Photovoltaic Panel Recycling: A Crucial Component for Achieving EU Sustainable Development Strategies

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Abstract

In the context of transitioning towards a more sustainable Europe, proper recycling of photovoltaic solar panels (PV) becomes an essential priority across the entire European Union. The EU member states are committed to increasing their green energy production, and the European Union's ambitious goal of reducing greenhouse gas emissions by 55% by 2030 further underscores the urgency. However, the rapid proliferation of PV installations raises concerns about end-of-life panel management and potential environmental hazards if not addressed adequately.

This article aims to present a comprehensive overview of the current state of challenges and deficiencies by assessing regulatory frameworks such as the Waste Electrical and Electronic Equipment (WEEE) Directive as well as current recycling practices across Member States. Furthermore, it is analyzing the installation dynamics of PV panels during the last decade and forecasts future patterns to predict possible recycling demands over the next 20 years. The findings highlight the importance of strong recycling infrastructure and legislative improvements to ensure the EU accomplishes its ambitious sustainability targets. This study adopts the framework of applied research that includes components of policy analysis and forecasting.

Investments in recycling infrastructure not only contribute to environmental protection but also create jobs and recover valuable resources. Collaborations with other European countries will yield economic benefits and strengthen international relations. By aligning with EU directives and leveraging national commitments to green energy, the European Union can position itself as a global leader in efficient photovoltaic solar panel recycling, contributing to a more sustainable world and achieving the goals of the Green Deal and Fit for 55 initiatives

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

JEL Classification: O13, P18, P48, Q53.

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1. Introduction

The European Green Deal positions renewable energy as the foundation of Europe's transition towards climate neutrality. Among renewable sources, solar photovoltaics have experienced the steepest cost decline and the highest deployment rate. Between 2010 and 2023 the levelised cost of PV electricity in the EU fell by over 80%, prompting widespread adoption across residential, commercial, and utility sectors (European Commission, 2024). Yet this success introduces a deferred environmental liability: millions of panels will soon reach end-of-life (EoL), demanding systematic collection and recycling.

Photovoltaic modules have an average operational lifetime of 20–30 years. Panels installed during the early expansion phase (2010–2015) are expected to enter the waste stream after 2030. Without effective recycling mechanisms, the EU risks replacing one sustainability issue—fossil-fuel dependence—with another: material scarcity and hazardous waste accumulation. EoL modules contain valuable raw materials such as aluminium, glass, silver, and silicon but also hazardous substances including lead (Pb) and cadmium (Cd). Improper disposal can lead to soil and groundwater contamination, while the loss of recoverable resources undermines the EU's Critical Raw Materials Act (2023).

Consequently, PV recycling serves dual objectives: environmental protection and strategic autonomy in raw materials. By converting end-of-life modules into secondary resources, the EU can reduce import dependency, cut greenhouse-gas emissions, and stimulate green-sector employment. However, these benefits hinge on cohesive legislation, infrastructure investment, and technological innovation.

The transition to renewable energy is a key component of the European Union's goal of sustainable development towards a more sustainable and environmentally friendly economy, particularly PV solar panels play a significant part in this transformation. As the implementation of solar energy expands, so does the demand for efficient end-of-life management of solar PV panels. Recycling these panels is more than a technical requirement, but also a critical component in achieving the EU's overall sustainable development goals.

The European Green Deal and the Fit for 55 initiatives emphasize the significance of circular economy concepts, that involve recycling solar PV panels as a critical component in decreasing waste, preserving resources, and decreasing the environmental effect of the production of energy.
The EU's commitment to increasing green energy production, coupled with the objective of reducing greenhouse gas emissions by 55% by 2030, underscores the

urgency of developing effective end-of-life management strategies for PV panels. This urgency is driven by the rapid proliferation of PV installations across member states, which raises concerns about the management of these panels once they reach the end of their lifecycle and the potential environmental hazards if not addressed adequately.

This article aims to present a comprehensive overview of the current state of PV panel recycling within the European Union. It will estimate the number of panels installed from 2012 to the present, assess the quantities of PV waste expected in the coming decades, and identify gaps in the existing recycling infrastructure. By analyzing the legislative framework and policies driving the transition to renewable energy, we emphasize the critical role of comprehensive recycling systems in achieving sustainability objectives. Additionally, we highlight the inherent economic opportunities in PV recycling investments, including job creation and resource recovery. By aligning with EU directives and leveraging national commitments to green energy, the European Union can position itself as a global leader in efficient PV solar panel recycling, thereby contributing to a more sustainable world and achieving the goals set out in the Green Deal and Fit for 55 initiatives.

