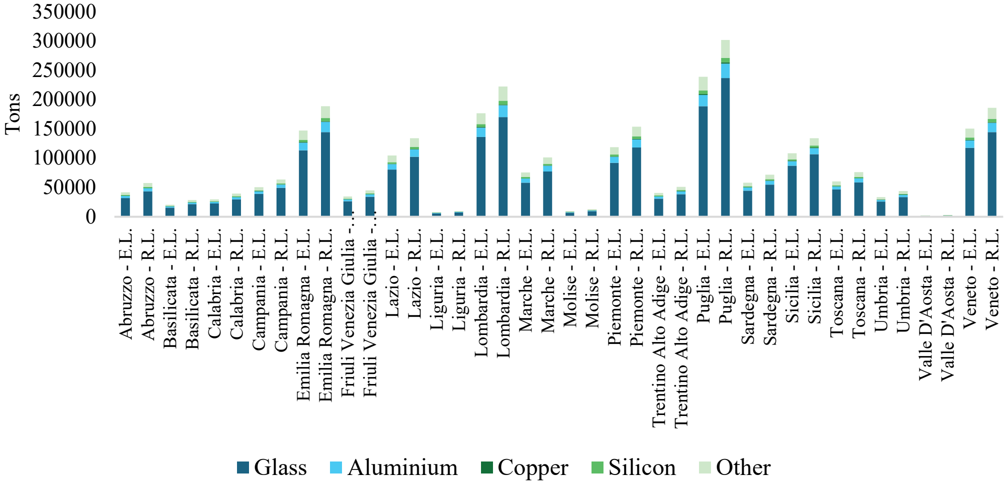

Fig. 6. Tons of PV waste in 2045 by regions - Early Loss (EL) and Regular Loss (RL) scenario.

3.3. *Amount of waste recovered*

Considering material recovery rates, it was estimated for each region how many of the materials that make up the PV panels can be recovered in the early loss case and the regular loss case (e.g., Fig. 7). Once again, data from 2045 were presented. The most critical material as far as recovery is concerned is glass, followed by aluminium, which is present in large quantities in first generation photovoltaic panels (about 10 %).

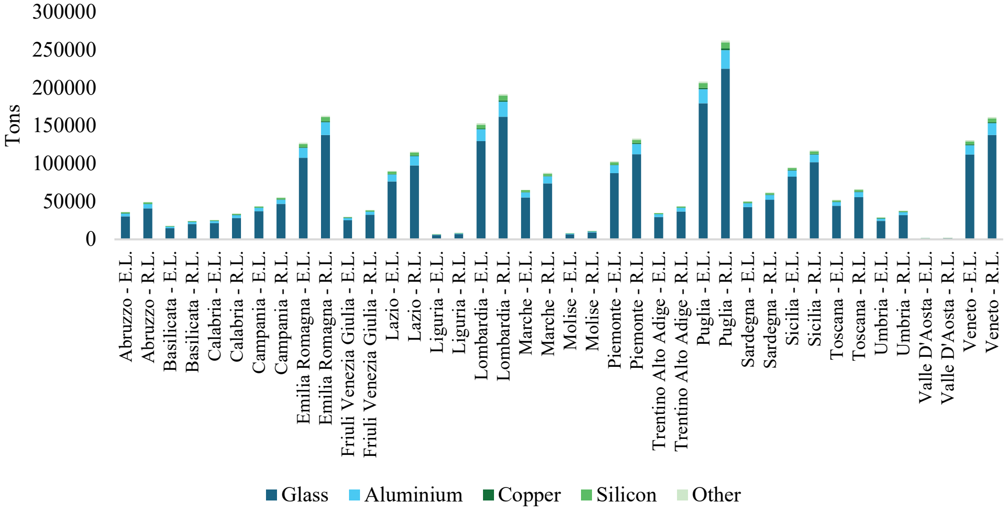

Fig. 7. Tons of PV waste recovered in 2045 by regions - Early loss (EL) and Regular loss (RL) scenario.

3.4. Earnings from recovered materials

Recycling of PV waste is crucial. not only to avoid environmental pollution but to conserve mineral resources and to have economical return from the process. Materials recovered from PV panels may represent a business for companies that decide to invest in this sector. As of 2045. revenues are estimated to be around 1 547 741 k€ in the Early loss case and 1 783 796 k€ in the Regular loss case. Also, in this case. the regions that could have a higher economic valuation are Puglia, Lombardy, Emilia Romagna and Veneto. Details of the individual materials for each region (e.g., Fig. 8).

