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Prediction of the Market of End-of-Life Photovoltaic Panels in the Context of Common EU Management System

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Abstract: A significant development of the photovoltaic market in the European Union has been observed recently. This is mainly due to the adopted climate policy and the development of photovoltaic technology, resulting in increased availability for consumers at lower prices. In the long run, increased installed PV capacity is associated with an increased amount of photovoltaic waste generated at the end of life. Since this waste belongs to the group of WEEE (waste electrical and electronic equipment) waste, it is subjected to high recovery levels. Existing installations for the highly efficient recycling of PV panels are just proofs of concept. However, the situation will change in the near future, and it will be necessary to implement a full-scale waste management system dedicated to PV waste. The paper estimates mass streams of photovoltaic waste generated by 2050 in individual EU countries. Consequently, the characteristics of the European market of waste PV panels are considered together with the demand of individual Member States for installations. The estimation enables the fulfillment of the Directive on WEEE recovery rates.

Keywords: end-of-life photovoltaic modules; recycling; upcycling; photovoltaic waste

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1. Introduction

Recently, a significant increase in the amount of energy obtained from renewable sources has been observed. These changes are primarily driven by the plan to implement energy transformation policy towards a significant minimization of emissions. These goals are included in international policies such as the Paris Climate Agreement [1]. The United Nations have introduced 17 Sustainable Development Goals (SDGs), where it shows 169 targets. The PV panels fit in SDG 7 (affordable and clean energy), SDG 12 (responsible production and consumption) and SDG 13 (climate action). The United Nations has shown that total renewable energy consumption increased by one quarter between 2010–2019, resulting in increased PV panel waste [2,3]. A significant percentage of renewable sources in future consumption indicates that solar energy will be one of the key elements of the energy mix. According to the estimates, it is expected to produce 25% of global electricity demand by 2050. It will lead to a significant reduction in CO_2 emissions, which is a part of climate action [4–7].

Consequently, there will be a significant increase in the end of life (EoL) of photovoltaic (PV) panels, which is estimated to be 20–35 years [8,9]. The recommended method of managing this waste is recycling. It allows for the recovery of materials such as glass, plastic or metals [9,10]. The market for recycling PV modules, despite numerous laboratory tests, is at the initial stage of development on an industrial scale. Due to the long usage period of the PV products, their development in global terms is not yet systematized and there is no dedicated infrastructure. The European Union (EU) has introduced a general legal framework [11,12].

Photovoltaic panels are basically classified into three generations: I (crystalline silicon cells), II (thin-film cells) and III (dye cells). The vast majority of installed photovoltaic modules to date have been crystalline silicon modules [13–15]. The recycling methods developed and tested so far are dedicated primarily to the first-generation modules, especially for industrial applications.

The aim of the article is to predict the market of the EoL photovoltaic panels in the European Union. The EU has heavily invested in photovoltaics in recent years. Predictions for the development of PV technology and the EU climate policy indicate an increase in this trend. Therefore, it will also be a large EoL market for PV panels in the long term. The internal market that characterizes the Community, including freedom of trade as well as a coherent economic and climate policy, argues for the creation of an EU market for photovoltaic waste. The paper attempts to determine the shape of such a system along with the implementation schedule. Among the scientific reports, no predictions of the EoL market for PV panels have been identified for the EU. There was also no attempt to set a time horizon for the construction of new waste recycling installations for waste management systems. The provided analysis is intended to be a basis for researchers and engineers aiming to establish the management system of EoL PV panels.

The scope includes the summary of the state of the art of recycling EoL PV panels. Then, the annual mass streams of PV waste generated in EU countries are predicted according to the adopted methodology, taking into account different photovoltaic technologies. On the basis of data analysis and adopted assumptions, a potential schedule of implementation of recycling in the EU is established. Different types of photovoltaic waste markets in the EU are also considered.

