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WASTE VALORISATION FROM PHOTOVOLTAIC PANELS AND ANALYSIS OF THE BUSINESS POTENTIAL FROM RECYCLING IN SPAIN AND ITALY

Silvia Oñate [1,*], Santiago Rosado [2] and Lidia Gullón [1]

[1] *Fundación Gómez Pardo, C/Alenza, 1, 28003 Madrid, Spain*
[2] *Universidad Politécnica de Madrid, Ríos Rosas 21, 28003 Madrid, Spain*

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ABSTRACT

Spain and Italy stand out as frontrunners in renewable energy adoption, particularly in photovoltaic (PV) technology, as part of the strategy for the Energetic Transition to clean sources. However, as Europe progresses towards clean energies, managing the end-of-life waste from solar panels emerges as a pressing challenge. In the coming years, the PV waste will grow exponentially, reaching 23 and 39 kt in 2030 in Italy and Spain, respectively. European regulations require that these wastes be properly managed using Circular Economy techniques to maximise the recovery of its components. Among these components, Si or Cu (CRM) are particularly important because of the supply risk and strategic importance to the EU. This study aims to forecast the magnitude of this waste stream in Spain and Italy from 2024 to 2030, both significant players in solar energy production, while also exploring the potential economic opportunities associated with its recycling.

1. INTRODUCTION

The general growing concern about global warming led to the holding of the "United Nations Climate Change Conference (COP21)," in 2018 in Paris, where the Paris Agreements were established "to substantially reduce greenhouse gas emissions to limit the global temperature increase this century to 2°C and to strive to limit this increase to even more than just 1.5°C" (Balthasar et al., 2019). These agreements forced an Energetic Transition to cleaner energy sources, such as renewable energies, to reduce greenhouse gas emissions (GHG) and the use of fossil fuels, both are key factors against global warming (Wolniak et al., 2022; Kumar, 2014). Since then, renewable energies suffered a boost in the development and implementation (Balthasar et al., 2019; Hinrichs-Rahlwes, 2012).

The European Union (EU) is a strong and active proponent of setting global ambitions and targets for climate protection (Młynarski, 2019). It has placed itself as one of the world leaders in energy transformation, reducing GHG emissions and substituting fossil fuel power generation with renewable energy (Wolniak, 2022). Among all renewables, solar energy is one of the most abundant and potential sources, contributing to 26% of global energy production (Kumar, 2014). Solar photovoltaic (PV), in particular, has great potential in terms of both technical and sustainable solutions for energy needs (Kumar, 2014). The PV power capacity in the EU is growing every year (Wolniak, 2022). It peaked in 2011, with 70% capacity of the worldwide installations. Now, the EU market accounts for only 50% of the worldwide PV capacity (Wolniak et al., 2022; Madsen et al., 2019).

The role of Spain and Italy in the global energy market should be highlighted because both countries are at the head of the PV capacity in the EU (EurObservER, 2023). These countries started with PV installations in the 90s, but it was not until the early 2000s that they began to build installations consistently. The two countries have developed this industry at different rates due to their circumstances. Both had a subsidy system to encourage installation (Ministerio de Industria, Turismo y Comercio, 2008; Ministerio de Industria, Turismo y Comercio, 2007).

In Spain, due to the financial crisis in 2008, the government removed the funds. This marked the end of the first Spanish "boom", which lasted from 2006 to 2008 and represented 3.384 MW installed. The second boom began in 2018 and continues to this day. By the end of 2022, the total number of installations increased to 67.886 with a total capacity of 22.256 MW.

The Italian growth period is only one and took place from 2005 to 2015. It overlaps with the European growth peak in 2011, when Italy had already installed 13.216 MW. In 2022, there were 1.225.431 PV installations, with a total

* Corresponding author:
Silvia Oñate
email: silvia.onate@fgomezpardo.es

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capacity of 25.064 MW. These figures highlight the difference in capacity of the Italian and Spanish PV installations, as Italy is more focused on self-consumption and Spain on industrial generation, which usually has bigger plants with greater capacity.