2. Literature review

The increasing use of photovoltaic (PV) panels in the European Union (EU) has led to growing concerns about their end-of-life management. As solar panels reach their useful life, effective recycling strategies become essential to reduce environmental impact and recover valuable materials. This literature review examines the current state of solar panel recycling capacity in the EU and explores scientific advances in the development of new recycling technologies.
The European Union has adopted several methods and rules to manage the recycling of photovoltaic (PV) panels, recognizing the growing relevance of long-term end-of-life management for these critical components of renewable energy infrastructure. The essential components of contemporary recycling systems and regulations are:

2.1 Waste Electrical and Electronic Equipment (WEEE) Directive

The EU has established regulatory frameworks to manage the waste generated by PV panels, primarily through the WEEE Directive. This Directive requires the recycling of PV panels, setting targets for recovery and recycling rates (European Commission, 2018). From 2019, Member States are required to achieve an 85% collection rate for WEEE, including PV panels, and to ensure that 80% of these panels are ready for reuse and recycling (Photorama Project, 2024). Following this directive:

- PV panel makers are categorized as electronic equipment producers and are responsible for collecting, treating, recycling, and disposing of PV panels in an ecologically friendly manner at the end of their lives.
- The directive establishes specified collection and recycling objectives for Member States to ensure that a large portion of waste PV panels are appropriately collected and recycled.
- The WEEE Directive requires that all treatment and recycling operations adhere to stringent environmental requirements, including the safe handling of hazardous chemicals and the recovery of important raw materials such as silicon, silver, and aluminum.

Recycling capacity in the EU is estimated to handle significant volumes of PV waste. For instance, Germany and France have developed advanced recycling facilities. Veolia's plant in France, operational since 2018, has a capacity to recycle around 1,300 tons of PV panels annually (WEEE Forum, 2021). The European Commission aims to significantly increase recycling capacity, with targets to reach 30 GW of dedicated EU capacity by 2025, which would facilitate more recycling (European Commission, 2023).

2.2 Circular Economy Action Plan (CEAP)

CEAP is part of the European Green Deal and seeks to make sustainable goods the standard in the EU while also ensuring that resources are used as long as feasible. This plan highlights:

- Strengthening Extended Producer Responsibility (EPR) programs that hold producers accountable for their goods' whole lifespan, including the post-consumer phase.
- Encouraging the design of PV panels with recycling and material recovery in mind, hence increasing recyclability and lowering environmental impact.
- Promoting research and development in advanced recycling technologies to increase the efficiency and efficacy of PV panel recycling operations.

Current recycling procedures and regulations for PV panels in the EU are influenced by strong regulatory frameworks such as the WEEE Directive and the Circular Economy Action Plan. However, obstacles such as uneven implementation and technical impediments must be overcome to fully accomplish the EU's sustainability goals. Continued innovation and stricter enforcement of existing rules will be critical in improving the recycling of solar PV panels throughout Europe.

2.3 Challenges in recycling solar panels

Recycling solar panels presents several technical and economic challenges. The complex composition of PV panels, which includes materials such as silicon, glass and various metals, complicates the recycling process. Traditional recycling methods, which involve mechanical separation and thermal processing, often result in the loss of valuable materials and are not always economically viable (Chowdhury et al., 2020).

In addition, the lack of standardized recycling protocols across the EU exacerbates the problem, leading to inefficiencies and inconsistent recycling outcomes. Variability in panel material design and composition further complicates recycling efforts, requiring adaptable and innovative recycling technologies (MDPI, 2024).

2.4 Scientific progress in recycling technologies

Recent scientific advances have focused on improving the efficiency and effectiveness of solar panel recycling processes. A significant area of research is the development of chemical and biological recycling methods that can recover a higher percentage of valuable materials while minimizing environmental impact.

Chemical recycling techniques, such as the use of selective leaching agents, have shown promise in efficiently extracting metals such as silver and indium from PV panels (Dias et al., 2016). In addition, hydrometallurgical processes, which involve the use of aqueous chemistry, are being optimized to improve recovery rates of silicon and other critical materials (Bertram et al., 2020).