2. The State of the Art of PV Panel Recycling—A Review

2.1. Characteristics of the Photovoltaic Market in the EU

In recent years, there has been a dynamic growth of the photovoltaic market in the EU. One of the most important reasons for this trend is the significant development of photovoltaic technologies, which results in decreased prices. Generally, it can be stated that this form of obtaining electricity has become price-competitive compared to traditional energy sources [5]. An important aspect is the system of subsidies, which has been enforced in various forms in some countries, including many European ones. In 2021, the total installed capacity in PV was almost 158 GW, which is 18.7% of the total installed capacity in PV globally. Compared to the previous year, this is an increase of approximately 16%. Figure 1 shows the top 10 markets for PV technology in the EU. The data characterizing individual markets include the installed capacity in PV in GW and the amount of electricity produced from PV in TWh for 2021 [16–18].

In the EU, Germany is the leader, with a PV capacity of 58.5 GW. Italy is ranked second, with 22.7 MW of installed PV capacity. They are followed by France, the Netherlands and Spain. These countries have the capacities of PV installations equal to approx. 14 GW. The last one in the top ten is Hungary, which has an installed PV capacity of 2.1 MW. Thus, there is a significant difference between the leader and the last country, which is still at the forefront of Europe. In terms of gross electricity production, the ranking is similar, although there are changes in the positions of individual countries. Countries with very good insolation conditions gain. As a result, their annual electricity production reaches high efficiency, such as in Spain and Greece [18,19]. Figure 2 [20] shows a geographical comparison of European countries in terms of irradiation and EPBT (energy payback time). The intensity of solar radiation per 1 m^2 of surface (irradiation) translates into the amount of electricity produced. Depending on the geographical location, the difference can be significant. The second indicator confirms this trend. The payback period for PV installation is shorter for regions with higher irradiation.

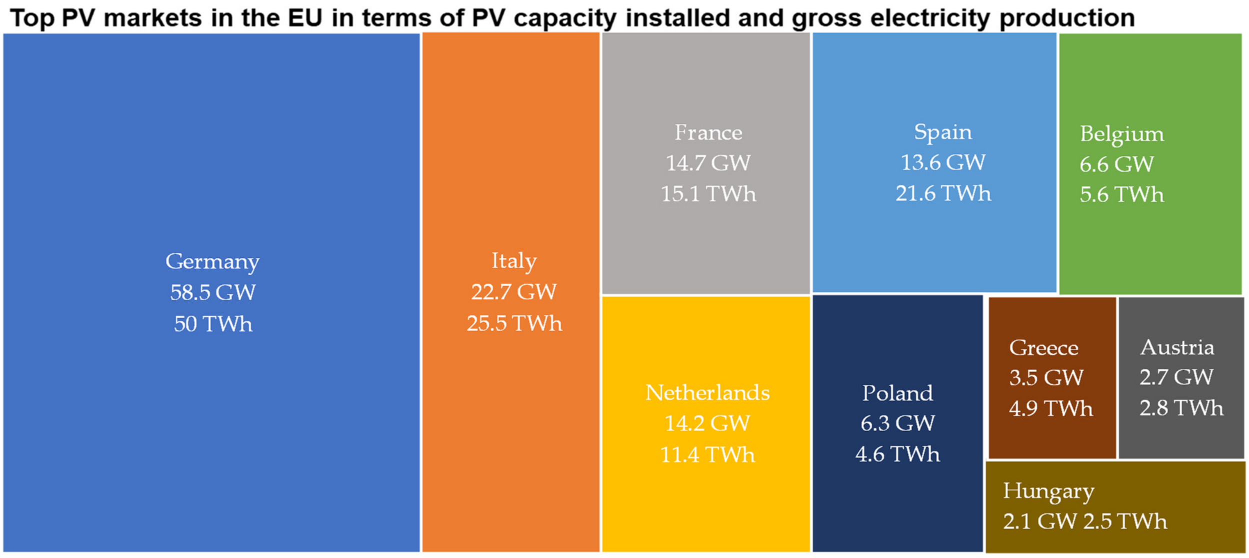


Figure 1. Characteristics of top PV markets in the EU—data for 2021.

