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The Importance of Photovoltaic Solar Panel Recycling in Romania: Aligning with the Green Deal and Fit for 55 Strategies

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Abstract. *Romania's flourishing solar energy sector necessitates responsible management of photovoltaic (PV) panel waste. The research examines at the current level of PV panel recycling and anticipates future production of waste. By examining data on solar production capacity and panel characteristics, the study forecasts a significant rise in PV waste.*

Supportive legislation and rising environmental consciousness have contributed to increased PV installations, but regulating the waste produced is essential. The analysis predicts a jump in trash volume, reaching at least 32,892 tons by 2033, a stunning 2336% increase over 2024-2032.

This represents an exceptional chance for Romania to become a European leader in PV panel recycling. Romania could establish an innovative industry, acquire recycled materials for new panels, and encourage a circular solar energy economy if it optimizes its waste management.

Together with EU policies to promote the use of recycled materials in the production process of new panels, a national PV waste management strategy needs to be developed, with collaboration between government, industry and environmental organizations.

This paper provides significant insights for participants in Romania's solar energy market. By identifying the challenges as well as opportunities relating to PV waste management, interested parties could collaborate proactively to build an economically viable future for solar energy in Romania.

Keywords: renewable energy, photovoltaic, recycling, circular economy.

Introduction

We are witnessing the balance of electricity generation starting to shift in favor of green power generation, with solar energy taking one of the top spots. Supporting green energy at the expense of conventional energy is also reflected in the Romanian government's policy of supporting the upward trend of building photovoltaic installations. Although solar energy provides a green and environmentally friendly alternative to conventional energy sources, it also creates new concerns including managing the waste stream.

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Solar panels are composed of various materials, including silicon, glass, metals (e.g., aluminum, copper), and potentially hazardous substances like cadmium and lead. The incorrect elimination of these panels might cause damage to the environment. Landfills are not suitable for solar panels due to the potential leaching of toxic materials into the soil and groundwater.

Photovoltaic solar panel recycling provides an environmentally friendly solution to working with this expanding waste stream. It facilitates the recuperation of valuable components such as silicon, which can subsequently be reinserted into the fabrication process, decreasing dependence on virgin resources. Recycling additionally decreases the negative ecological impact of extracting and manufacturing new resources.

The European Union (EU) has set ambitious goals for climate change mitigation through the European Green Deal and the Fit for 55 package. These initiatives highlight the shift to a circular economy, meaning that resources continue to be in circulation for as long as possible. Photovoltaic solar panel recycling aligns perfectly with these objectives by promoting resource efficiency and reducing reliance on landfills.

Romania, as a member state of the EU, is obligated to comply with these environmental directives. Establishing a strong photovoltaic solar panel recycle system is critical for Romania in order to fulfill its sustainability responsibilities while additionally contributing to the EU's goals regarding climate change. A well-established recycling sector may also provide new opportunities for economic growth, create employment opportunities, and promote Romania as a leader in the regenerative economy of solar energy. The presented research seeks to examine at the present situation regarding photovoltaic solar panel recycling in Romania. It will analyze the current recycling infrastructure, policies, and challenges as well. The research will additionally examine the best practices implemented in other EU member states and possible approaches to implement a reliable and environmentally friendly photovoltaic solar panel recycling industry in Romania.

This paper has significance because it provides an exhaustive examination of the present scenario and prospective approaches, which may help to shape policy and guide interested parties in Romania's solar energy industry. A strong recycling strategy will guarantee the sustainable future of Romania's solar energy transformation and assist accomplish the EU's Green Deal and Fit for 55 objectives.

Literature Review

Solar Energy Growth and Waste Generation

The global solar PV market is experiencing exponential growth. According to the International Energy Agency (IEA, 2022), the cumulative installed solar PV capacity reached 392 gigawatts (GW) in 2021. This rapid growth is expected to continue, with projections suggesting that solar PV will be the dominant source of electricity generation by 2050 (REN21, 2022). Yet, this upward trajectory generates concerns about the rising number of end-of-life solar panels that are getting disposed. A study by WMG, University of Warwick, estimates that global solar panel waste will reach 78 million metric tons by 2030 (Warwick Manufacturing Group (WMG), University of Warwick, 2016).

