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"Gheorghe Asachi" Technical University of Iasi, Romania

PHOTOVOLTAIC PANELS RECYCLING TO CREATE SILICON VALUE CHAIN: PARSIVAL PROJECT

Pietrogiovanni Cerchier[1*], Francesco Miserocchi[1], Luca Pezzato[1], Luc Federzoni[2], Maria Lucia Protopapa[3], Nicola Taurisano[3], Vitantonio Valenzano[3], Matilde Amadio[4], Emiliano Tolusso[4], Francesco Marzullo[4], Santiago Rosado[5], Silvia Oñate[5], Lidia Gullon Corral[5], Leticia Presa[6], Jan Philipp Mai[7,8], Julian Pudack[7], Lars Krüger[7], Silvia Rizzato[9], Giuseppe Maruccio[9], Katya Brunelli[10]

[1]9-Tech srl, Via Triestina bassa 74, 30020 Eraclea, IT
[2]CEA & SolReed, 17 Av. des Martyrs, 38000 Grenoble, FR
[3]ENEA, Cittadella della Ricerca, SS7, 72100 Brindisi, IT
[4]ERION, Via Angelo Scarsellini, 14, 20161 Milano, IT
[5]Fundación Gómez Pardo, Calle Alenza, 1, 28003 Madrid, ES
[6]Universidad Politécnica de Madrid, Calle Ríos Rosas, 21, 28003 Madrid, ES
[7]JPM Silicon, Wilhelmsgarten 3, 38100 Braunschweig, DE
[8]NorcSi, Weinbergweg 23, 06120 Halle (Saale), DE
[9]University of Salento, Piazza Tancredi, 7, 73100 Lecce, IT
[10]University of Padova, Via Marzolo 9, 35131 Padova, IT

Abstract

Apulia in Italy and Extremadura in Spain are regions characterized by an intensive installation of photovoltaic (PV), which are expected to generate a large amount of PV waste in the next 15 years (~300k tons in Apulia and ~380k tons in Extremadura) but there are no dedicated PV recycling plants in these areas. PARSIVAL aims to solve this problem by proposing PV refurbishment and End-of-Life (EOL) PV recycling technologies.

The PARSIVAL technology for recycling, one of the most advanced in Europe, is able to recover all the valuable materials contained in PV panels (aluminium, glass, copper ribbons, silver, silicon PV cells), but further research is needed to refine the recovered materials in order to commercialize them and, in particular, to find a final market for the recovered PV cells. The latter contain mainly silicon that is a Critical Raw Material, but the presence of paste of aluminium and silicon nitride hinders its reuse. Therefore, the project is also investigating the most profitable ways to valorise silicon, which can be recovered from PV waste, in three different applications (Li-ion batteries, ferroalloy, and aluminium industry). In addition, PARSIVAL is evaluating the feasibility of a refurbishing and recycling plant in Apulia and the replicability of the results in Extremadura contributing to the creation of refurbishment and recycling networks and professionals, through Higher Education Institutions (HEIs) in these areas. The project results were promising: both refurbishment and recycling processes have been validated and the recovered silicon was successfully tested in the addressed applications.

Key words: photovoltaic, recycling, refurbishment, silicon

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[*] Author to whom all correspondence should be addressed: e-mail: info@9tech.it

1. Introduction

The world's total installed PV capacity exponentially increased since 1990: it reached 1 TW by the end of 2022 (IRENA, 2023) and is expected to rise further to 1.6 TW by 2030 and 4.5 TW by 2050 (Weckend et al., 2016). The European Photovoltaic Industry Association predicted that PV energy might contribute up to 12.6% of the world's electricity needs by 2040, implying that significant amounts of PV modules will be installed in the future.

Taking into account that the mean lifetime of PV panels is 25 years and considering the dramatic growth experienced in the PV industry since 2000 (Chowdhury et al., 2020), significant quantities of photovoltaic panel waste will be produced within a few years and will continuously increase in the future. It has been predicted that the worldwide solar PV waste could unlock between 1.7 and 8 million tons of raw materials (glass, Si, Ag, Cu, Al) by 2030, rising further to about 78 million tons by 2050 (Weckend et al., 2016). Therefore, recycling PV waste for recovering valuable materials, while minimizing the waste generated, is becoming relevant for the solar energy industry. Furthermore, in recent years, recyclers have noticed that the real lifetime of PV modules is even less than 15 years (Artas et al., 2023; Libra et al., 2023).

The PV module performance can degrade due to several factors, such as UV irradiation, temperature, humidity, mechanical shock, local pollutants and toxic fumes, and this degradation leads to premature replacement of the modules (Ndiaye et al., 2013; Saneie et al., 2024). Another problem is that around 40% of photovoltaic modules, although functioning, are replaced due to poor efficiency or only due to the presence of small, easily repairable damages. All these factors contribute to the generation of huge volumes of PV waste.