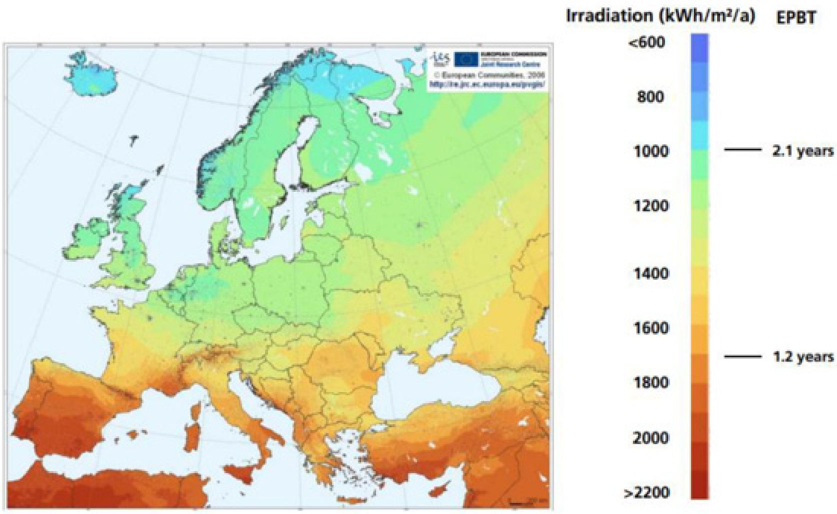


Figure 2. Irradiation and EPBT (energy payback time) in European countries according to the JRC European Commission [20].

Portugal and Italy, as well as the Balkan countries, Romania, Bulgaria and the southern part of France, also have very good geographical conditions for solar energy. This is conducive to the development of PV technology.

According to forecasts [5,6], PV technology will account for an increasing share in electricity production. In addition, the EU climate policy, defined, e.g., as part of the Renewable Energy Directive, sets a target for the share of renewable sources in energy production of 40%, with the possibility of increasing to 45% [21]. One of the key technologies to achieve this goal will be PV.

2.2. The EU Legislation

The method of managing PV waste in the EU has been established by an EU Directive. This is Directive 2012/19/EU, under which PV devices are classified as waste electrical and electronic equipment (WEEE—waste electrical and electronic equipment) [11]. According to this directive, the development of PV panels currently requires 85% efficiency in the recovery of secondary raw materials. Thus, unlike other parts of the world, direct landfill of EoL PV panels is not allowed. An additional aspect is imposing the responsibility to cover the costs of collection and recycling on producers of PV panels. This is known as extended producer responsibility (EPR) [22,23]. A manufacturer is broadly defined here as any manufacturer, distributor/seller, importer and distance seller that is involved in the PV industry in the EU [24].

In addition to recycling as a method of managing EoL utility panels, their reuse is also being considered. This can take place directly after the user has returned or after adaptation. The expected lifetime of the PV panels does not mean that the device is unable to generate electricity at the end of its useful life. The reason for the return will often be a reduction in the performance of the product. Currently, there is a small market for secondary photovoltaic modules, which is difficult to assess [24,25]. However, after some time, this part of the EoL PV panels will also be managed in a different way.

2.3. Methods of the Photovoltaic Panels Recycling

Photovoltaic panels are generally classified as belonging to three generations: I, II and III. The first generation includes crystalline silicon (c-Si) panels. They constitute the vast majority (approx. 95%) of currently used panels [23]. Second-generation modules account for about 5%, while third-generation panels are practically not considered in real-scale installations. The first generation includes crystalline silicon panels: mono- and polycrystalline (also known as multicrystalline). The second generation includes thin-film technologies: cells based on amorphous silicon (aSi) and silicon-free cells—CIGS (copper indium gallium selenide), CdTe (cadmium telluride) and perovskite. Among the modules with crystalline cells, monocrystalline cells are currently more often used, while in the case of the second generation, the use of CdTe cells prevails. The last generation includes dye cells, which are based on the phenomenon of photosynthesis [24,25].