When PV modules were first installed in the EU in the 2000s, they had a lifespan of 25 years; as the technology progressed, the lifespan increased to 35 years in 2023 (Sultan et al., 2022). However, the capacity to transform light into energy is not constant over the years. Up to 10 years, the module's transformation yield remains constant at more than 90% of conversion. Then, it drops to 80% in 25 years. Some modules need to be replaced in these years, generating waste. The expected end-of-life of the modules combined with the number of installations in both countries raises concerns about the volume of waste that is going to be generated by PV modules (Marcuzzo et al., 2022; Chowdhury et al., 2020) and the difficulties related to its management.

This study analyses the forecast of waste generation in Spain and Italy in the following years and assesses the potential value of this specific waste toidentify the business opportunity of PV recycling, in addition to the needs regarding waste management and the Circular Economy policies.

2. PHOTOVOLTAIC PANEL WASTE PRODUCTION

The data of the historical installations, together with the end-of-life of the solar panels, provide a forecast of the waste generation in the coming years. It is presented in Figure 1.

The waste growth forecast for the coming years is exponential. Spain expects to reach 5 kt in 2025, while Italy will not reach 5 kt until 2027. By 2030, Spain will be close to 40 kt and Italy 25 kt.

The increase in waste is mainly due to the ageing of the PV panels. As the first installations in Spain were built between 2006 and 2008, the systems are now around 20 years old, and some will soon need to be replaced. The boom in Italy came years later, and the situation will be the same as in Spain, with a delay of a few years (around 2 years). As the years go by, the installations will become obsolete and produce more waste.

Although the specific number of facilities, their capacity and their age are available parameters, there is no clear consensus on the rate of waste generation. Based on the available literature, the amount of accumulated waste expected by 2030 in Spain is estimated to be between 71 and 180 kt (Santos et al., 2018), which is in line with the data shown in the graph. On the contrary, the Italian prediction is quite far from the data presented. In 2015, a forecast predicted a waste accumulation in 2030 of 757 t compared to the 23.000 t displayed in Figure 1 (Paiano, 2014). This estimation only considers those installations before 2013, while the model used in this research considers all installations until 2023. What can be said, for sure, is that PV waste generation will increase exponentially in the coming years and have to be managed.

3. PHOTOVOLTAIC PANEL WASTE VALUE

The waste generated by the PV industry is a potential source of business, although PV waste processing still presents some challenges in terms of economic feasibility (Masoumian et al., 2015). The economic profit of PV recycling is around 0,58 $/MW, which means around 0,0076 €/t (Corcelli et al., 2018; Peeters et al., 2017). This small profit potential, coupled with the challenges of proper waste management and fluctuating commodity prices, makes PV waste recycling a real challenge (Peeters et al., 2017).

In EEUU, which had a PV energy cumulative capacity of 40.500 MW in 2020, 450 M$ value creation is predicted (Majewski et al., 2021) between 2030-2060 (Domínguez et al., 2019). Comparing the PV capacity of EEUU against Spain and Italy's capacities (11.700 MW and 21.700 MW, respectively), it is possible to expect an interesting business opportunity in both countries.

The average composition of PV panels based on the bibliography (Paiano, 2014; Corcelli et al., 2018; Choi et al., 2014; Latunussa et al., 2016), and the stock prices of different components sourced from the Mineral Commodity Summaries report of the United States Geological Survey (US Geological Survey, 2023; Mineral Commodity Summaries, 2024; Di Giuseppe, 2020; Recycling, 2024) and differ-

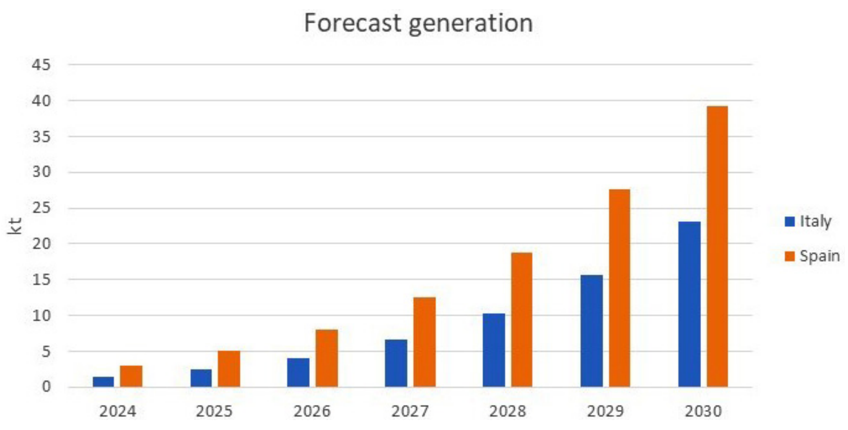

FIGURE 1: Forecast generation of Spanish and Italian PV waste from 2024 to 2030.

ent bibliographies (EVA Prices, Monitor, 2024) have been analyzed is displayed in Table 1.

