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RESEARCH ACTIVITY ON PV WASTE RECYCLING IN ENEA

Maria Lucia Protopapa [1,*], Giuliana Ansanelli [2], Massimiliana Pietrantonio [3] and Marco Tammaro [2]

[1] *ENEA, Brindisi Research Center, S.S. 7 Appia km 706, 72100 Brindisi, Italy*
[2] *ENEA, Portici Research Center, p.le E. Fermi, 1, 80055 Portici (NA), Italy*
[3] *ENEA, Casaccia Research Center, via Anguillarese, 301, 00123 Roma, Italy*

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ABSTRACT

ENEA is dedicating significant efforts to the research activity concerning the treatment of End-of-Life (EoL) photovoltaic panels (PVs), which is a worldwide emergent issue to be urgently solved. With PVs typically having a lifespan of 25 years, the volume of PV waste is projected to increase rapidly by 2030. This issue is compounded by the composition of photovoltaics, which includes hazardous materials, necessitating the development of technological solutions to mitigate the environmental impact of commonly used recycling methods. Additionally, strategic materials present in PVs make the valorization of recovered materials highly advantageous. ENEA is actively involved in several research projects focused on EoL PVs recycling. This article will outline the main objectives of these projects and present the key findings achieved by ENEA's research team.

1. INTRODUCTION

The installed photovoltaic (PV) power worldwide has experienced exponential growth since 1990, reaching 1047 GW by the end of 2022 (Irena, 2023). Under IRENA's 1.5°C Scenario, this growth would continue, exceeding 5400 GW by 2030 and 18200 GW by 2050 (Irena, 2023). Considering the typical lifespan of a photovoltaic panel, which ranges from 25 to 30 years, it is estimated that approximately 60 to 78 million tons of panels will require disposal globally by 2050 (Irena and IEA-PVPS, 2016).

The performance of PV modules can degrade due to various factors, including UV irradiation, high temperatures, humidity (Oreski, 2005), mechanical shock, local pollutants, and toxic fumes. Aging effects can lead to electrical shock, moisture and pollutant ingress, and overall failures of PV modules. It's worth noting that the improper disposal of EoL PVs not only results in the loss of resources such as silicon, aluminum, and glass but also poses significant environmental risks due to the leaching of metals like Al, Cu, Ni, and Pb from crystalline silicon (c-Si) or amorphous silicon (a-Si) module pieces, depending on pH conditions.

Dismissed PVs constitute a resource of useful and precious materials (silicon, silver, copper, aluminum). Some of them, such as silicon, are classified by the European Union as strategic materials, i.e. materials that can be used for strategic areas such as renewable energy, digital, aerospace and defense technologies, but they are at risk of potential future supply shortages; that is, global imbalances between supply and demand are expected for these materials. Additionally, strategic raw materials possess unique properties that make them challenging to substitute in various technologies. For instance, silicon is utilized in approximately 95% of PVs currently available on the market for converting solar energy into electrical energy (Fraunhofer, 2023). China stands as the primary global supplier of silicon, accounting for 76% of the worldwide production (CRM, 2023). Silicon holds critical importance not only in the photovoltaic and electronics industries but also in metallurgy and numerous other supply chains (SCREEN, 2023; Carrara, 2023). Despite silicon being the second most abundant element in the Earth's crust after oxygen (RSC, Daviddarling), it primarily exists in nature as silica (SiO_2). Its production from silicon oxide entails high environmental impact due to its energy-intensive nature. Therefore, the ability to recover silicon from EoL PVs becomes immensely beneficial for reintegrating it into various supply chains. Nonetheless, it's imperative for recovery technologies to have minimal environmental impact to ensure a sustainable approach to supplying this valuable material.

Directive 2012/19/EU (2012), transposed into Italian law by Legislative Decree 49/2014 and subsequent amendments, introduced EoL PVs into the category of waste electrical and electronic equipment (WEEE) for the first time. It mandates the recovery of materials composing these modules up to 80% by weight. This recovery target can be met for c-Si PVs by recovering glass and aluminum frames ex-

* Corresponding author:
Maria Lucia Protopapa
email: lucia.protopapa@enea.it

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clusively. In fact, silicon PVs are typically formed by the silicon cell embedded between the upper glass (on the front side) and a polymeric multilayer foil called backsheet (on the backside). Both the glass and the backsheet perform the function of protecting the cell from environmental factors such as rain, wind, hail and dust. They are glued to the cell by mean of the encapsulant material which is generally Ethylene Vinyl Acetate (EVA). The cell is then "encapsulated" between the two layers of EVA, which form a protective and insulating sheet around it and acts as a binder between the cell itself and the upper (glass) and lower (polymeric) layers of the PV panel. The whole stack is embedded in the aluminum frame. Therefore, a photovoltaic module is typically made of glass for approximately 70% of its weight, aluminum for 15%, silicon for 3% and other metals (<1%), including silver and copper, used to make electrical contacts and in pastes soldering.