Biological methods, including the use of microorganisms and enzymes, emerge as sustainable alternatives to traditional recycling methods. These biological processes offer the potential to selectively degrade certain components of PV panels, facilitating the recovery of high-purity materials (Wang et al., 2019).

In addition, innovations in panel design, such as the development of modular and easily demountable panels, are being explored to improve recyclability. These designs aim to simplify the separation of different materials, making the recycling process more efficient and cost-effective (Sica et al., 2018).

2.5 Identified research gaps

Key deficiencies highlighted in the literature include: ***(1)*** lack of standardized recycling protocols; ***(2)*** limited economic data; ***(3)*** insufficient consumer awareness; and ***(4)*** slow adoption of eco-design. Emerging directions encompass closed-loop recycling, machine-learning for material sorting, and Life-Cycle Assessment (LCA) comparisons (Bertram et al., 2024).

3. Research methodology

Research questions/Aims of the research

In the context of the energy transition and the rapid growth of installed PV panel capacity in the EU, the management of waste from these panels is becoming a significant challenge. By utilizing data from publicly available sources (Eurostat), the study aims to assess the quantity of PV waste generation and identify existing infrastructure gaps within the EU. Utilizing an exploratory research approach to identify and analyze how PV panel recycling is carried out in the context of EU sustainable development policies. The technique includes the following critical components:

1. Analyze historical data on installations of solar panels in the EU over the previous decade to generate a baseline for the purpose of the research.
2. Utilize official publications from EU authorities along with private sector to obtain precise information on the estimated lifespan and degradation rates of solar PV panels.
3. Apply statistical models to forecast the future volume of solar PV panels in the EU over the next 20 years, accounting for factors such as installation rates, technical improvements, and legislative changes.
4. Analyze the acquired data to identify critical barriers to solar PV panel recycling, such as logistical constraints, technology restrictions, and cost factors.
5. Assess the efficacy of current recycling systems and policies, identifying gaps and opportunities for improvement.

Applying this approach, the study intends to give a complete knowledge of the role of solar PV panel recycling in meeting the EU's sustainability goals, as well as practical solutions for Member States to overcome the obstacles they encounter.

Research methods

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

1. *Solar Production Capacity*: Historical data on EU's solar photovoltaic production capacity in Megawatts (MW) for the period 2012-2022 was retrieved from Eurostat. Data is expressed annually, for main activity producers.
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 the European Union.

The annual number of PV panels installed was calculated using the formula:

$$Number\ of\ installed\ panels = \frac{Solar\ production\ capacity\ at\ EU\ level\ (MW)}{Average\ capacity\ per\ panel\ (W)} \times 1{,}000{,}000$$

For example, for 2012, the number of panels installed is:

$$\frac{63{,}403.7\ MW}{200\ W} \times 1{,}000{,}000 = 317{,}018{,}625\ panels$$

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 2022.

$$Weight\ of\ PV\ panels\ (tons) = \frac{Number\ of\ installed\ panels}{1.000}$$

For example, for 2012, the total weight of installed PV panels is:

$$317{,}018{,}625\ panels \times \frac{15kg}{panel} = 4{,}755{,}279.4\ tons$$

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.

$$PV\ waste\ after\ 2o\ years\ (tons) = Totalweight\ of\ PV\ panels\ (tons) - Defects\ per\ year\ (tons)$$

Applying the failure rate of 0.05% per year over 20 years for 2012, in 2032 the total weight of PV waste is:

$$4{,}755{,}279.4\ tons - (4{,}755{,}279.4\ tons \times 0{,}0005\ \times 20) = 4{,}707{,}726.6\ tons$$