Not all the Secondary Raw Materials (SRM) listed in the previous table present potential for valorization. The ethylene vinyl acetate (EVA) and the polyvinyl fluoride (PVF) are not always recoverable from the thermal processes applied for the PV waste recovery (Majewski et al., 2021; Latunussa et al., 2016). The recycling yield of each material indicated in the previous table is based on the bibliography (Domínguez et al., 2019; Choi et al., 2014). However, it is strongly dependent on the recycling technique. Moreover, Silicon and Silver show very high recycling rate, which can not be reached with standard mechanical techniques but with a reduction technology expected in 2026 (Domínguez et al., 2019).

The combination of the recycling yield with the current price of basic materials and metals (US Geological Survey, 2023; Mineral Commodity Summaries, 2024; Di Giuseppe, 2020; Recycling, 2024) provides an initial estimation of the PV waste value of 748,07 €/ t.

Based on the waste production data per year, the expected business opportunity from PV recycling for each country is shown in Table 2.

Considering only the potential revalorization of metals and glass for the estimated PV waste generation, the potential business opportunity for PV waste recycling in Italy, together with Spain, is around 133 M€.

However, another study established a maximum OPEX of 596 €/t to produce silicon of metallurgy grade (Spath et al., 2022), which would reduce the PV waste recycling business in Spain and Italy to around 27 M€ in the next six years.

All this underlines the importance and fundamental role of recycling technologies. It also shows that they will be a key factor in solving the waste management problem. However, there is room for improvement in terms of economic viability, the key factor being the development of improved technologies for the recovery of the various components.

Several promising techniques for the recovery of the main metals are currently available in Europe (Aravelli et al., 2021; Dias et al., 2019; Dias et al., 2018; Dias et al., 2016). One of these opportunities is developed in the PARSIVAL project, whose main objective is to recover and recycle silicon from solar cells and reuse it for different applications such as Li-ion batteries, ferroalloys, and after a purification process, again in PV cells.

4. CONCLUSIONS

This research shows that with the development of solar PV energy in Europe and the installations made during the 2000s, especially in Spain and Italy, they will face the challenge of the imminent generation of waste from PV panels. By 2030, these two countries will account for around 65 kt of PV waste.

Proper management of this waste is essential to raise a sustainable business model along the entire value chain and also to achieve the actual transition to clean energies. Although this management can be a challenge, it creates an opportunity for a source of Secondary Raw Materials.

TABLE 1: General composition of PV waste and unit value of the components in the market.

Secondary Raw Materials (SRM)	Composition (kg/t)	Recycling yield (%)	PV waste value (€/ PV t)	Stock Price (€/ton)
Glass	739,42	96,96%	46,60	65,00
Al	166,30	100,00%	402,20	2.418,55
Cu	20,96	88,89%	122,26	6.562,02
Ethylene vinyl acetate (EVA)	81,76			3.166,67
Polyvinyl fluoride (PVF)	35,27			8,26
Si metal	39,96	92,31%	144,11	3.907,08
Ag	0,06	95,00%	32,90	588.119,66
Others	11,60			
Total	1000		748,07	

TABLE 2: Estimation of the PV waste value per year in the Spanish and Italian market.

Secondary Raw Materials (SRM)	Italy (€)	Spain (€)	Total (€)
2024	1.054.380	2.299.634	3.354.015
2025	1.822.489	3.782.871	5.605.360
2026	3.040.429	6.036.272	9.076.702
2027	4.909.806	9.355.719	14.265.525
2028	7.691.330	14.092.824	21.784.154
2029	11.705.538	20.628.461	32.334.000
2030	17.321.172	29.316.754	46.637.926
Total	47.545.145	85.512.538	133.057.684

This business opportunity should be deeply analysed, considering not only the income but also the operating costs.