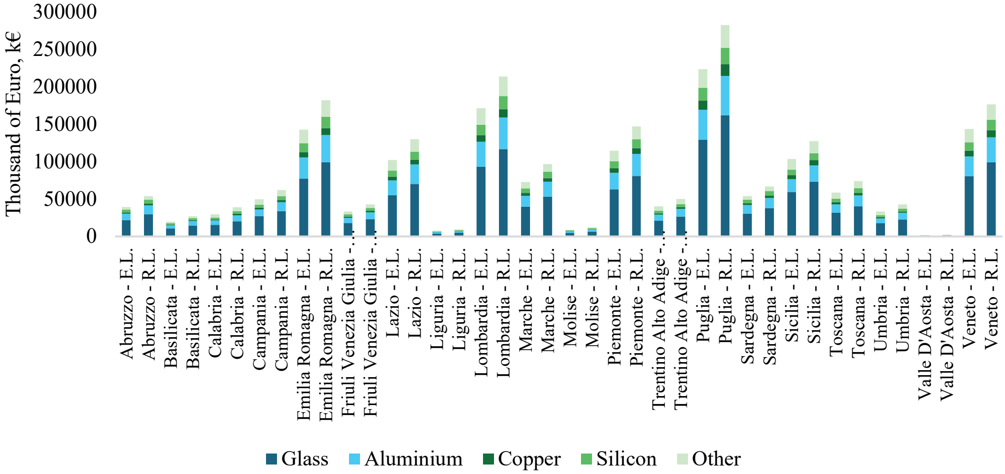

Fig. 8. Earning from recovered materials in 2045 by regions - Early loss (EL) and Regular loss (RL) scenario.

4. CONCLUSION

This study underlined the critical relevance of sustainable waste management from end-of-life PV panels in a period of widespread deployment of renewable technology. We used a predictive methodology to provide a detailed estimate of the quantity of PV waste that will be created in Italy in the next years. as well as highlight the associated obstacles and opportunities.

Our research provides an in-depth and specific insight. enabling targeted and effective planning for the recovery and recycling of PV modules at regional level. We demonstrated how the economic valorization of recovered materials can offer attractive opportunities from an entrepreneurial point of view.

The management implications of the circular economy in the PV panel industry necessitate a strategic and coordinated approach at the governmental level. Implementing circular economy techniques in the renewable energy sector is not only desirable but also necessary.

The suggested methodology, which includes a detailed economic assessment, is an essential tool for stakeholders interested in PV waste management. This paper stresses the importance of innovative, sustainability-oriented policies and techniques for optimising the recovery of valuable resources while lowering environmental damage.

Addressing the solar waste problem in Italy and elsewhere necessitates a collaborative effort by module manufacturers, policymakers, academics, and individuals. Only through a comprehensive and collaborative strategy can we hope to achieve a truly sustainable energy future in which every end represents a new beginning.

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ANNEX 1

The prices of the materials considered for the analysis are summarised in Table A1.

TABLE A1. PRICE OF MATERIALS

Material	€/kg
Glass	0.72
Aluminium	2.14
Copper	7.73
Silver	638.53
Tin	22.98
Zinc	2.39
Silicon	2.75
Lead	1.86
Cadmium	1.01
Tellurium	81.65
Indium	422.02
Germanium	1228.5

ANNEX 2

New installed capacity by Italian region for different years are reported in Fig. A1.

Fig. A1: New installed capacity by regions (MW).

ANNEX 3

In sections 3.1. 3.2. 3.3 and 3.4 we have limited the presentation of results to the year 2045 only. This choice is motivated by the fact that 2045 is one of the years with the highest waste generation from PV panels installed in the period 2000–2022. Importantly, all analyses conducted are also available for the years not included in the presentation. The increase in waste, and consequently material and profits from this process, shows an increasing trend over time. Looking at the data from 2045, it is possible to fully understand the extent of this expanding market and its criticality in terms of material recovery. It should be considered that the materials used in the production of photovoltaic panels are of a critical nature. Therefore, with a view to the circular economy and sustainable management of the Earth's resources, it is essential to take a proactive approach to ensure that these materials do not one day become scarce on Earth.