The disposed PV panels are typically landfilled although these devices could keep working if properly refurbished. At the moment, refurbishment is never performed and only 10% of EoL PV panels are recycled worldwide: this causes a significant environmental impact (Lunardi et al., 2018). Moreover, the only recycling approach for EoL PV panels at industrial scale is a shredding-based mechanical treatment, which recovers aluminum from frames, copper from wires and glass granules from shredded mixture sieving. This downcycling of PV waste causes the loss of important raw materials like silver and silicon contained in PV cells. These two materials represent over 60% of the total economical value of the material in a photovoltaic module (Peplow, 2022), and therefore with mechanical shredding, only 35% of the theoretical economic value can be extracted.

Many EU countries like Germany, Italy, France and Spain, where the installation of PV is concentrated, are starting to address the problem of PV recycling. This problem will become even more acute in the next few years, especially in some regions of RIS (Regional Innovation Scheme) countries, where many photovoltaic systems have been installed without the presence of advanced recycling plants.

Apulia (South of Italy) is the second region in Italy for installed PV power capacity (2.9 GW, 13.4% of the national installed capacity) and it is a RIS region where the issue is particularly relevant: ~300k tons of PV waste will be collected in the next 15 years. The case of Extremadura, with 3.9 GW of installed capacity (23.4% of the PV solar energy of the country), is similar. In both regions, there are no recycling plants yet, so there is an urgent need to establish a structured value chain to recycle and reuse the valuable materials contained in PV.

The expertise and technologies created by the PARSIVAL consortium can address this issue. The project aims to: i) assess the feasibility of establishing a waste PV refurbishment and recycling plant in Apulia (IT); ii) close the silicon value chain by the analysis of applications for the silicon recovered from PV; iii) build up a solid network able to support PV panels recycling; iv) exploit results in Extremadura; and v) increase the skills of students in Apulia on the themes of recycling, recovery, reuse and substitution of CRM. The novelty of this work is significant, as PARSIVAL is not only exploring two innovative technologies for refurbishment and recycling, but it is also one of the few studies investigating the specific applications for PV cells recovered from end-of-life PV panels.

In this work, the results of the first year of the project are presented: the analysis of PV waste stream in Apulia and Estremadura; tests with refurbishment and recycling technologies; application of recovered silicon in aluminium industry; production of ferroalloys and anodes of batteries with recovered silicon.

2. Material and methods

2.1. Value Chain analysis of PV panels in Apulia and Extremadura

2.1.1. Installation analysis in Italy and Apulia

Information regarding the consistency of installed photovoltaic systems in Italy is scattered. The most reliable sources include data collected and published by the Gestore dei Servizi Energetici (GSE) and made public through the Atlaimpianti web interface. Reconstructing the historical series of installed systems is achievable using data from Terna's Gaudì portal, which is accessible thanks to sector associations. The data collected and used for the reconstruction ranges from 2005 to 2021, and takes into account information such as the number of systems and nominal installed power.

2.1.2. Installation analysis in Spain and Extremadura

The analysis of PV installations in Spain and the Spanish region of Extremadura is based on a bibliographic study, but also on the Pretor online tool, developed by the Spanish Ministry for Ecological Transition. This tool allows to identify all renewable energy licenses in Spain by region. In the specific case of Extremadura, the year of installation has been identified, but not in other regions. As an alternative, the data for the whole of Spain were obtained through several bibliographies (Heras-Saizarbitoria et al., 2011).

Data on self-consumption in Spain are based on the bibliography, but information for Extremadura is lacking due to the absence of official data on self-consumption installations by region. All data for Extremadura and Spain are organized by year, starting from 2004, when PV energy was introduced in Spain, up to 2023, to calculate the cumulative installed power for each year in these region and country. After a detailed analysis of the situation, the main periods of growth and stability caused by specific events, can be identified. This anticipates the behaviour of PV waste production in the study areas.

2.2. Photovoltaic refurbishment and recycling

2.2.1. Refurbishment

The repair and reuse of photovoltaic modules is an important topic because it avoids the production of new modules and therefore helps avoid significant greenhouse gas emissions and the extraction of rare or critical materials. The diagnostic and repair technologies for modules that help extend module life were developed by CEA and tested on several modules. Some PV modules (ref. Solarworld Sunmodule plus SW270 from 2017) were repaired and qualified in semi-industrial configuration.

The following operations were carried out on the different modules:

1. cleaning and visual inspection of the modules;
2. change of the three diodes of the modules;
3. verification of electrical performance by flash test;
4. checking the correct functioning of the cells by electroluminescence;
5. wet leakage test.

The wet leakage current test is an electrical withstanding test carried out on electrical appliances to evaluate the electrical isolation of the housing. The test is performed by immersing the appliance in water with one cable connected to the appliance's electrical wires and the other cable connected to the water.

2.2.2. Recycling

Photovoltaic modules that cannot be refurbished must be valorized in a different way, and recycling should be the preferred one.

The recycling technology developed by 9-Tech (Mazzi et al., 2024), shown in Fig. 1, was implemented in the PARSIVAL project. This technology can present significant advantages over existing solutions in terms of quality of recovered materials (Cerchier et al., 2022).