Environmental Impact of Improper Disposal

Improper disposal of solar panels can have detrimental environmental consequences. Landfills are not suitable for these panels due to the presence of hazardous materials like cadmium and lead. These materials can leach into the soil and groundwater, contaminating water resources and posing health risks (Hernandez et al., 2016). Additionally, the glass and plastic components of solar panels

take centuries to decompose in landfills, occupying valuable space and hindering waste management efforts (Leal Filho et al., 2019).

Advantages of PV Panel Recycling

PV panel recycling provides a long-term solution for the management of PV waste. Recycling allows the recovery of valuable materials like silicon, which accounts for a significant portion of a solar panel's cost and environmental footprint (European Copper Institute, 2021). Recycled silicon can be reintroduced into the manufacturing process, reducing reliance on virgin resources and minimizing the environmental impact associated with mining and processing new materials (PV Cycle, 2023). Additionally, recycling conserves energy and reduces greenhouse gas emissions compared to virgin material production (Xing et al., 2022).

EU Directives and the Circular Economy

The EU has established itself as a leader in promoting sustainable waste management practices. The Waste Framework Directive (2008/98/EC) sets ambitious targets for waste reduction and recycling, including the development of specific waste streams like end-of-life vehicles and electronic waste (European Commission, 2008). The Circular Economy Action Plan (2020) further emphasizes the importance of transitioning to a circular economy, where resources are used more efficiently and waste generation is minimized (European Commission, 2020). This plan specifically identifies solar panels as a priority waste stream and calls for the development of harmonized standards and regulations for their collection, treatment, and recycling (European Commission, 2020).

Best Practices in Photovoltaic Solar Panel Recycling

Several EU member states have adopted successful approaches to photovoltaic solar panel recycling. Germany, for instance, has implemented a well-established take-back system where producers are responsible for collecting and recycling waste panels (Photovoltaik-Geräteverordnung (PvG), 2016). This system is financed through a pre-paid levy incorporated into the sale price of new panels. France has adopted a similar approach, with a focus on traceability and producer responsibility (Arrêté du 23 février 2010 relatif aux conditions de prise en charge des panneaux solaires photovoltaïques usagés, 2010). Additionally, research and development efforts are underway to improve recycling technologies and maximize resource recovery rates (European Photovoltaic Industry Association (EPIA), 2023).

Challenges and Opportunities in Romania

While the EU directives set a clear direction, significant challenges remain in implementing a robust photovoltaic solar panel recycling system in Romania. A particular issue is the absence of established facilities for gathering, transporting, and processing PV waste. Additionally, there is a need for clear regulations regarding producer responsibility and waste management practices specific to solar panels (Apostol et al., 2021).

Although these drawbacks, Romania has the chance to acquire knowledge from successful models in other EU member states and establish a sustainable and effective recycling system. Encouraging development and research efforts in this field may outcome in innovative concepts and more effective recycling approaches. Furthermore, establishing a well-functioning recycling industry can create new economic opportunities, generate jobs, and position Romania as a leader in the circular economy of solar energy (Brumana et al., 2022).

Knowledge Gaps and Future Research Directions

Several knowledge gaps exist regarding photovoltaic solar panel recycling in Romania. Limited data is available on the current volume and composition of end-of-life solar panels in the country. Additional research is required for assessing the sustainability of the economy and the environment of the various recycling mechanisms in Romania. Furthermore, the social embrace and general awareness of solar panel recycling demand a closer look.

Any additional study that addresses these information deficits may serve clarify policy makers and assist participants in the Romanian solar energy market. This research is able formulate a systematic national scheme to promote photovoltaic solar panel recycling, promising the long-term viability for solar energy in Romania and fitting Romania with the EU's Green Deal and Fit for 55 targets.

Methodology

This paper utilizes an exploratory research approach to identify and analyze how PV panel recycling is carried out in Romania. By utilizing data from a combination of publicly available sources (e.g., Eurostat) and private sources, the study aims to assess the quantity of PV waste generation and identify existing infrastructure gaps within the country.