One of the most adopted EoL PVs pre-treatment process, before recycling, consists in the hammer milling of PV panels, once the aluminum frame and the cables/junction box have been removed. The outputs of this first step consist of three different materials: a fraction of vitreous fragments, EVA agglomerates, and splinters containing the active material (silicon) embedded within polymeric layers, besides silicon powder, aluminum, and copper bits. This fraction contains precious resources of potentially recyclable materials such as polyethylene terephthalate (PET), silicon, and metals. Therefore, it would be desirable to develop recycling processes useful to recover them.

The recycling methods currently adopted can be divided into two categories: thermal and mechanical. In both cases they can be followed by chemical (etching) and/or mechanical treatments for the possible recovery of other materials (silicon, copper, silver, etc.). For the recovery of metals and silicon with high purity, a subsequent hydrometallurgical treatment is required.

In conventional heat treatments, heating is carried out between 500 and 600°C, usually inside furnaces with a controlled atmosphere, for complete removal of the layers of EVA and the backsheet. It is worth mentioning that there are different types of backsheet on the market, some of which are based on fluorinated polymers which, due to their particularly toxic fluorine content, impose constraints on the methods of treatment. The plants that should burn the fluorinated backsheets, to obtain the silicon cells as residue, must be equipped with systems for controlling and reducing fluorine in the fumes. In detail, by burning fluorinated backsheets, hydrogen fluoride is produced (Ardente, 2019, Danz et al. 2019, Fraunhofer, 2017), which can be subsequently removed from the gas phase via wet or dry systems where alkaline reagents are added to retain the halogens in solid form (e.g., CaF_2) (Aryan et al., 2018, Biganzoli et al., 2015, Vehlow, 2015). As an alternative to thermal treatment, PV panels could be delaminated to separate the silicon cell from the backsheet; then, recyclable PET could be recovered from the backsheet, while the silicon cell could be thermally treated to recover silicon powder by eliminating the encapsulant polymeric material.

Mechanical processes involve crushing, initially in a coarse manner and then finely, with the aim of reducing the contact surface between the glass, EVA, and backsheet layers. This reduction facilitates detachment, which is followed by subsequent chemical and/or physical treatments such as sieving and gravimetric separation. The crushing processes demand significant energy expenditure, particularly as they yield satisfactory results (with a recovery rate of approximately 95%) only after undergoing at least two grinding stages—first coarse and then fine—to achieve the finest possible mesh size. However, these processes also come with a drawback: the hammers and knives utilized for crushing experience high levels of wear due to the inherent hardness of the glass and silicon composing the panels. Silicon dioxide (SiO_2), for instance, ranks at level 7 on the Mohs Scale, where diamond, the hardest material, is classified at level 10.

ENEA's research activities, concerning EoL PVs treatment and processing, are primarily aimed at providing technical solutions to reduce the environmental impact of commonly used recycling methods. Additionally, ENEA's focus extends to the valorization of materials recovered from EoL PVs, particularly silicon extracted from PV cells, which can be utilized as anode material in lithium-ion batteries. The main ongoing research projects involving ENEA, concerning EoL PVs recycle, will be herby described and the key results obtained will be presented.

2. RECENT RESEARCH PROJECTS INVOLVING ENEA

2.1 Mission Innovation IEMAP

Italy is a member country of Mission Innovation (MI), a global multilateral cooperation initiative born in Paris in 2015 whose primary aim is to accelerate the innovation processes of clean technologies, both in the public and private sectors, through the commitment of the participating countries to double the public share of investments dedicated to research, development and innovation of decarbonisation technologies in order to make clean energy accessible to consumers and create green jobs and commercial opportunities. Within Mission Innovation, the IEMAP (Italian Energy Materials Acceleration Platform) project, financed by MASE for the years 2022-2024, intends to create an experimental and computational infrastructure for the accelerated design and selection of advanced materials for energy. As part of the MI IEMAP Project, ENEA is implementing new methodologies with low environmental impact for the treatment of EoL PVs and hydrometallurgical processes for the recovery of valuable materials (WP4, LA 4.4, 4.5 and 4.6). Moreover, a mechanical process for the recovery of silicon powder and the reuse of the recovered silicon in lithium-ion batteries has been optimized (WP2, LA 2.5, 2.7 and 2.9).