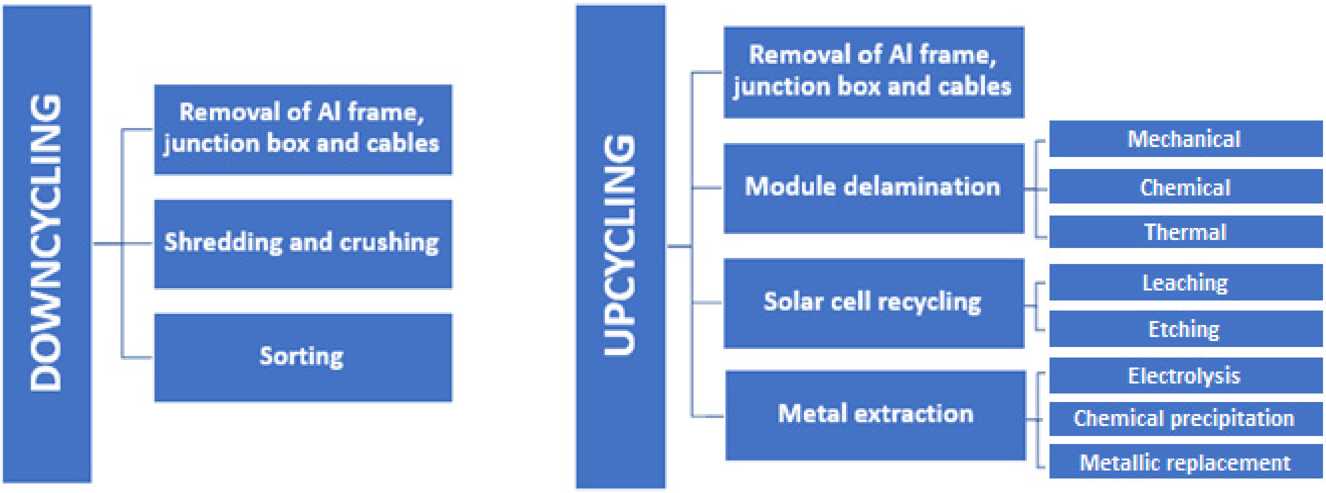
In general, recycling methods can be divided into downcycling and upcycling. Downcycling is so-called low-value recycling, which recovers materials of lower purity that are therefore more difficult to reuse. Upcycling in reverse recovers materials of higher purity or quality, suitable for reuse [26].

Both approaches start with the same action, namely removing the aluminum frame, cables and junction box. In the next stage, other processes are already taking place. Downcycling is a simplified method that results in the recovery of most of the glass and aluminum. As a standard, the next stage is fragmentation of the module on the glass recycling line, crushing, and then glass and aluminum sorting processes. Partial recovery of ferrous metals also takes place here. The other components present in the module, i.e., silicon, metal residues, glass, plastic and aluminum, form a mixture that ends up in landfills. Hence, downcycling can be described as a simple method of recycling PV panels that does not require significant energy inputs or high investment costs and allows for a reduction in the landfilling of a significant amount of this type of waste. On the other hand, it limits the number of recoverable raw materials, as well as lower-quality recycled raw materials. In addition, the mixture remaining after the process may contain metals, the introduction of which into the environment should be limited, and high-calorie components that should not be landfilled [27–30].

Upcycling aims to recycle other components, e.g., Ag, Si, Cu, Cd, Te. The first common step is followed by a series of thermal, mechanical or chemical processes that allow for the recovery of many high-purity materials. This results in higher upcycling complexity, as well as higher investment and operating costs. In addition, the chemical or thermal processes used here require energy and the use of chemical compounds. Process products that require management, such as fly ash from thermal processes, should also be included. As part of upcycling, there are many methods dedicated to various types of PV modules, mostly crystalline silicon modules [29,31].

In general terms, the upcycling of first-generation solar panels includes the following steps:

- removal of the aluminum frame, cables and junction box;
- separation of the glass from the silicon wafer in a thermal, mechanical or chemical process;
- separation and purification of silicon cells and special metals (e.g., silver, tin, lead, copper) using chemical and electrical techniques [29].
- The individual stages of downcycling and upcycling are presented in Figure 3.



(**a**) (**b**)

Figure 3. Methods of the crystalline PV modules recycling: (**a**) downcycling; (**b**) upcycling.

Thin-film panels require some modifications to the recycling processes. More detailed information on the technology of recycling photovoltaic modules can be found in articles [27–35].