Data Acquisition and Analysis

The research applies a multi-step data acquisition and analysis process:

1. **Solar Production Capacity:** Historical data on Romania's solar energy production capacity in Megawatts (MW) for the period 2012-2022 was retrieved from Eurostat. For prosumers section, the period 2022 – 2024, the data was retrieved from ANRE reports. Specialists from the ANRE estimate that in 2024, photovoltaic systems installed by prosumers will reach an installed capacity of over 2,500 megawatts (MW)
2. **Yearly Installed Capacity:** Year-on-year differences in PV energy production were calculated to estimate the annual increase in installed PV panel capacity.
3. **Estimation of Installed Panels:** Building upon the work of Divya et al. (2023), three potential power ratings (200 W, 300 W, and 400 W) per panel were considered to estimate the yearly number of installed PV panels in Romania.
4. **Estimation of Installed Weight:** Corresponding to the assumed power ratings, three weight estimations (15 kg, 20.5 kg, and 22.5 kg) per panel were used to calculate the total annual tonnage of installed PV panels in Romania from 2012 to 2024.
5. **PV Waste Estimation:** A standard industry failure rate of 0.05% (Jacob Mars, Casey McDevitt, 2024) per year was applied to estimate the total quantity of PV waste expected after a 20-year lifespan, which represents the average lifespan of PV panels.

Additionally, prosumer data from 2022 to 2024 was retrieved and analyzed using the same calculation methods.

Table 1. The evolution of the solar production capacity in Romania

Reported Year	Solar production capacity (MW) (1)	Type of production	Yearly installed solar capacity (MW) (2)	Average capacity per panel (W) (3)	Number of installed PV panels (4) = (2)/(3) * 1000000	Weight per PV panel (kg) (5)	Total weight of PV panels (tons) (6) = (4)/(5)	Defects per year (tons) (7) = (6) * 0.05%	PV waste after 20 years (tons) (8) = (6) - ((7)*20)	End-of-use Year
2012	8.00	industrial	8.00	200.00	40,000.00	15.00	600.00	0.30	594.00	2032
2013	451.00	industrial	443.00	200.00	2,215,000.00	15.00	33,225.00	16.61	32,892.75	2033
2014	838.00	industrial	387.00	200.00	1,935,000.00	15.00	29,025.00	14.51	28,734.75	2034
2015	888.00	industrial	50.00	300.00	166,666.67	20.50	3,416.67	1.71	3,382.50	2035
2016	918.00	industrial	30.00	300.00	100,000.00	20.50	2,050.00	1.03	2,029.50	2036
2017	1,014.00	industrial	96.00	300.00	320,000.00	20.50	6,560.00	3.28	6,494.40	2037
2018	1,029.00	industrial	15.00	300.00	50,000.00	20.50	1,025.00	0.51	1,014.75	2038
2019	1,030.00	industrial	1.00	300.00	3,333.33	20.50	68.33	0.03	67.65	2039
2020	1,034.00	industrial	4.00	300.00	13,333.33	20.50	273.33	0.14	270.60	2040
2021	1,078.00	industrial	44.00	400.00	110,000.00	22.50	2,475.00	1.24	2,450.25	2041
2022	1,988.00	industrial	910.00	400.00	2,275,000.00	22.50	51,187.50	25.59	50,675.63	2042
				Total industrial:	7,228,333.33		129,905.83	64.95	128,606.78	
2022	478.00	prosumers	478.00	400.00	1,195,000.00	22.50	53,111.11	13.44	26,618.63	2042
2023	1,225.68	prosumers	747.68	400.00	1,869,200.00	22.50	42,057.00	21.03	41,636.43	2043
2024	2,500.00	prosumers	1,274.32	400.00	3,185,800.00	22.50	71,680.50	35.84	70,963.70	2044
				Total prosumers:	6,250,000.00		166,848.61	70.31	139,218.75	
				Total:	13,478,333.33		296,754.44	135.27	267,825.53	

Source: Authors' own research.