2.1.1 The thermomechanical delamination of the PV panel

The methodology developed by ENEA, that is proposed as an alternative to thermal and mechanical processes, is based on the ENEA-BetaTech patent N.102017000033488 (Italian Patent and Trademark Office, UIBM). The process consists of a method for recovering the main components (glass, EVA, backsheet, cells, electrical contacts) of the c-Si

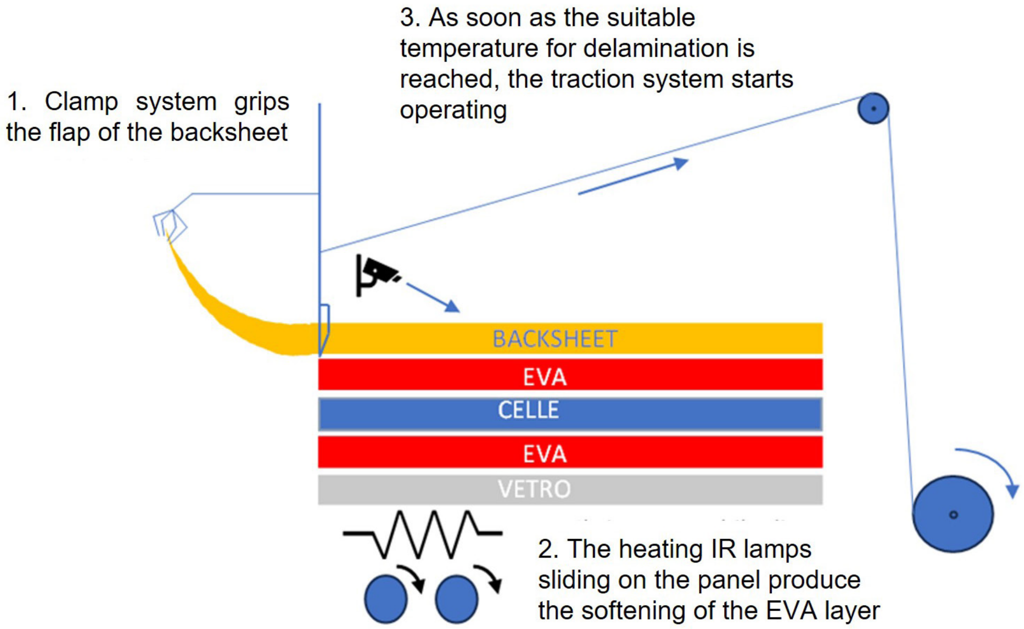

FIGURE 1: Principles of operation of the PROTEO Prototypal System at the ENEA Casaccia Research Center, Rome.

PVs through a heat treatment inducing the partial thermal degradation of the EVA layer, allowing separation of the different components. Thanks to the avoided degradation of the entire EVA and backsheet layers, as in other methods based on thermal treatments, gaseous emissions into the atmosphere are much lower. Compared to the other methods currently used, it has the advantage of being cheaper, as it is less energy-consuming, it has a low environmental impact and finally it allows recovering backsheet and EVA.

Within MI-IEMAP the Technology Readiness Level (TRL) of the process has increased to 4-5 since a prototypal plant, based on the patented technology, has been realized (Figure 1). Therefore, the process parameters (heat source, exposure time, distance between the heat source and the surface of the panel) have been tested on two types of panels on the market. To this aim it has been necessary to recognize the structure and chemical composition of the panels. It is worth mentioning that EoL PVs do not present any label indicating their structural composition. Therefore, the EoL panels have been characterized before the treatment through several characterization techniques (FTIR, Raman, XRD and XRF spectroscopy).

2.1.2 The recovery of metals through hydrometallurgical processes

Metals are found in various components of the PVs, including the aluminum frame, screws, pins, junction box, cells, and copper ribbons. For the aluminum frame, screws, pins, and junction box, once these materials are selectively separated, they can be sent for recycling through established recovery chains. However, for the cells and ribbons, the metals within the PV panel must be extracted and purified. To ensure the representativeness of the sample and the scalability of the process across the entire category, two distinct types of PVs were selected, differing significantly in size, weight, production year, and technological characteristics. The first panel (PV type A) belongs to an older generation, with a production history of over 30 years, while the second panel (PV type B) is from a newer generation, manufactured in 2016. Table 1 presents the percent-

TABLE 1: Percentage composition of the examined panels.