2.4. The Current State of Photovoltaic Waste Recycling in the EU

Although the amount of PV waste is not at a high level at the present time, the first recycling plants have already been built. Currently, they do not have high processing capacity. Rather, they are test installations, although they carry out recycling with a high recovery rate. The largest is the Veolia plant in France, which converts the PV modules delivered there with a recycling rate of 96% for c-Si PV modules [33]. The organizer of the collection and transport of EoL PV panels here is PV Cycle. The scope of the company's operations is similar to that of an operator in the deposit-refund system. Therefore, PV Cycle aims to create a voluntary and sustainable take-back program for EoL PV panels, and then subject them to the development. The system is currently being tested primarily in France, where 1300 Mg of panels were processed at the Veolia plant through PV Cycle in 2018. The plan for 2022 is 4000 Mg [36–38].

Among the companies involved in the recycling of PV panels, the German companies Loser Chemie and Solar World can also be mentioned. Loser Chemie has several collection points where it collects several types of photovoltaic systems (c-Si, CdTe, CIGS). The company developed and patented original processes using mechanical and chemical treatment to recycle solar cells [39]. SolarWorld [40] also has its own c-Si recycling method. A significant number of laboratory tests are available for different methods of recycling photovoltaic panels. Some of the results are listed below.

The starting stage of upcycling is the separation of the glass from the solar cell. Between these two layers is a hard-to-remove layer of a bonding polymer–EVA (ethylene-vinyl acetate). Mechanical, thermal or chemical methods can be used for this purpose. As part of mechanical separation, grinding and crushing are most often used. A relatively high efficiency of glass recovery was obtained in the study [41], where triple grinding was used, in which 91% of the glass was recovered. A different approach was used in studies [33,42]. In the first case, delamination was performed using a cryogenic process. In the second, a hot knife cut was used. This method turned out to be the most effective among mechanical methods, as it allowed for the recovery of 98% of glass [42].

Among the methods of thermal delamination, the most commonly used process is pyrolysis. This allows for thermal decomposition of the EVA layer, which occurs at a temperature of approximately 500 °C within 1 hour. An undoubted advantage is the high recovery of glass and the preservation of the high quality of separated silicon cells. In the case of mechanical methods, this material is often of lower quality. The disadvantages of such a solution are high costs and energy consumption and the generation of harmful products of the thermal process [43].

Chemical delamination methods rely on the use of inorganic and organic solvents. The characteristic features of this method are its duration, which can be up to several days, and high demand for chemicals. Currently, methods of significantly accelerating the process are being investigated. According to [44], the process of dissolving the EVA layer in toluene using ultrasonic radiation takes less than 1 hour.

The next step in the recycling of PV panels is the separation of silicon and metals by leaching and etching, which require chemicals. The methods used here allow for the recovery of silicon. The implementation method affects the purity of the recovered material [45,46]. In the case of complex methods, it is possible to recover high-purity silicon, which can be reused in photovoltaic products. Simplified methods, usually preceded by an invasive mechanical process of separating the glass from the solar cell, result in the recovery of much lower-quality silicon [42].

The last step of upcycling is the extraction of the metals left over from the leaching or etching process in solution, which can be accomplished by electrolysis, metallic replacement or chemical precipitation. In order to compare the effectiveness of these three methods, one can refer to [47] on the recovery of silver from photovoltaic modules. The element recovery rates obtained were 89.7, 87.4 and 99.5%, respectively.

Based on the results of upcycling research available in the literature, the currently achievable recovery rates of individual materials contained in the EoL of photovoltaic panels were determined. Data are presented in Table 1 [41–52].

Table 1. Recovery efficiency of PV module components.

Component	Recovery Efficiency
Aluminum	100%
Copper	99%
Glass	98%
Tellurium	80–95%
Silicon	76–95%
Lead	93%
Silver	30–99.5%
Indium, Germanium, Gallium	20–40%

Assessment of the environmental impact of recycling waste PV panels carried out by [53–56] indicates a significant advantage over other management methods. When comparing different recycling methods, the situation is difficult to evaluate unequivocally; however, chemical processes are mentioned as having the greatest impact on the environment [31,57]. Considering the economic aspect of recycling generally leads to the conclusion about the financial losses associated with the recycling of PV waste. Only in case of a stable, large stream of PV waste, the profitability of the recycling plant can be established [51,58].

Nevertheless, it should be noted that currently, the upcycling of photovoltaic panels does not take place on a large scale and is rather for demonstration [26]. Photovoltaic waste that is not upcycled is currently downcycled, reused or stored. The exact waste streams for each management method have not been identified. However, it should be noted that the stream of this type of waste will increase every year. According to the prediction of [5], the amount of PV waste in the world in the 2030 will be 1.7–8 million Mg.