Results and discussions

Between 2012 and 2013, the number of installed PV panels increased significantly, from 40,000 to 2,215,000 panels. Due to the requirement to achieve green generation standards and reduce CO2 emissions, PV integration inside distribution networks has expanded in this period. By growing the percentage of renewable energy sources, the green certificate as a tradable technique enhanced environmental factors in addition to the widespread usage of PV units. Companies use green certificates to certify that a specific amount of electrical energy is produced from renewable resources. It should be mentioned that a significant part of the income of the companies that produce electricity from renewable resources results from the trading of green certificates.

Producers of electricity from renewable energy sources and companies required to buy green certificates are permitted to trade green certificates in a transparent, centralized, and non-discriminatory manner on the centralized markets run by the electricity market's commercial operator.

Companies may take in consideration investing in green certificates for the following reasons:

- compliance meaning that the company can meet the legal requirements that require to obtain a percentage of energy from renewable sources without generating a supplementary cost generated by the renewable energy infrastructure.
- marketing/branding.
- diversification meaning that it can help companies to lower the risks associated with the fluctuation in energy price. Subsequently, it may additionally help organizations manage future standards focused on reducing carbon emissions.
- emphasizing environmental responsibility. It helps enterprises communicate to the public, current and upcoming investors, and other interested parties that they promote energy from renewable sources and minimize their carbon footprint.

Following 2013, there is a general variation in the number of installations, reflecting legislative changes.

The peak years for PV panel installations are 2013 and 2022, with 2,215,000 and 2,275,000 panels installed. This result might be attributed to high market demand, favorable policies, technical breakthroughs and lowering prices of solar energy systems or a mix of all the above - might all contribute to the overall rise seen in the figure above.

The Romanian National Energy Regulatory Authority (ANRE) has established the standard for reducing the yearly limit of green certificates between 2013 until 2019. The objective was that this measure would translate into lower energy costs for the end user, whether they are residential or commercial. The quota was cut even more dramatically in 2014 and 2015, however energy prices (for consumers) did not go down at that time. As a result, producers of power from renewable sources suffered greatly as a result of ANRE's choices, since their income from certificates was significantly cut.

When Romania joined the EU in 2007, it gained access to the carbon emission allowance scheme. The free allowances apply to the same five industries that pollute the most: energy, chemicals, metal and iron, car manufacturing, pulp and paper, which are considered major polluters, with installations totaling more than 20 megawatts.

Since 2019, carbon emission certificates have been assimilated to financial assets, which has immeasurably increased speculative transactions, leading to an increase in price and, subsequently, to a decrease in supply. This is one of the reasons why after 2020, the expanding use of PV panels indicates a new increased interest in renewable energy sources and a potential move toward greener energy alternatives and an easy transition to a low carbon economy.

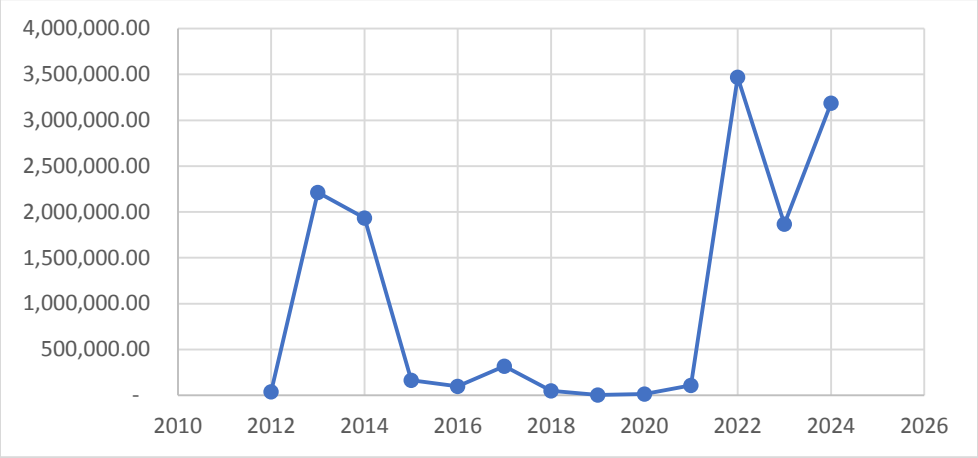
Thousands of certificates are traded between Romanian enterprises on an extremely active certificate market. If the cost of a certificate was 15 euros during the COVID-19 epidemic, it increased to 90 euros at the start of 2022 and then stabilized at 79 euros.