During the project, some tests were performed on different PV panels in the TRL6 pilot plant. The process begins with the manual removal of the aluminium frame and junction box, followed by a thermo-mechanical treatment to remove the polymeric fraction, and delaminate the PV panel. Specifically, the PV modules undergo a controlled heating to fully combust the EVA encapsulant efficiently; during this step the temperature of the chamber exceeds 400°C. After the heating treatment, a machine removes the copper wirings, and the material is firstly sieved with a 2 mm perforated sheet. Finally, the mechanical separation of the PV cells from glass is carried out and PV cells are recovered in form of pieces with dimensions of 1-20 cm^2.

Glass, copper ribbons, and PV cell are the end products of the process. Silicon, the primary material in PV cells, is recovered from PV panels in the form of fragments. These fragments contain not only silicon but also other functional materials such as silicon nitride, aluminium and silver, which are an integral part of the functioning of the cell. While these materials contribute to the functioning of the PV cells, they pose significant challenges in the recycling process as they are considered impurities for further applications of silicon. The PV cells, before their use in the different applications, undergo hydrometallurgical treatment to remove silver from the surface of PV cells and recover it.

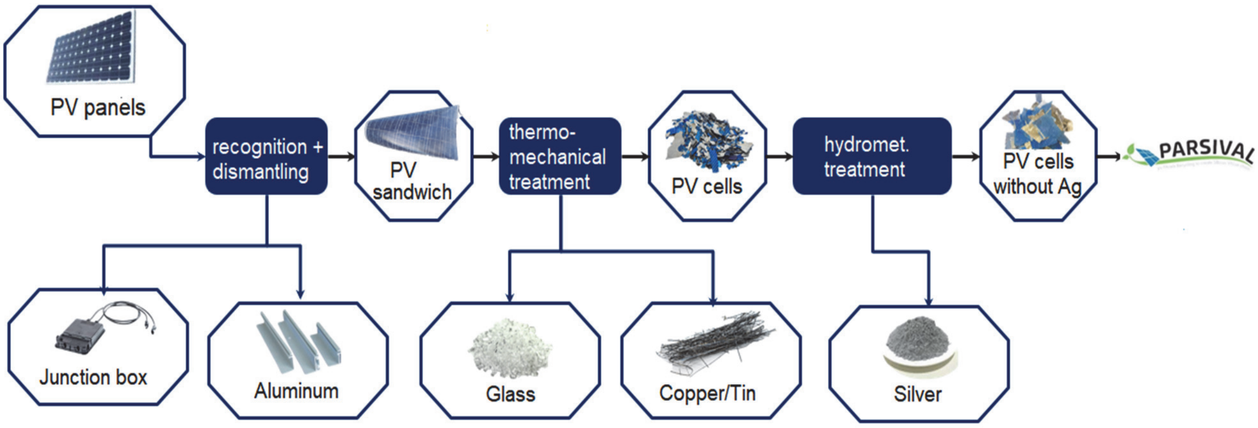


Fig. 1. 9-Tech technology process flowchart

2.3. Reuse of silicon silicon PV cells without silver

2.3.1. Aluminium industry

The use of PV cells has been investigated in aluminium industry, with the advantage that aluminium, commonly present in PV cells, does not represent an impurity. Despite this advantage, the integration of recycled silicon into aluminium alloys, has achieved limited success so far. In fact, previous melting tests reveal poor solubility and yield, attributed to several factors including oxidation, the presence of silicon nitrides which limit wettability, and inadequate mixing with the melt. To address these challenges, experiments have been conducted testing different binders and additives to improve the solubility of silicon in aluminium alloys.

2.3.2. Ferroalloy production with STILLMETAL process

The use of PV cells without silver has been investigated as reagent in STILLMETAL process for the ferroalloy production. STILLMETAL is an upscaling project funded by EIT RawMaterials (2022-2024) and proposes a process to solve the problem of the steel "white" slag, which is considered a waste and must to be disposed of in landfill. STILLMETAL process involves the reaction in the molten state, at high temperatures, between white slag and specific reagents to produce a valuable metal, containing silicon with the composition of a Ferroalloy (FeSi), and a residual oxide slag that can be used in cement industry. The reaction was firstly simulated with Thermodynamic Software Fact Sage 8.2, using FSstel, FTmisc and FToxid databases. Numerical simulations were carried out in order to obtain a FeSi with an amount of Si higher than 40%, and a residual oxide slag with low melting temperature. For the simulation the white slag compositions reported in Table 1 and the following composition of PV cell were used: 90% Si and 10% of aluminium paste.

The results of the simulation were experimentally validated in TRL5 pilot plant (an induction furnace with stirring). The materials were mixed inside a bucket and then put inside a crucible of graphite with the external part of ceramic. During the test the temperature of the system was measured by a pyrometer positioned above the crucible and the data were recorded from the PC connected to the probe. The solidified materials, recovered inside the crucible the day after the tests, were characterized with SEM-EDS analysys using a Cambridge Stereoscan 440 electon microscope equipped with a Philips PV9800 EDS.