One of the basic problems of recycling EoL photovoltaic panels is unprofitability. Current waste volumes are still low, implying economic impediments to the development of existing processes. Comparing the economics of recycling other WEEE waste, the profits from the sale of recovered materials are too small to cover the costs of upcycling PV waste. In addition, the production PV modules use less valuable materials, such as copper, silver or tellurium. This is an advantage of technology development for environmental impact. Paradoxically, however, this reduces revenues from the sale of secondary raw materials. Nevertheless, the extended producer responsibility (EPR) system and the growing EU targets for the recovery of materials, including from WEEE waste, are factors in favor of the development of upcycling methods towards increasing profitability, practicality and efficiency, as well as reducing environmental impact.

3. Materials and Methods

3.1. Materials for Prediction of the Amount of PV Waste by 2050

The prediction of the amount of waste generated in the EU countries by 2050 is based on [18]. This is a summary of the amount of installed PV power in the years 1996–2021. Cumulative values and annual growths for the EU are summarized in Table 2.

Table 2. Cumulative capacity of installed PV in the EU between 1996–2025.

Year	PV Capacity [MW]	Year	PV Capacity [MW]	Year	PV Capacity [MW]
1996	57.8	2006	3.214.0	2016	89.184.0
1997	75.7	2007	4.979.0	2017	93.906.0
1998	92.5	2008	10.381.5	2018	101.712.7
1999	117.0	2009	16.735.2	2019	117.735.7
2000	182.1	2010	29.923.4	2020	136.137.0
2001	279.1	2011	52.203.0	2021	157.606.0
2002	362.0	2012	69.235.0	*2022*	185.331.0
2003	591.3	2013	77.449.0	*2023*	218.919.0
2004	1.293.0	2014	81.346.0	*2024*	259.678.0
2005	2.269.0	2015	85.364.0	*2025*	309.677.0

In order to complete the analysis of the amount of PV waste generated, the installed PV capacity in 2022–2025 was also estimated. The prediction of the annual growth of photovoltaic installations contained in [50] was used. The material includes the expected annual increases in PV capacity for top markets in the EU. In case of the remaining countries, the general increase scenario was set. Assumptions regarding the increase in new photovoltaic installations in selected countries are presented in Table 3.

Table 3. Annual PV capacity increase in selected European countries.

Country	PV Capacity Increase	Country	PV Capacity Increase	Country	PV Capacity Increase
Germany	16%	Denmark	43%	Belgium	12%
Spain	20%	Italy	7%	Hungary	21%
Netherlands	23%	Portugal	44%	Austria	21%
France	21%	Greece	19%	Ireland	120%
Poland	24%	Sweden	37%	Bulgaria	30%

For the remaining countries, general annual forecast power increases were adopted, which for individual years are 18% in 2022, 20% in 2023, 19% in 2024 and 18% in 2025, according to the medium scenario in [50].

Figure 4 shows the installed capacity in the years 2005–2025 in individual EU countries in the context of the value of the annual increase. These data are compared with the cumulative installed PV capacity for EU-27 countries.