	PV type A	PV type A	PV type B	PV type B
	(g)	(% p/p)	(g)	(% p/p)
Aluminum frame	1400	31	3500	17,5
Glass	1730	38,4	12250	61,3
Backsheet	80	1,8	640	3,2
PV cells	290	6,4	800	4
Ribbons	45	0,01	80	0,4
Screws and pins	10	<0,01	10	<0,01
Junction box	230	5,1	400	2
Silicone	15	<0,01	40	0,01
EVA	700 calculated by difference	16	2280 calculated by difference	11,3

age composition of these two panels. Notably, the composition of the two PV types varies significantly for each component fraction. When comparing the older generation device (PV type A) to the more recent one (PV type B), the weight percentage of the fraction containing materials of higher economic value (PV cells) decreases, while the percentage of glass increases. The glass fraction, once separated, can be recycled, whereas the fractions containing metals and plastics require treatment for valorization.

Chemical characterization of the cells and ribbons conducted using the Agilent MP-AES 4100 spectrometer (Table 2) has revealed that silver (Ag) is the most abundant and valuable material within the cells, reaching up to 8% by weight, while copper (Cu) accounts for approximately 80% of the ribbons, with tin (Sn) comprising 28%.

The separation of these elements has involved the following steps:

- Leaching;
- Fractional precipitation;
- Separation and purification of products.

In Figure 2, the diagrams depicting the processes for recovering Ag from PV cells (a) and Cu from ribbons (b) through hydrometallurgical methods are presented.

Subsequently, the recovered materials have been characterized using various analytical techniques. Cu and Ag have been obtained as products with defined chemical specifications and purity levels. Specifically, the two products obtained are:

1. CuC_2O_4 (Copper Oxalate): Purity grade: >96%. Usage: This high-purity copper compound finds applications in various fields. It is primarily utilized in laboratory settings for analytical and synthetic purposes. CuC_2O_4 serves as a reagent in qualitative and quantitative analysis, particularly in identifying the presence of certain ions in solution, such as calcium, barium, and strontium, by forming insoluble precipitates. Additionally, it acts as a precursor for synthesizing other copper compounds. For instance, it can be decomposed to yield copper oxide (CuO) or reduced to produce metallic copper. These compounds have several applications including catalysts, pigments, and electrical conductors.
2. AgBr (Silver Bromide): Purity grade: >96%. Usage: Silver bromide is a photosensitive material primarily employed in traditional photography and certain specialized printing techniques. Its light-sensitive nature makes it suitable for creating photographic images on photosensitive films and papers. While its use has declined with the rise of digital photography, it still holds significance in specific segments of analog photography and specialized printing processes.

Data concerning the characterization of primary materials present in EoL PVs, as well as information regarding the extracted secondary materials, have been submitted to the IEMAP platform. This facilitates the creation of a database containing the chemical and microstructural properties of the secondary extracted raw materials related to the initial PV type and treatment parameters.

2.1.3 The reuse of silicon for lithium-ion batteries

Within MI-IEMAP, ENEA is also working on the reuse of silicon-based powder recovered from EoL PVs as anode material for lithium-ion batteries (LIBs). The recovered silicon will replace graphite, currently used to make the anode of commercial LIBs. It is worth mentioning that natural graphite is a strategic material imported for the 40% from China (CRM, 2023). The objective of the research activity is to obtain high-capacity anodes for LIBs with higher energy densities than commercial ones. Silicon offers a theoretical specific capacity of 4200 mAh g^{-1} (Huggins, 1999), considerably higher than the theoretical specific capacity of graphite (372 mAh g^{-1}). The limiting factor of silicon, used as anodic material, is related to its volumetric expansion which can reach values up to 300% during battery charge-discharge cycles (Rahman et al, 2021). Such a high volumetric variation involves progressive fragmentation and loss of active material (which is electrically isolated from the rest of the electrode) with the progress of charge-discharge cycles, resulting in a rapid decrease of the accumulated capacity.

TABLE 2: Chemical characterization of ribbons and cells for the two analyzed PVs (Type A and B).