From the PV waste components with recycling potential, aluminium is the most valuable element because of its high content, and silver due to the high-market value of the metal. Silicon and copper are important, not only due to their economic value but also due to their supply risk in the EU, which makes them Critical Raw Materials. Currently, the PV waste value is estimated to be around 748 €/t.

Currently, there are several PV waste recycling techniques in development, and the main challenge is to develop a recycling process with low operative costs to make it economically feasible for SRM recovery. The PARSIVAL project is an example of this and could improve the sustainable supply of raw materials to the EU.

In any case, the business potential in Italy and Spain over the next five to six years is promising. Approximately 85 M€ (gross revenues) can be obtained for PV waste treatment.

There are several issues that are out of the scope of this publication but should be analysed in order to better understand the future of this waste. Firstly, a deep study and validation of the model used for waste forecasting is needed. This model could be applied to other countries of the EU to analyse the business potential as a whole. In addition, an in-depth analysis of the recycling techniques is needed to identify the value of the products (metals) obtained. In particular, the grade of silicon metal obtained from the PV waste recycling is a key parameter. Finally, it is necessary to know the costs of the recycling operations in order to analyse the overall economic viability.

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REFERENCES

Balthasar, A.; Schreurs, M.A.; Varone, F. Energy Transition in Europe and the United States: Policy Entrepreneurs and Veto Players in Federalist Systems. 2019.

Wolniak, R.; Skotnicka-Zasadzień, B. Development of Photovoltaic Energy in EU Countries as an Alternative to Fossil Fuels. 2022.

Kumar, B. A study on global solar PV energy developments and policies with special focus on the top ten solar PV power producing countries. 2014.

Hinrichs-Rahlwes, R. Renewable energy: Paving the way towards sustainable energy security. 2012.

Młynarski, T. MLYNARSKI Unia Europejska w procesie transformacji 2019. 2019.

Madsen, D.N.; Hansen, J.P. Outlook of solar energy in Europe based on economic growth characteristics. 2019.

EurObservER. Photovoltaic barometer 2023. 2023. Available online: https://www.eurobserv-er.org/photovoltaic-barometer-2023/.

Ministerio de Industria, Turismo y Comercio. Real Decreto 1578/2008, de 26 de septiembre, de retribución de la actividad de producción de energía eléctrica mediante tecnología solar fotovoltaica para instalaciones posteriores a la fecha límite de mantenimiento de la retribución del Real Decreto 661/2007, de 25 de mayo, para dicha tecnología. 2008.

Ministerio de Industria, Turismo y Comercio. Real Decreto 661/2007, de 25 de mayo, por el que se regula la actividad de producción de energía eléctrica en régimen especial. 2007.

Sultan, S.M.; Abdullah, M.Z. A new method for assessing photovoltaic module cooler based on lifespan effectiveness factor. 2022.

Marcuzzo, R.; de Araujo, W.C.; Maldonado, M.U.; Vaz, C.R. A multi-country simulation-based study for end-of-life solar PV panel destination estimations. Sustainable Production and Consumption 2022, 33, 531-542, DOI 10.1016/j.spc.2022.07.021. Available online: https://www.sciencedirect.com/science/article/pii/S2352550922001956.

Chowdhury, M.S.; Rahman, K.S.; Chowdhury, T.; Nuthammachot, N.; Techato, K.; Akhtaruzzaman, M.; Tiong, S.K.; Sopian, K.; Amin, N. An overview of solar photovoltaic panels' end-of-life material recycling. Energy Strategy Reviews 2020, 27, 100431, DOI 10.1016/j.esr.2019.100431. Available online: https://www.sciencedirect.com/science/article/pii/S2211467X19301245.

Santos, J.D.; Alonso-García, M.C. Projection of the photovoltaic waste in Spain until 2050. 2018.

Paiano, A. Photovoltaic waste assessment in Italy. 2014.

Masoumian, M.; Kopacek, P. End-of-Life Management of Photovoltaic Modules. IFAC-PapersOnLine 2015, 48, 162-167, DOI 10.1016/j.ifacol.2015.12.076. Available online: https://www.sciencedirect.com/science/article/pii/S2405896315027007.