4. Results and discussion

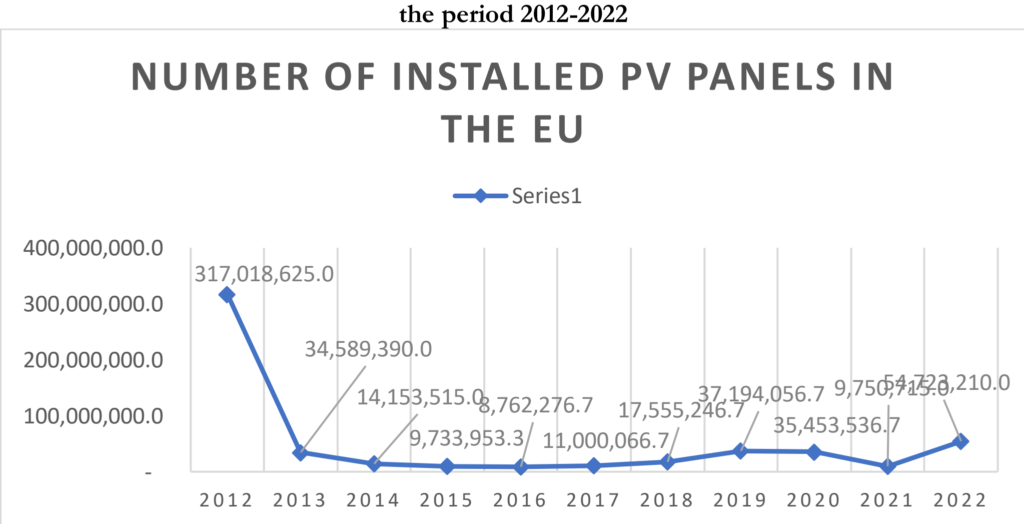
The results of our calculations are found in Table 1. The number of photovoltaic panels installed at EU level during the period 2012-2022 and the estimated PV waste panels at EU level during the period 2033-2042.

Table 1. The number of photovoltaic panels installed at EU level during the period 2012-2022 and the estimated PV waste panels at EU level during the period 2033-2042

TIME	European Union - 27 countries (from 2020)	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	63,403.73	63,403.7	200.0	317,018,625.0	15	4,755,279.4	2,377.6	4,707,726.6	2032
2013	70,321.60	6,917.9	200.0	34,589,390.0	15	518,840.9	259.4	513,652.4	2033
2014	73,152.31	2,830.7	200.0	14,153,515.0	15	212,302.7	106.2	210,179.7	2034
2015	76,072.49	2,920.2	300.0	9,733,953.3	20.5	199,546.0	99.8	197,550.6	2035
2016	78,701.18	2,628.7	300.0	8,762,276.7	20.5	179,626.7	89.8	177,830.4	2036
2017	82,001.20	3,300.0	300.0	11,000,066.7	20.5	225,501.4	112.8	223,246.4	2037
2018	87,267.77	5,266.6	300.0	17,555,246.7	20.5	359,882.6	179.9	356,283.7	2038
2019	98,425.99	11,158.2	300.0	37,194,056.7	20.5	762,478.2	381.2	754,853.4	2039
2020	109,062.05	10,636.1	300.0	35,453,536.7	20.5	726,797.5	363.4	719,529.5	2040
2021	112,962.33	3,900.3	400.0	9,750,715.0	22.5	219,391.1	109.7	217,197.2	2041
2022	134,851.62	21,889.3	400.0	54,723,210.0	22.5	1,231,272.2	615.6	1,218,959.5	2042
Total		134,851.6		549,934,591.7		9,390,918.6	4,695.5	9,297,009.4	

Source: Authors' own research.

Figure 1. The number of photovoltaic panels installed at EU level during the period 2012-2022



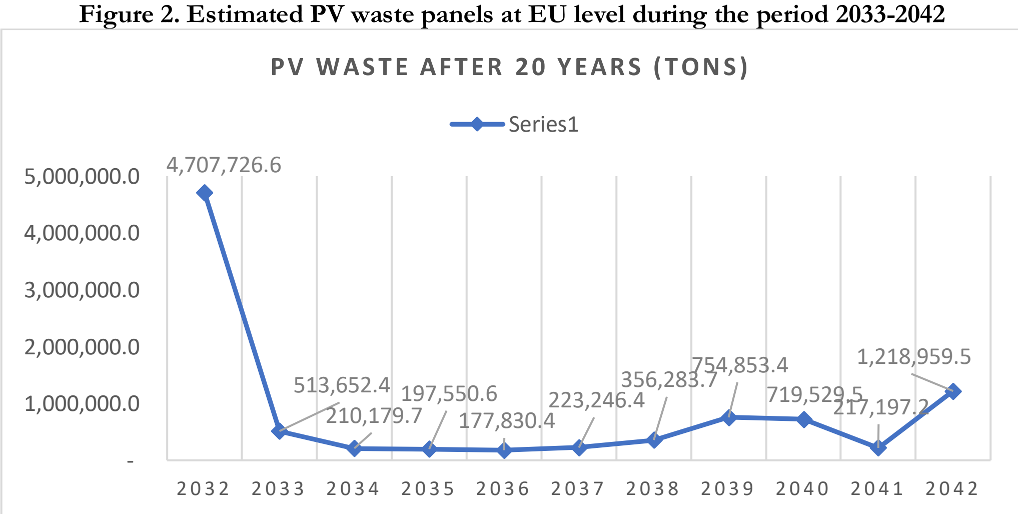
Source: Authors' own research.