2.3.3. Li-ion anode production

In recent years, natural graphite has been extensively utilized as the anode material for lithium-ion batteries. However, the EU has recently designated natural graphite as a CRM, prompting recommendations for its partial or complete replacement with non-critical or end-of-life materials. Silicon emerges as one of the most promising alternatives to replace natural graphite.

Silicon has the capacity to form lithium alloys, boasting a theoretical specific capacity of 4200 mAh g^{-1} (Huggins, 1999), significantly surpassing the theoretical specific capacity of graphite (372 mAh g^{-1}) and metallic lithium (3800 mAh g^{-1}).

The primary challenge of utilizing silicon as an anodic material lies in its volumetric expansion, which can reach up to 300% during battery charge-discharge cycles (Rahman et al., 2021). This substantial volumetric variation leads to progressive fragmentation and active material loss, resulting in a rapid decline in accumulated capacity.

Furthermore, the recent categorization of silicon as a strategic material by the EU, coupled with the high environmental impact of silicon production from SiO_2, underscores the importance of its recovery and recycling, particularly from end-of-life products such as photovoltaic panels (Blömeke et al., 2023; https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en).

Within PARSIVAL Project, a process has been developed to recover silicon-based powder suitable for reuse as anode material for (lithium ion batteries) LIBs. Two samples of silicon PV cells, obtained using 9-Tech process, were used for the tests. One sample was untreated (fragments of cells without any further chemical treatment) whereas the other one was treated with nitric acid (30% v/v) and sodium hydroxide (30% v/v) solutions by University of Padova in order to remove aluminium and silver. These two samples underwent a mechanical process, which involved a series of grinding and sieving steps to eliminate oxidized components with low electrical conductivity and reduce silicon powder to sub-micrometric dimensions.

This approach aims to achieve a high surface area and minimize volumetric expansion of the anode material during cell operation. Subsequently, the powder was characterized using various diagnostic techniques and mixed with an electronic conductor (nano-carbon) and a polymeric binder to ensure electronic conduction and mechanical stability to the electrode, respectively. This mixture was dispersed in water and deposited onto a copper sheet, serving as a current carrier.

After solvent removal and drying, the electrode, in ribbon form, underwent electrochemical characterization (voltammetry, impedance, and charge/discharge cycles in electrochemical cells) to validate its performance.

3. Results and discussion

3.1 Value Chain analysis of PV panels in Apulia and Extremadura

3.1.1 Installation analysis in Italy and Apulia

Starting from the mid-2000s, the State promoted a regime of incentives aiming at the establishment of photovoltaic energy facilities.

These initiatives successfully met expectations, featuring financial incentives for electricity generation and the option to feed surplus energy into the grid, enabling private entities to sell excess energy for profit. The steady decline in production costs played a pivotal role in advancing this sector. The period between 2005 and 2013 marked a surge in photovoltaic energy adoption in Italy, propelling the country to outperform other nations in global rankings.

From 2010 to 2013, the total installed power capacity surged from less than 4.000 megawatts to 17.000 megawatts. Throughout this golden decade, the sector maintained an impressive average annual growth rate of 63.7%. However, with the conclusion of State subsidies that fueled growth, Italy's progress in photovoltaics experienced a notable slowdown, leading to more modest growth figures. It wasn't until 2018 that the country surpassed the threshold of 20.000 megawatts in installed capacity. As of December 31st, 2022, there are 1.225.431 PV installations in Italy, with a total capacity of 25.064 MW. Installations with a capacity equal to or less than 20 kW make up 93% of the total in terms of quantity and 26% in terms of capacity. The average size of the installations is just slightly above 20 kW.

The graph provided in Fig. 2 presents a comprehensive overview of the progression of both the number and capacity of photovoltaic installations in Italy during the period from 2008 to 2022. Notably, it highlights the initial phase of swift expansion, which was largely propelled by various public incentive schemes, particularly the last three iterations of the Conto Energia. These initiatives played a significant role in fostering the rapid deployment of photovoltaic systems across the country. It is worth noting the surge during the three-year period 2008-2011, which led Italy to become the second country in the world in 2012 in terms of total installed capacity, right after Germany (IEA, 2013). Italy added 9.3 GW in 2011 with the help of such uncapped feed-in tariffs. However, a notable shift occurred in 2013, marking the beginning of a consolidation phase within the Italian photovoltaic industry. During this period, the growth trajectory transitioned to a more gradual and steadier pace until 2019, the year that marked the beginning of the new incentive scheme FER1.

Italy has firmly established its symbolic milestone achievement of 20.000 megawatts of installed PV power. Surpassing the target with 20.108 megawatts at the close of 2018, this figure continued to ascend, reaching 20.865 megawatts in 2019. Describing the geographical distribution of photovoltaic plants in Italy poses a unique challenge. In contrast to other forms of energy where clear distinctions exist between Northern, Central, and Southern Italy, the landscape of national solar electricity is notably fragmented. Regional (and even provincial) rankings undergo significant variations based on different criteria such as the number of plants and installed nominal power.