Element	% (w/w) Ribbons in PV type A	% (w/w) Ribbons in PV type B	% (w/w) Cells in PV type A	% (w/w) Cells in PV type B
Na	<0,03	<0,03	0,03	0,03
Al	<0,03	<0,03	0,13	8,85
Cu	57,5	77	0,12	1,88
Ca	<0,03	<0,03	<0,01	0,08
Ag	0,7	1,4	7,9	1,8
Sn	27,7	13	0,08	0,08
Pb	13,2	7	0,4	0,33
Ni	<0,03	<0,03	0,06	<0,01
Fe	<0,03	<0,03	<0.01	0,02
Si, Ti, V, Cr, Mn, Co, Pd, Zn, Cd, Ba, Au	<0,03	<0,03	<0,01	<0,03
Residue	no	no	90	86

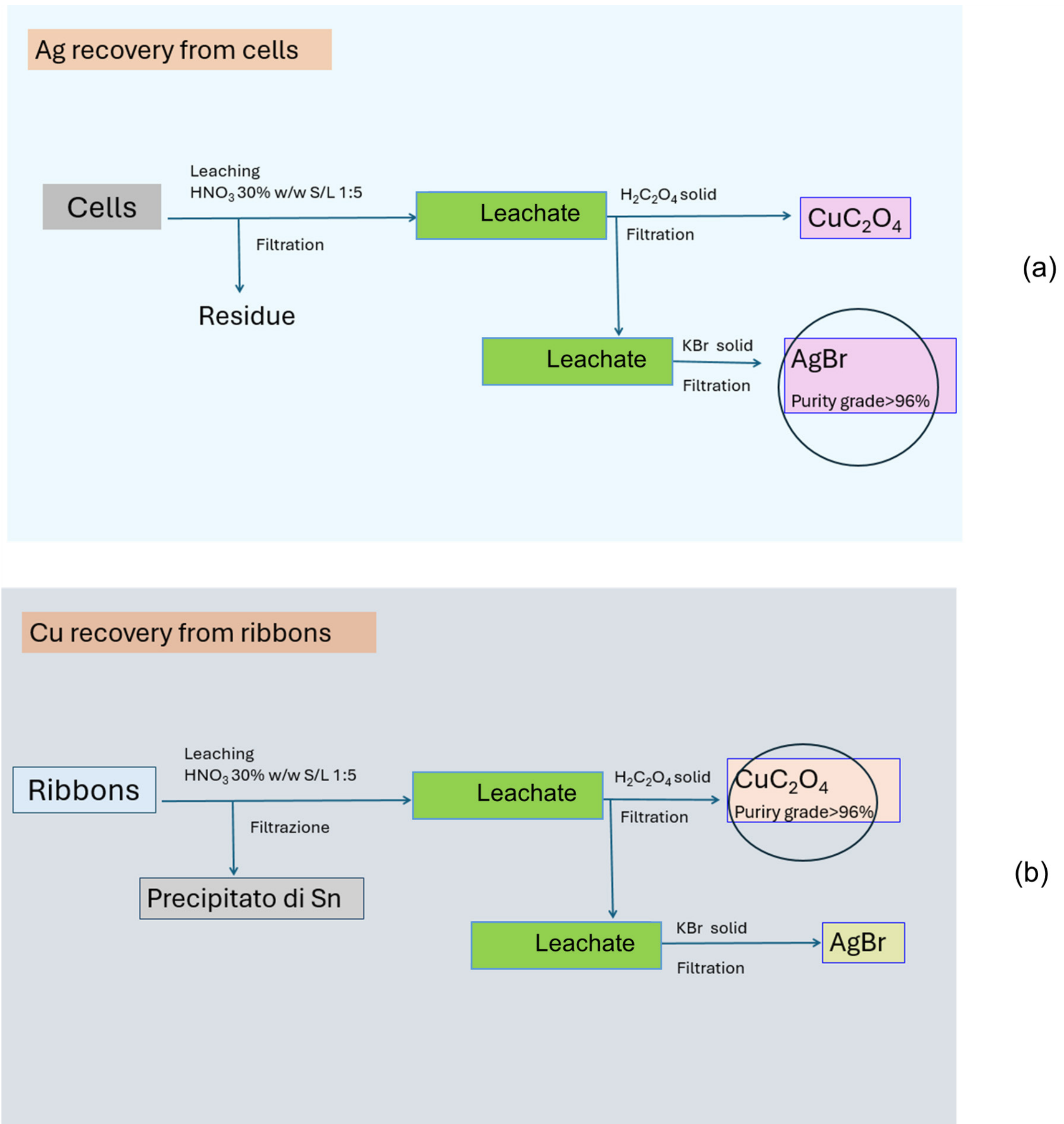

FIGURE 2: Processes for the recovery of Ag from PV cells (a) and Cu from ribbons (b) by hydrometallurgical methods.

The process illustrated in Figure 3, based on the ENEA patent N.102023000018996 deposited on September 15, 2023 (Italian Patent and Trademark Office, UIBM), has been employed in order to recover silicon-based powder suitable to be reused as anode material for LIBs.