The debut of the war in Ukraine and the effects of the energy crisis that our country faced in 2020, determined the need to obtain energy independence. This is another reason why the increase in the number of PV installed is noticeable.

Even though variations in installed capacity can be observed in the years under review, the general trend is an increasing installation of PV panels in the coming years. The increase could be further stimulated by raising public awareness of the negative environmental impact of fossil fuel-based power generation.

In order to achieve cheap and sustainable electricity, it is essential to know the dynamics of the PV panel market, a relatively young market in the economic environment, where competition between panel manufacturers can generate significant progress in the development of new technologies to increase the power output, lifetime and efficiency of panels.

Chart 1. The number of photovoltaic panels installed in Romania during the period 2012-2024 (2023-2024 only panels installed by prosumers are registered)

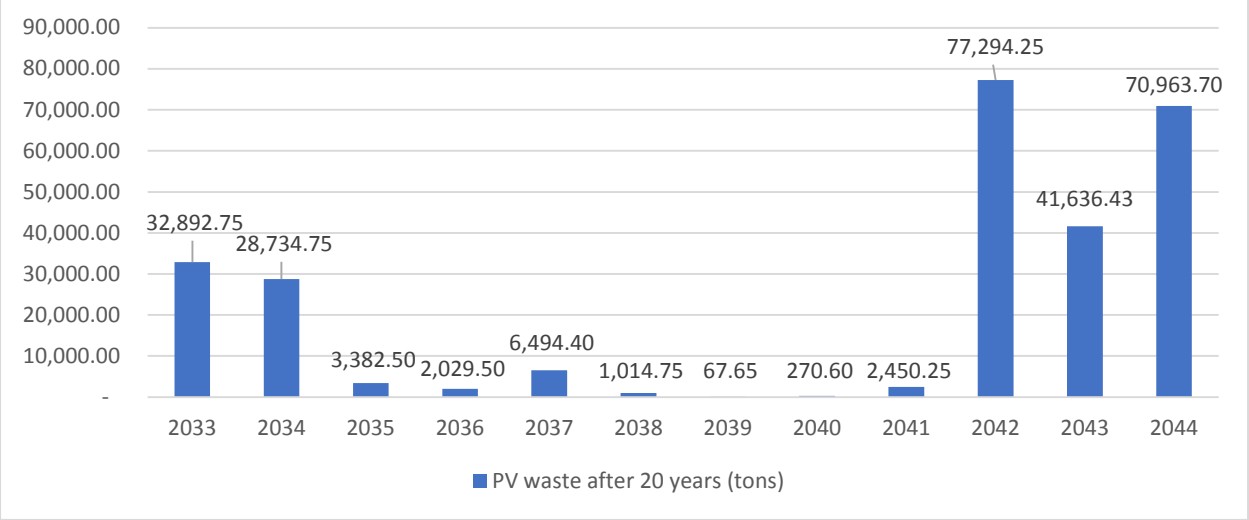


Source: Authors' own research.

PV Waste Generation

The study estimates a rising trend in PV waste generation in Romania over the coming years (2033-2042). Furthermore, it is observed that, based on the number of photovoltaic panels installed in the period 2022 - 2024, at least 135 tons of waste are generated each year.

Chart 2. Estimated PV waste panels in Romania during the period 2033-2044. (2043-2044 only estimated PV waste panels generated by the prosumers)



Source: Authors' own research.

Regarding the estimated PV waste in Romania for the period 2033-2042, the figure indicates a rising trend in PV waste generation each year, representing the growing quantity of PV panels that have reached the end of their useful life. This pattern corresponds with the anticipated rise in PV installations over time, which will raise waste production as a result.