3.1.2. Installation analysis in Spain and Extremadura

Spain's historic PV installation is characterized by two periods of growth. The first period goes from 2006 to 2008, and the installed capacity increased from 132 to 3.384 MW. This increase was the result of the subsidy system offered by the Spanish government to encourage the installation of PV panels, aiming to achieve an installed capacity of 371 MW by 2010. In May 2007, the RD 661/2007 was published, providing a subsidy of 0.44 €/kWh for PV facilities (compared to the electricity price of 0.075 €/kWh). This subsidy was reduced to 0.32 €/kWh from September 2008 through RD1578/2008. This promotion system for PV energy ended in 2009 (Fernández-González et al., 2020; https://www.global-regulation.com/translation/spain/1445573/royal-decree-661-2007%252c-of-may-25%252c-which-regulates-the-activity-of-production-of-electrical-energy-in-special-regime.html).

PV energy continued to grow moderately until the beginning of the second growing period in 2019, when it increased exponentially again. In 2018, before the second explosive growth period, the PV capacity in Spain was 4.780 MW. In 2023, it reached around 22.256 MW. During this period, the reduction in the manufacturing costs of PV panels directly impacted PV energy production, being the fundamental factor in the growth of PV energy in Spain since 2018. The situation in Extremadura follows the same trend (Fig. 3). Between 2006 and 2008, the installed power increased from 240 to 549 MW.

Since 2018, from 558 to 5.724 MW positioning itself as one of the leaders in energy production in Spain with a contribution of 24% to national generation. Self-consumption started in Spain later compared to other countries.

Table 1. Chemical composition of the white slag

CaO	*MgO*	Al_2O_3	SiO_2	Fe_2O_3	*MnO*	*Others*
49.6	7.9	9.1	31.1	2.0	-	bal
51.9	7.4	14.2	23.8	0.6	0.4	bal
49.6	6.0	29.1	14.7	0.1	0.2	bal

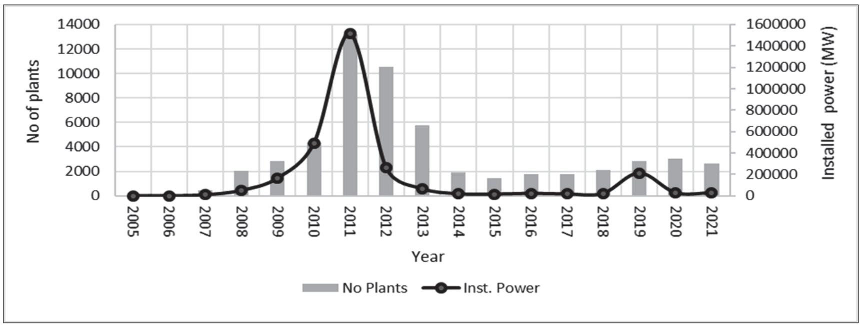


Fig. 2. Installations in Italy overtime 2005-2021. Data source: Terna – Gaudì, 2023

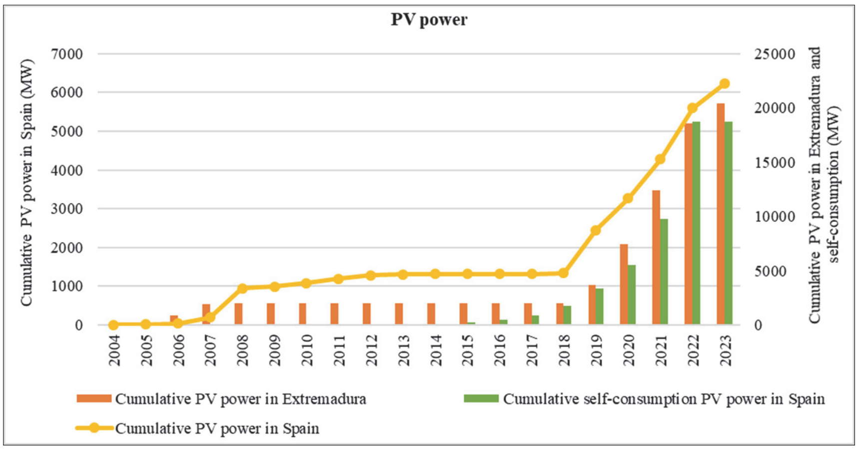


Fig. 3. Cumulative PV power in Spain, Extremadura and self-consumption (Spain) in the period 2004-2023

The key year is 2018 when the installation of PV panels for self-consumption increased exponentially from 484 MW in 2018 to 5.249 MW in 2022.This is due to several factors. The removal of regulatory barriers such as the “Sun Fee” in 2018, the high price of electricity in Spain, the aid provided by the Recovery Funds, the authorization to develop collective self-consumption plants and the regulations established by the European Union to make buildings more energy efficient. According to the bibliography, self-consumption could reach between 9.000 MW and 14.000 MW of installed capacity by 2030. It will enable the achievement of the Self-consumption Roadmap goal of 9 GW in 2024.