The results show a significant increase in the annual installed PV capacity in the EU, from 63,403.73 MW in 2012 to 134,851.62 MW in 2022. This increase reflects the EU's commitment to renewable energy sources. Despite the fluctuations, the overall trend from 2012 to 2022 indicates progress in increasing the installed PV capacity.

The increase in installed PV capacity suggests that the EU is on a strong trajectory toward adopting renewable energy. However, the result also highlights a potential challenge: the significant amount of PV panel waste that will be generated as these panels reach the end of their life cycle. This indicates a need for robust waste management and recycling strategies to handle the future disposal of PV panels.

The Figure 1 underline the EU's commitment to expanding its renewable energy infrastructure through increased PV panel installations. While this trend is positive for renewable energy adoption, it also calls for proactive measures to manage the lifecycle of PV panels, including their eventual disposal.

Figure 2. Estimated PV waste panels at EU level during the period 2033-2042



Source: Authors' own research.

The graph underscores the dual nature of the EU's renewable energy transition: while the increase in PV panel installations is a positive step towards sustainability, it also poses significant waste management challenges. By proactively addressing these issues through advanced recycling, strong policies, and collaborative efforts, the EU can ensure that its commitment to renewable energy remains environmentally beneficial in the long term.

Detailed Interpretation of the Figure 2:

1. **Peak in 2032**: The graph shows a significant peak in PV waste in 2032, amounting to 4,707,726.6 tons. This peak corresponds to the massive installations of PV panels in 2012, which were depicted in the first graph. Given that PV panels typically have a lifespan of around 20 years, the panels installed in 2012 are reaching the end of their lifecycle by 2032, resulting in a large volume of waste.
2. **Rapid Decline (2033-2036)**: Following the peak in 2032, there is a rapid decline in the amount of waste, dropping to a low of 177,830.4 tons in 2036. This decline reflects the reduced installations of PV panels in the years following 2012, specifically from 2013 to 2016, as seen in the earlier graph.
3. **Subsequent Fluctuations (2037-2041)**: After 2036, the graph shows fluctuations in the amount of PV waste generated. Notable increases in waste occur in 2039 (754,853.4 tons) and 2040 (719,529.5 tons), which correspond to the years of increased PV installations in 2017 and 2019, as seen in the first graph. These fluctuations indicate periods where installations picked up again, leading to corresponding waves of panel retirement and waste generation 20 years later.
4. **Significant Increase in 2042**: In 2042, there is a marked increase in PV waste, reaching 1,218,959.5 tons. This increase is linked to the substantial installations of PV panels in 2022. The data suggests a renewed push in PV installations around this time, reflecting the EU's ongoing commitment to renewable energy sources.

5. Conclusions

The results of this study illustrate a significant increase in the annual installed PV capacity in the EU from 63,403.73 MW in 2012 to 134,851.62 MW in 2022, reflecting the EU's steadfast commitment to renewable energy sources. However, this growth also presents a substantial challenge: the management of a large volume of PV panel waste expected as these installations reach the end of their lifecycle. The data underscores the necessity for robust waste management and recycling strategies to handle the future disposal of PV panels.

The projections indicate a peak in PV waste in 2032, corresponding to the massive installations in 2012, followed by fluctuations in waste volumes due to varying installation rates in subsequent years. By proactively addressing these challenges through the development of advanced recycling technologies, strong policy frameworks, and collaborative efforts across member states, the EU can ensure that its renewable energy commitment remains environmentally beneficial in the long term.

Investments in recycling infrastructure not only contribute to environmental protection but also offer significant economic benefits, including job creation and resource recovery. Enhanced recycling capacities, standardized protocols, and increased public awareness are essential to support the circular economy and maximize the sustainability of PV panel use.

In conclusion, while the increase in PV panel installations is a positive step towards achieving the EU's renewable energy goals, it also necessitates comprehensive and efficient recycling systems to manage the lifecycle of these panels. By aligning recycling initiatives with the broader objectives of the Green Deal and Fit for 55 strategies, the European Union can lead the way in sustainable energy practices, setting a global standard for the responsible management of photovoltaic solar panels.

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