The innovative process, which consists of an appropriately studied sequence of grinding and sieving steps, aims to eliminate the oxidized components with low electrical conductivity and to reduce the silicon powder to sub-micrometric dimensions to obtain, in the electrode manufacturing phase, a high surface area and low volumetric expansion of the anode material during cell operation. The powder was then characterized with different diagnostic techniques and was mixed with an electronic conductor (nano-carbon) and a polymeric binder, with the aim of guaranteeing electronic conduction and mechanical stability to the electrode, respectively. This mixture was dispersed in water and deposited on a copper sheet (having the function of a current carrier). After removal of the solvent and drying, the electrode was electrochemically characterized (voltammetry, impedance, and charge/discharge cycles in electrochemical cells) to validate its performance. The electrochemical tests, carried out preliminarily, have shown that silicon, obtained through recycling processes of PVs without resorting to chemical purification methods, can form alloys with lithium and can therefore potentially be used to create high-voltage anodes.

At present the invention is at TRL 4 (technology validated in the laboratory). Further studies are necessary to improve the electrochemical performance of the battery obtained, especially in terms of life cycles and capacity decay.

2.2 The PARSIVAL Project

The PARSIVAL (PV PAnels Recycling to create SIlicon VALue chain) project, funded by the KIC EIT RawMaterials

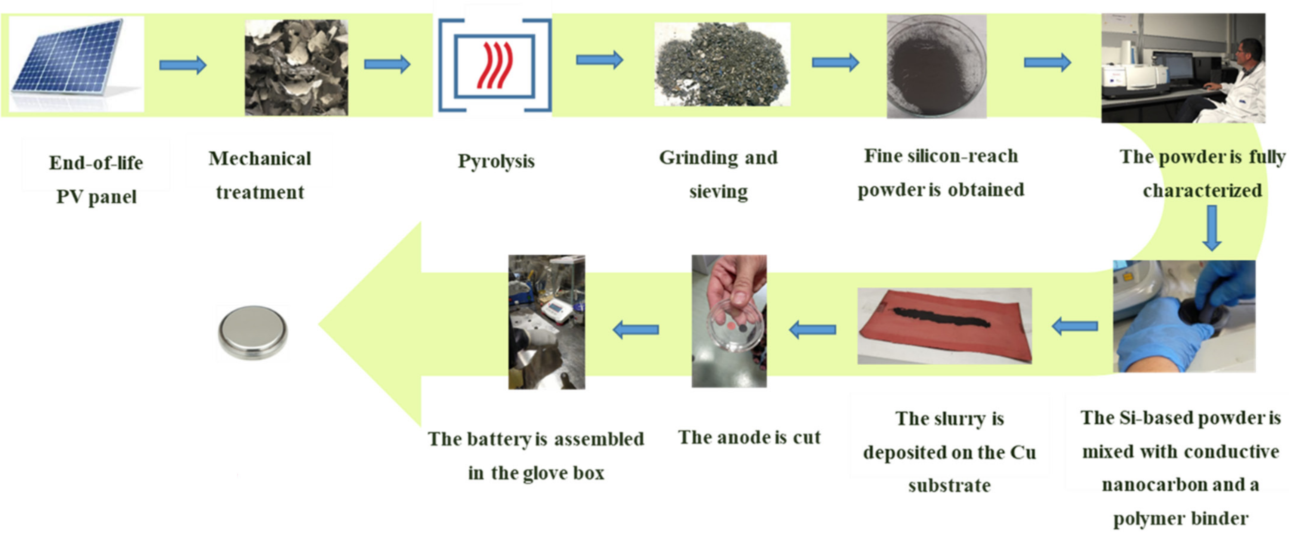

FIGURE 3: The ENEA process, based on the ENEA patent N.102023000018996 (Italian Patent and Trademark Office, UIBM), employed to recover a silicon-based powder suitable to be reused as anode material for LIBs.

for the years 2023-2024, aims to leverage the knowledge triangle and establish a European network focused on the challenge of recovering and reusing materials from EoL PVs, particularly silicon. The goal is to lay the groundwork for the development of facilities dedicated to refurbishing and recycling decommissioned PVs. This initiative seeks to extend the lifespan of repairable PVs and repurpose materials, recovered from PVs that are no longer viable for use, in various supply chains.

Specifically, the project will explore three different applications for silicon:

- Silicon-based ferroalloys,
- Material for battery anodes,
- Production of new photovoltaic cells.