However, the self-consumption field still has some challenges, for example, the zero-waste regulation, which states that the surplus of solar installation does not go to the national grid but remains in the production centre. In 2022, self-consumption covered 1.8% of the country’s demand. Furthermore, it could have covered another 0.4%, but the difficulty of accessing the supply network and the zero-waste prevents its providing, and it is replaced by natural gas supply instead.

The development of PV energy will ultimately involve the management of PV panel waste. Under the general assumption that the lifetime of a PV panel is 25 years (Chowdhuryet al., 2020) it is expected that the generation of this waste in Spain will increase exponentially in the coming years. However, the exact waste generation is currently under discussion, and it is expected to reach 0.4-0.8 Mt of PV waste by 2040 (Kastanaki and Giannis, 2022; Santos and Alonso-García, 2018).

3.2. Photovoltaic refurbishment and recycling

3.2.1. Refurbishment

In Fig. 4a the result of a flash test is reported. It can be seen a normal behavior of a repaired module (Voc of 37 V and a Isc of 8.8 A). In Fig. 4b the results of the electroluminescence test are shown. The image reveals regions where cells have defects: as shown in one can identify small cracks that will not make problem for the reuse of the module. The developed process for refurbishment showed to be very efficient in finding defect and guaranteeing proper working of refurbished modules.

However, to create a market, it is important to provide confidence in these products. Also, it is important to guarantee the quality and safety of the repair by carrying out specific tests which will be carried out on all the repaired modules. Finally, repairs must be durable. To do this, it is necessary to ensure that the repairs will allow the module to have a long residual lifespan. This was ensured by accelerated aging tests specific to each repair. Based on this important know-how, the CEA is created the spin-off SOLREED, which aims to be the first company in Europe to carry out repair and reuse on a large scale.

3.2.2. Recycling

During the experimental phase, ended in January 2024, more than 1380 kg of end-of-life PV modules have been treated, and the prototype showed a high recovery yield of around 90% and a raw material purity high enough to be suitable for other applications. Specifically, from 100kg of PV panels, can be recovered: 65 kg of glass, 19 kg of aluminium, 2 kg of junction boxes (mainly composed of plastic and copper, 3 kg of PV cells (mainly composed of silicon), 1 kg of copper ribbons, and 0.05 kg of silver. Focusing on silicon, 9-Tech technology is able to recover up to 95% of it, with a purity higher than 90%. These data were confirmed by certified laboratories that performed several analyses on the materials recovered. In Fig. 5. are shown the materials recovered with 9-Tech technology. Moreover, the process showed low energy consumption, comparable to that of mechanical treatments.

3.3. Reuse of silicon

3.3.1. Aluminium industry

The trials to improve the solubility of silicon in aluminium alloys with the additives have shown promise in enhancing the integration of recycled silicon, potentially leading to better yields. However, the addition of these substances introduces extra costs, complicating the economic viability of this recycling pathway.

3.3.2. Ferroalloy production with STILLMETAL process

Several simulations were performed and the indicative results of a simulation are shown in Fig. 6. In this case, ferroalloy is characterized by an amount of Si higher than 40% (47.9% that corresponds to a FeSi-50) and the residual oxide slag has low melting temperature (lower than 1400°C) and a right composition to be used in cement industry.

In order to validate the results of the simulation, experimental tests were carried out with TRL5 pilot plant (induction furnace) using a crucible of graphite (W215/130 h330mm). The day after the test, the crucibles were broken to recover the solidified materials inside. In all tests, it was possible to observe two distinct phases: on the top the oxide phase (residual oxide slag), and on the bottom the metallic one (ferroalloy), as can be noted in Fig. 7.

From the SEM and EDS analysis of the ferroalloy it resulted that the composition was homogenous along the height with an average value of Si of about 44%, lower than the expected one of 47.9%. Moreover, the amount of Al also in this case is higher than the one expected (4% instead of 2%). The microstructure resulted homogenous in the different part of the ferroalloy and with also a homogeneous silicon average.

In the ferroalloy four different phases were present (Fig. 8.): the phase 1 richer in Si (53.3%); the phase 2 richer in Fe (23.4%) with 37.2%Si; the phase 3 richer in Al (15.9%) with 43.2%Si; and the small phase 4 richer in Ti (26.0%) with 38.3% Si.

3.3.3. Li-ion anode production

The production of anodes for batteries presents a less demanding environment for the use of recycled silicon, despite the presence of impurities. Metals, in general, can enhance the electrical conductivity of anodes, suggesting that the impurities in recycled silicon might not be as detrimental in this application. This paves the way for utilizing recycled silicon from PV panels, where the strict purity requirements of other applications are relaxed.

Preliminary electrochemical tests performed on anodes prepared using the silicon PV cells powder have demonstrated that this silicon can form alloys with lithium. Thus, the potential for creating high-voltage anodes in lithium-ion batteries is confirmed. Also, the proprietary technology developed by NorcSi for silicon anode production has demonstrated encouraging results.