Corcelli, F.; Ripa, M.; Leccisi, E.; Cigolotti, V.; Fiandra, V.; Graditi, G.; Sannino, L.; Tammaro, M.; Ulgiati, S. Sustainable urban electricity supply chain – Indicators of material recovery and energy savings from crystalline silicon photovoltaic panels end-of-life. Ecol Ind 2018, 94, 37-51, DOI 10.1016/j.ecolind.2016.03.028. Available online: https://www.sciencedirect.com/science/article/pii/S1470160X16301327.

Peeters, J.R.; Altamirano, D.; Dewulf, W.; Duflou, J.R. Forecasting the composition of emerging waste streams with sensitivity analysis: A case study for photovoltaic (PV) panels in Flanders. Resour Conserv Recycling 2017, 120, 14-26, DOI 10.1016/j.resconrec.2017.01.001. Available online: https://www.sciencedirect.com/science/article/pii/S0921344917300010.

Majewski, P.; Al-shammari, W.; Dudley, M.; Jit, J.; Lee, S.; Myoung-Kug, K.; Sung-Jim, K. Recycling of solar PV panels- product stewardship and regulatory approaches. Energy Policy 2021, 149, 112062, DOI 10.1016/j.enpol.2020.112062. Available online: https://www.sciencedirect.com/science/article/pii/S0301421520307734.

Domínguez, A.; Geyer, R. Photovoltaic waste assessment of major photovoltaic installations in the United States of America. Renewable Energy 2019, 133, 1188-1200, DOI 10.1016/j.renene.2018.08.063. Available online: https://www.sciencedirect.com/science/article/pii/S0960148118310139.

Choi, J.; Fthenakis, V. Crystalline silicon photovoltaic recycling planning: macro and micro perspectives. J Clean Prod 2014, 66, 443-449, DOI 10.1016/j.jclepro.2013.11.022. Available online: https://www.sciencedirect.com/science/article/pii/S0959652613007865.

Latunussa, C.E.L.; Ardente, F.; Blengini, G.A.; Mancini, L. Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels. Solar Energy Mater Solar Cells 2016, 156, 101-111, DOI 10.1016/j.solmat.2016.03.020. Available online: https://www.sciencedirect.com/science/article/pii/S0927024816001227.

US Geological Survey. MINERAL COMMODITY SUMMARIES 2023. 2023. Available online: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://pubs.usgs.gov/periodicals/mcs2023/mcs2023.pdf.

Mineral Commodity Summaries 2024. 2024. Available online: https://pubs.usgs.gov/periodicals/mcs2024/mcs2024.pdf.

Di Giuseppe, D. Characterization of Fibrous Mordenite: A First Step for the Evaluation of Its Potential Toxicity. Crystals 2020, 10, DOI 10.3390/cryst10090769.

Recycling – secondary material price indicator. 2024. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Recycling_%E2%80%93_secondary_material_price_indicator.

Ethylene vinyl Acetate (EVA) Price and forecast. 2022. Available online: https://www.chemanalyst.com/Pricing-data/ethylene-vinyl-acetate-74#:~:text=VAE%20in%20Europe%20price%20hovered,3420%2FMt%20during%20March%202022.&text=North%20America%20saw%20an%20increase,Texas%20in%20the%20first%20quarter.
Spath, M.; Wieclawska, S.; Sommeling, P.; Lenzmann, F. Balancing costs and revenues for recycling end-of-life PV panels in the Betherlands. 2022. Available online: https://www.stichting-open.org/wp-content/uploads/2022/12/22-12822_tno_rapport_recycling_zonnepanelen_-def.pdf.
Aravelli, S L K Gopalamma; Ramavathu, S.N. Smart and sustainable technologies for recycling photovoltaic panels. 2021.
Dias, P.; Veit, H. Recycling Crystalline Silicon Photovoltaic Modules. 2019.
Dias, P.; Schmidt, L.; Gomes, L.B.; Bettanin, A.; Veit, H.; ´a, A.; Bernardes, M. Recycling Waste Crystalline Silicon Photovoltaic Modules by Electrostatic Separation. 2018.
Dias, P.; Javimczik, S.; Benevit, M.; Veit, H.; Bernardes, A.M. Recycling WEEE: Extraction and concentration of silver from waste crystalline silicon photovoltaic modules. 2016.