There are significant increases in PV waste in particular years, like as 2033 and 2042, when waste tonnage grows remarkably. These increases might be attributed to three important variables: the timing of large-scale PV installations, the lifespan of certain PV panel generations and yearly failure rate of 0.05%.

Increasing accumulations of PV panel waste are creating a number of environmental problems from storage, recycling and management of the resulting materials. In this sense, there is a need to update existing laws with the new challenges, develop appropriate infrastructures for the proper management of PV panels that are taken out of use.

Anticipating the increase in the amount of waste from photovoltaic panels is the impetus for supporting research into the development of technologies that enable their efficient recycling and the recovery of resources that have been used for reuse in the production of new photovoltaic panels.

Conclusion

The exploratory research method was used to calculate the quantities of waste from the operation of photovoltaic panels that will be generated in the next few years, based on the power plants already installed and to identify the year when Romania will face a real problem in managing this waste. Thus, the study highlighted the following aspects:

- Increasing number of photovoltaic panels installed: Financial mechanisms to support the growth of solar electricity production as well as rising conventional electricity prices have led to the installation of an increasing number of photovoltaic panels.
- Market Dynamics: Understanding competition, price fluctuations, and emerging technologies in the solar panel market is crucial for informing future trends and opportunities.
- PV Waste Generation: With the construction of the new solar power generation facilities, it is necessary to develop solutions for the proper management and recycling of PV panel waste.
- Partnership and Innovation: By working together with key stakeholders (government agencies, PV panel importers and manufacturers, solar electricity producers, the recycling industry and environmental organizations), can be identified the optimal solutions to the challenges associated with the amount of PV panel waste.
- Policy Recommendations: Supportive policies, research & development, infrastructure development, and public awareness campaigns are crucial for ensuring the sustainable growth of the solar energy sector in Romania.

Projecting Waste Generation

The study allowed us to identify that in the coming years there will be a significant increase in the generation of PV panel waste, showing that by 2032 at least 1350 tons of PV panels will be produced in Romania. While this initial amount may not necessitate the immediate development of a dedicated recycling facility, the situation changes dramatically in 2033. In that year, the projected waste volume jumps to at least 32,892 tons, reflecting a staggering 2336% increase compared to the total waste generated between 2024 and 2032.

Opportunities and Challenges

The results of the research can be interpreted both as challenges and as new opportunities for Romania. The gradual increase in quantities until 2032 gives Romania time to develop an efficient waste management system, where the collection infrastructure, the development and application of new recycling technologies and the re-introduction of recycled materials into the production chain are well established.

Romania as a Recycling Hub

However, this challenge also presents a significant opportunity. Moreover, as there is currently no pressure on significant quantities of PV panel waste, by developing a modern PV panel recycling industry, Romania has the opportunity to become a major player in this field. This could involve servicing both domestic waste and potentially accepting waste from other European countries. With a strong recycling infrastructure, Romania could secure a reliable source of recycled materials to produce new solar panels, fostering a circular economy within the solar energy sector.

Recommendations and Future Policy Directions

To capitalize on this opportunity, several key recommendations emerge:

- Government and Industry Collaboration: In order to avoid a real problem regarding the lack of infrastructure for managing future quantities of photovoltaic panel waste, it is necessary to develop a strategy in this area, within which there is cooperation between the Romanian Government and private sector stakeholders.

- Research and Development: Investing in research and development efforts focused on optimizing PV recycling technologies specific to the Romanian context is crucial.
- Public Awareness Campaigns: Developing public awareness campaigns on the responsible management of PV panel waste and the economic and financial benefits of recycling.

EU Policy Considerations

Furthermore, the European Union (EU) can play a vital role in fostering PV panel recycling. Policy development at the EU level should encourage PV panel manufacturers to incorporate recycled materials into new panel production. This would create a robust market demand for recycled materials, further incentivizing investment in the recycling infrastructure, as we can see right now in the rPET market.