By refining and remelting recycled silicon, this technology aims to produce high-quality silicon suitable for use in anodes. While preliminary outcomes are promising, further validation is necessary to confirm the efficacy and scalability of these approaches.

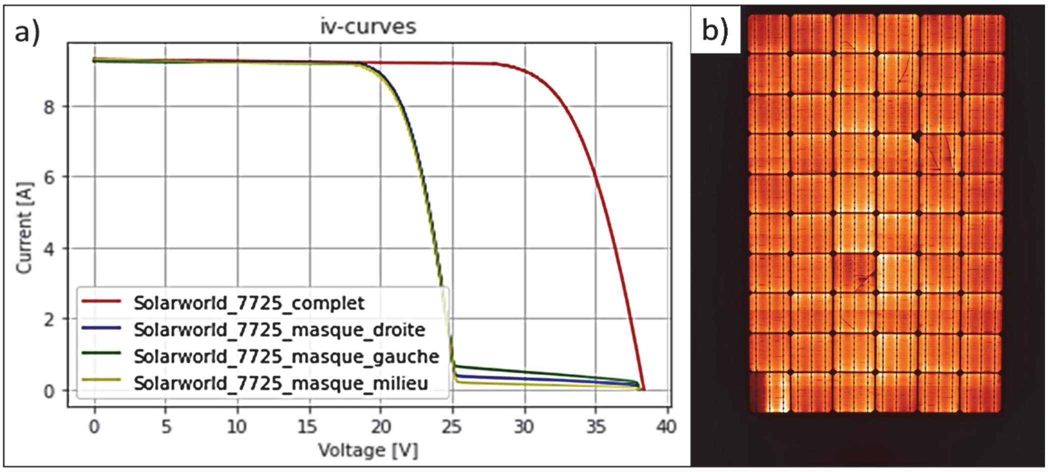


Fig. 4. a) Flash test result showing I-V curve on one module, b) Electroluminescence test showing some small cracks on cells

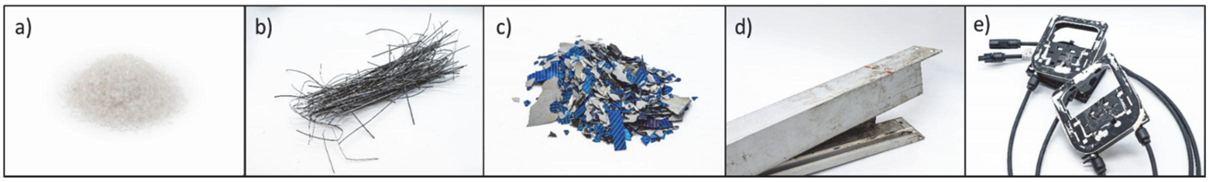
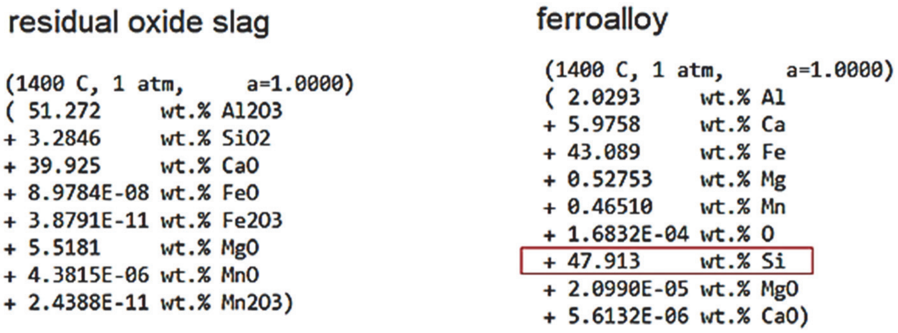


Fig. 5. Materials recovered in a 9-Tech demo plant that perform thermomechanical recycling from left to right: a) glass, b) copper ribbons, c) silicon PV cells, d) Aluminium, e) Junction boxes



residual oxide slag

```
(1400 C, 1 atm,     a=1.0000)
( 51.272     wt.% Al2O3
+ 3.2846     wt.% SiO2
+ 39.925     wt.% CaO
+ 8.9784E-08 wt.% FeO
+ 3.8791E-11 wt.% Fe2O3
+ 5.5181     wt.% MgO
+ 4.3815E-06 wt.% MnO
+ 2.4388E-11 wt.% Mn2O3)
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ferroalloy

```
(1400 C, 1 atm,     a=1.0000)
( 2.0293     wt.% Al
+ 5.9758     wt.% Ca
+ 43.089     wt.% Fe
+ 0.52753    wt.% Mg
+ 0.46510    wt.% Mn
+ 1.6832E-04 wt.% O
+ 47.913     wt.% Si
+ 2.0990E-05 wt.% MgO
+ 5.6132E-06 wt.% CaO)
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Fig. 6. Results of the simulation with FactSage8