PARSIVAL operates as a Regional Innovation Scheme (RIS) capacity building project, targeting territorial challenges associated with raw material extraction, recycling, and reuse within RIS areas. These areas typically comprise countries with moderate or modest innovation scores as defined by the European Innovation Scoreboard.

The project's activities are concentrated in two European regions situated within RIS areas that are experiencing emerging issues with EoL PVs disposal: Apulia, in Italy, and Extremadura, in Spain. Apulia ranks as the second largest Italian region in terms of installed photovoltaic capacity (3.05 GW). Given that PVs typically have a lifespan of around 25 years and the surge in photovoltaic installations occurred predominantly in the 2000s, a significant volume of decommissioned solar panels is anticipated to require management in the coming years. Approximately 300,000 tons of decommissioned solar panels are projected to accumulate in Apulia within the next 15 years.

Presently, there are no specialized treatment facilities for handling this type of waste in either Apulia or Extremadura.

Nine partners from four European countries (Italy, France, Germany, and Spain) are involved in the Project, each with their own designated tasks:

- 9Tech: coordination, feasibility study to implement its own recycling process in the Apulia Region, supply of recovered silicon/aluminum cells to study different applications.
- ENEA: development of a treatment process to make the recovered silicon suitable for application in lithium-ion battery anodes, communication and dissemination activities.
- ERION: analysis of PV installations in Apulia and forecasting of PV waste streams, contribution to the feasibility study for the implementation of a refurbishment/recycling plant.
- University of Padova: development of a treatment process to produce silicon-based ferroalloys from recovered photovoltaic cells, scientific education and dissemination activities.
- CEA: support for the feasibility study for the implementation of a photovoltaic panel treatment plant in Apulia region to repair and reuse EoL modules.
- JPM Silicon: validation of purification processes to make the recovered silicon suitable for different applications, in particular photovoltaics.
- University of Salento: high education and dissemination initiatives on recycling in Apulia.
- Gomez Pardo Fundation: Study for the implementation of project results in Extremadura (Spain).
- NORCSI: realization and validation of anodes and batteries using silicon recovered from EoL PVs.

2.3 The ReSiELP Project

The purpose of the ReSiELP (Recovery of Silicon and other materials from EoL PVs) project, funded with 2.5 million euros under the Knowledge Innovation Community on Raw Materials (KIC Raw Materials), was to optimize the recycling of EoL c-Si PVs, for efficient resources utilization and waste reduction, in accordance with European legislation 2012/19/EU (also known as the WEEE Directive) and the principles of the circular economy. ReSiELP was a three-year project, implemented between 2017 and 2020.

Specifically, ReSiELP aimed to develop a recycling method for recovering not only the major components of c-Si PVs, like glass and aluminum (from the frame), but also the minor components that are precious and critical elements, such as silicon, silver, and copper (Audoin et al., 2019; Cerchier et al., 2022). Indeed, silicon is currently classified as a critical raw material, and silver is very close to reaching critical status. The first phase of the ReSiELP recycling method concerns the separation and recovery of glass, aluminum (frame), copper, and PV cells, by combining mechanical and thermal treatments. In detail, PV panels, after removal of aluminum frame and junction box by manual disassembling, undergo a thermal treatment, in order to eliminate the polymeric fraction (EVA encapsulant and backsheet). Afterwards, copper electrical ribbons are manually collected, while a separating machine (equipped with a vibrating table, a cooling fan for mechanical air separation, and a 3 mm mesh net) is used to separate glass and silicon cells. Copper is sent to recyclers whereas the recovered glass is reused as inert material in prefabricated concrete elements, to promote sustainable construction and reduce the depletion of non-renewable natural resources. As for the silicon cells, after removing glass contamination, they undergo a hydrometallurgical treatment, consisting of two phases. In the first phase, sodium hydroxide is used to remove aluminum from the backside of the silicon cells, while the second phase utilizes nitric acid to detach silver electrical contacts from the front side of the cells. Silver is hence recovered through precipitation as silver chloride which is reduced to metallic silver (99.9% purity), through a heat treatment, in a muffle, containing sodium carbonate. As for the silicon from hydrometallurgical treatment, it goes through further basic and acid chemical treatments, mainly based on the use of sodium hydroxide and tartaric acid, to reach a purity of 6N (99.9999% silicon) and become suitable for reuse in the PV sector.