By implementing these recommendations, Romania has the potential to avoid the challenges associated with PV waste management and become part of the solution to overcome this challenge, which several Western European countries are currently facing. Moreover, the Romanian state would contribute to the development of a more sustainable solar electricity sector based on the principles of the circular economy.

Future Research Directions

This study serves as a starting point for further research in this domain. Several areas warrant further investigation:

- Detailed Waste Composition Analysis: A more comprehensive analysis of the composition of PV waste generated in Romania is needed to optimize recycling processes and recover valuable materials.
- Economic Feasibility of Recycling: More research studies need to be carried out to increase the economic feasibility of recycling photovoltaic panels and to develop new technologies that will make it possible to recover as much as possible of all the resources used in the production of the panels.
- Life Cycle Assessment of PV Systems: Conducting a life cycle assessment of PV systems in Romania can provide a holistic evaluation of their environmental impacts, including waste generation.

By developing new research directions, significant contributions can be made to the sustainability of the energy sector and the identification of new economic growth opportunities associated with the management and recycling of photovoltaic panels.

References

Apostol, L., Gnandt, M., & Papandreou, Z. (2021). Challenges and opportunities for a circular economy of solar panels in Romania. Journal of Cleaner Production, 280, 124323.

Brumana, D., Waeijen, F., Mugerauer, A., & Bertram, M. (2022). A review of solar panel recycling in the European Union: Current state and future perspectives. Resources, Conservation and Recycling, 185, 104480.

European Commission. (2008). Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Waste Framework Directive). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32008L0098

European Commission. (2020). Circular Economy Action Plan. https://ec.europa.eu/newsroom/know4pol/items/664852

European Copper Institute. (2021). Photovoltaic Recycling in Europe. https://www.intersolar.de/home

European Photovoltaic Industry Association (EPIA). (2023). Photovoltaic Recycling in Europe. https://www.europeansources.info/record/website-european-photovoltaic-industry-association-epia/

Hernandez, L. L., et al. (2016). Environmental risk assessment of cadmium telluride (CdTe) photovoltaic modules. Progress in Photovoltaics: Research and Applications, 24(11), 887-900.

International Energy Agency (IEA). (2022). World Energy Outlook 2022. https://www.iea.org/reports/world-energy-outlook-2022

Leal Filho, W., Müller, A., & Pocioly, L. (2019). Addressing the challenge of end-of-life solar panels: A comprehensive review. Sustainability, 11(22), 6523. https://doi.org/10.3390/su11226523

Photovoltaik-Geräteverordnung (PvG) [German Ordinance on Photovoltaic Devices]. (2016). Bundesministerium der Justiz und für Verbraucherschutz. [In German]. https://www.sonnenenergie.de/sonnenenergie-redaktion/SE-2016-06/Layout-fertig/PDF/Einzelartikel/SE-2016-06-s014-DGS_Service-01.pdf

PV Cycle. (2023). The environmental benefits of recycling solar panels. https://pvcycle.org/

REN21. (2022). Renewables 2022 Global Status Report. https://www.ren21.net/reports/global-status-report/

Warwick Manufacturing Group (WMG), University of Warwick. (2016). Global Waste Solar Panels Recycling. https://www.sciencedirect.com/science/article/pii/S0956053X18300576

Xing, Y., Han, L., & Li, H. (2022). Life cycle assessment of recycling crystalline silicon solar panels: A review. Resources, Conservation and Recycling, 180, 106223.

Divya, A., Adish, T., Kaustubh, P., & Zade, P. S. (2023). Review on recycling of solar modules/panels. Solar Energy Materials and Solar Cells, 253, 112151.

Marsh, J., McDevitt, C. (2024). How often do solar panels fail? https://www.energysage.com/solar/average-solar-panel-failure-rate/

Eurostat, https://ec.europa.eu/eurostat/databrowser/view/nrg_inf_epc__custom_10768460/default/table?lang=en

ANRE report (2023). Situația privind promovarea energiei electrice produse de capacități electrice din surse regenerabile aparținând prosumatorilor la data de 30.09.2023. https://anre.ro/wp-content/uploads/2023/11/Situatie-prosumatori-30.09.2023.pdf