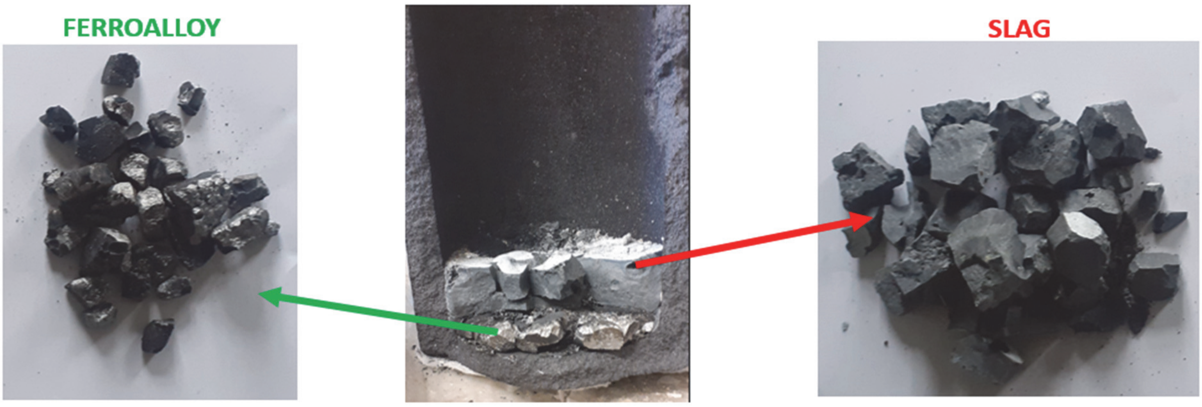

Fig. 7. Cross-section of the crucible coming from one experimental test

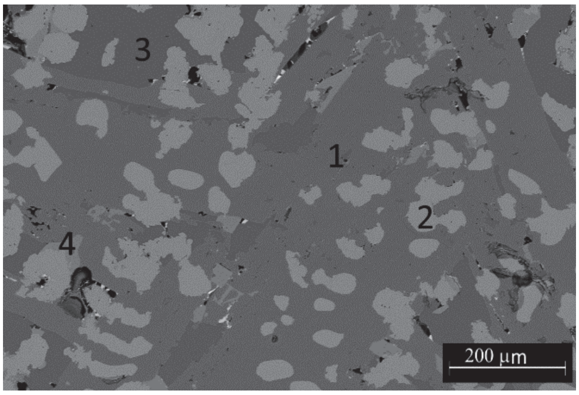

Fig. 8. SEM backscattered electrons images and EDS analysis of the central part of the ferroalloy

4. Conclusions

The PARSIVAL project represents a significant leap toward sustainable photovoltaic panel management. By introducing cutting-edge recycling and refurbishment technologies, the project tackles the impending challenge of PV waste in regions with intensive solar installations like Apulia and Extremadura. The analysis of installations suggests that million tons of PV waste are expected by 2040.

PARSIVAL showed that refurbishment of PV modules is possible and is a promising solution to increase PV lifetime. Furthermore, the feasibility of the recovery of all the raw materials from end-of-life panels, in particular silicon, a strategical raw material for the EU was also assessed.

The reuse of silicon recovered from PV panels is a complex process, hindered by the presence of impurities and the challenges associated with meltability and refinement. Despite these obstacles, innovative solutions and technologies are emerging, offering new pathways for the sustainable use of recycled silicon.

Specifically, the exploration of silicon reuse in applications such as aluminium industry, ferroalloys and Li-ion batteries produced promising results and will contribute to more sustainable and circular economy. In detail, the preliminary tests in the aluminium industry production have shown good performance of the recycled silicon, the use in the ferroalloys production allowed obtaining an alloy comparable with the FeSi-50 and the first anodes produced with recycled silicon showed good performances form the electrochemical point of view.

Further research and development are essential to optimize these processes, reducing costs, and enhancing the economic and environmental benefits of silicon recycling in the context of the growing solar energy sector. From a practical perspective, identifying various potential markets for silicon recovered from PV panel recycling will enhance the profitability of the entire process, enabling more widespread recycling of PV waste. This clearly results also in relevant social impact, considering the importance for future generations to recover critical materials and avoid landfill disposal. From the scientific point of view both the re-use of the silicon in the ferroaloys production and in the production of anodes is extremely innovative and the project can result the starting point of future research in the field.

Furthemore the project contributes to several Sustainable Development Goals (SDGs) such as SDG 7, affordable and clean energy by promoting the recycling of PV panels, ensuring access to affordable, reliable, sustainable, and modern energy for all; SDG 9, industry, innovation, and infrastructure, by representing a significant advancement in recycling technology, contributing to the development of sustainable industries; SDG 12, responsible consumption and production, by supporting sustainable consumption and production patterns and by enabling the recycling and refurbshiment of PV panels in a manner that maximises the recovery of valuable materials; SDG 13, climate action, by reducing CO_2 emissions and contributing to efficient use of resources to climate action efforts.

PARSIVAL's structured value chain for material recovery holds promise for transforming PV waste management practices and fostering a more sustainable solar industry.

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