Within the project, ENEA contributed to the development of the management system for gaseous effluents resulting from the PV thermal treatment and the design of the process for the neutralization of the wastewater from PV cells hydrometallurgical treatment (Cerchier et al. 2022). Additionally, ENEA assessed the sustainability of every process phase through the Lyfe Cycle Assessment (LCA) and Lyfe Cycle Costing (LCC) methodologies (Ansanelli et al.,2021; Fiorentino et al., 2022). The LCA analyses indicated that, overall, the ReSiELP recycling process brings environmental advantages, thanks to the retrieval of secondary materials from EoL c-Si PVs. Similarly, the LCC analyses showed that, due to the recovery of secondary materials, the ReSiELP recycling process achieves a net reduction in environmental damage costs (externalities).

2.4 The EVERPV Project

The EVERPV project (Highly efficient delamination technologies to recover and reuse metals, glass, polymers from EoL PVs), funded under the Horizon Europe program (HORIZON-CL5-2022-D3-03-09), is dedicated to the development of recycling solutions for EoL c-Si PVs, in a circular economy perspective and in compliance with the European WEEE Directive. It is a 36-months project, started in 2023, which aims to develop a technology that is both efficient and environmentally, economically, and socially sustainable.

Specifically, within EVERPV project, two delamination processes will be developed up to TRL 7 (pilot plant), one utilizing grinding and the other based on the ENEA-BetaTech patent N.102017000033488 (Italian Patent and Trademark Office, UIBM), exploiting infrared (IR) radiation technology to weaken the encapsulant. A third hybrid process will also be investigated, involving the thermal treatment of c-Si PVs, after removing backsheet through grinding or by exploiting the IR radiation.

In the EVERPV project, ENEA will define the optimal conditions of the hydrometallurgical treatment for Ag, Cu and Sn recovery. Moreover, ENEA researchers will develop the technical specifications for implementing the "IR delamination methodology" at TRL7.

Finally, ENEA, in collaboration with other project Partners, will assess the economic and environmental performance of the delamination and purification processes, studied by EVERPV, through Life Cycle Costing (LCC) and Life Cycle Assessment (LCA) methodologies, in compliance with UNI EN ISO standards 14040-14044 (2006). The objective is to identify the economically and environmentally critical points enabling targeted improvement interventions and supporting the development of sustainable recovery technologies. Furthermore, the environmental and economic impacts of the two investigated delamination processes (grinding and IR), scaled up TRL7, will be compared with those of an established and innovative technology, involving the use of hot knives. This comparison aims to promote technologies that are better, from an economic and environmental point of view, than those currently available. Additionally, the environmental impacts and the economic costs associated with the processes, set up within EVERPV, for recovering and purifying materials from EoL c-Si PVs, will be assessed and compared with those related to the production of corresponding virgin materials.

Lastly, in line with guidelines developed by the Life Cycle Initiative and the United Nations Environment Programme, the social impacts of the recycling processes, developed through the EVERPV project, on various stakeholder groups, will be assessed, considering factors such as working conditions, job creation or loss, and the need for specialized skills.

Any positive results will be very valuable for fostering material recovery from EoL c-Si PVs, at both entrepreneurial and political levels.

3. CONCLUSIONS

ENEA research activity, dedicated to the challenging issue of EoL PVs recycle, is mainly focused to provide solutions to some critical issues limiting the sustainable recovery and valorization of materials from EoL PVs. Within RESIELP project (2017-2020), ENEA contributed to the development of a management system for the gaseous effluents resulting from the thermal treatment and design of the process for the neutralization of the wastewater from PV cells hydrometallurgical treatment. Additionally, ENEA conducted an environmental assessment of every process phase using the LCA methodology. Within MI-IEMAP (2022-2024), ENEA is now developing a process, based on the ENEA-BetaTech patent N.102017000033488 (Italian Patent and Trademark Office, UIBM) allowing the recovery of the main components of PVs (glass, EVA, backsheet, cells, electrical contacts) through an IR heat treatment allowing the partial thermal degradation of the EVA layer. Avoiding the degradation of the entire EVA and backsheet layers, as other methods based on thermal treatments do, gaseous emissions into the atmosphere are reduced. The methodology will be brought to TRL 7 within EVERPV Project and will be compared (and eventually integrated) with grinding technology. Moreover, within MI-IEMAP, ENEA is investigating the possibility to employ silicon recovered from EoL PVs in lithium-ion batteries through a mechanical process based on the ENEA patent N.102023000018996 (Italian Patent and Trademark Office, UIBM). Within PARSIVAL capacity building project, ENEA is finding out technical solutions for the treatment of silicon cells recovered by 9-Tech plant, in order to obtain a suitable silicon-based anode material for lithium-ion batteries.

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