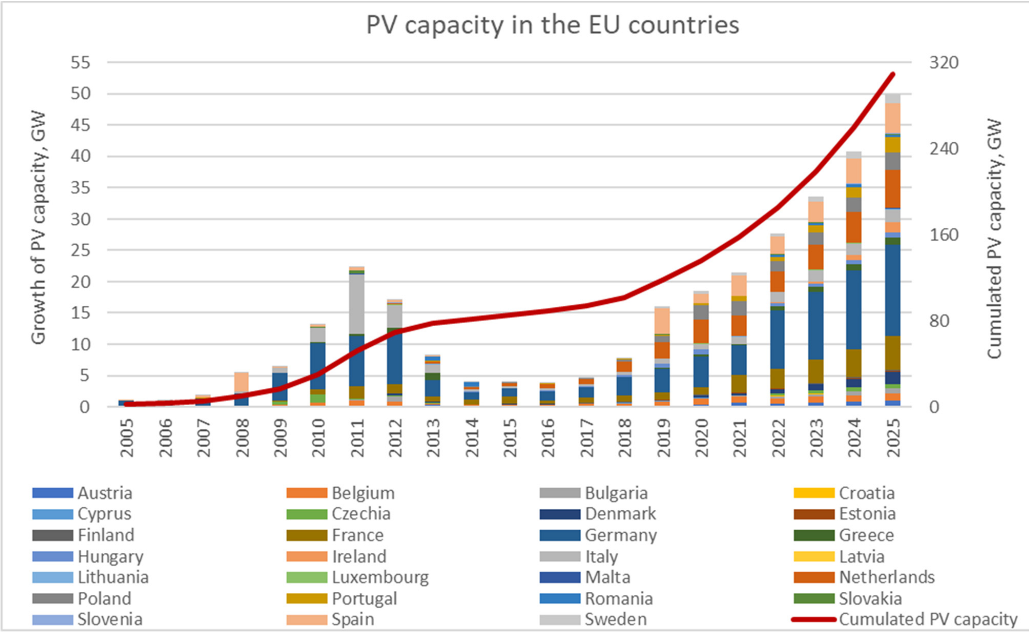


Figure 4. PV capacity—cumulated and annual increase—in the EU.

For the EU, there are generally two periods characterized by a significant increase in photovoltaic installations. These are the years 2010–2012 and 2019–2025 (also according to the prediction). Since 2012, there has been a period of several years of a relevant slowdown in PV investments compared to previous years in some EU countries. It was an issue in Germany, France, Italy, Spain, Czechia and Belgium, which have been the countries with some of the largest shares in the PV market. It can be compared by annual growth of PV capacity for these periods.

Estimates of the share of individual PV technologies are based on the analysis of the Frauenhofer Institute [26], which provided the shares of individual PV technologies in previous years. The data cover the years 1997–2021. Based on the forecast contained in [5], it was determined that the share of 2nd-generation technology in the years 2022–2025 will amount to approximately 5%, and amorphous modules (aSi) will not be practically used. In the case of 1st-generation technology, an increase in monocrystalline modules is assumed at the expense of polycrystalline ones. This is due to the development of monocrystalline technology, which, achieving higher efficiencies, becomes price-competitive with polycrystalline technology. The list of shares of individual PV technologies is shown in Figure 5.

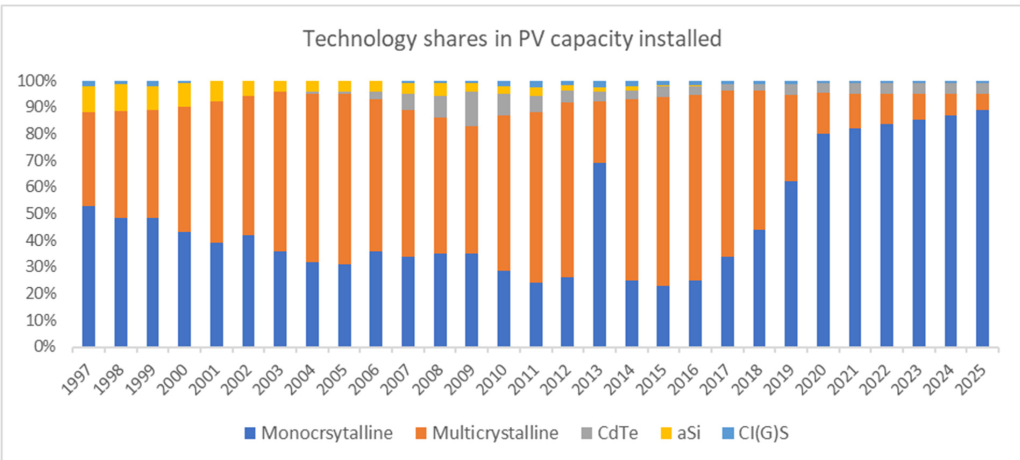


Figure 5. Shares of PV technologies between 1997–2025.

3.2. Assumptions for the Predicition of PV Waste Streams

In order to estimate the mass stream of PV waste in subsequent years, the following assumptions were made.

1. The service life of the installed photovoltaic panels is defined as 25 years. Therefore, the annual increase in waste in the years 1996–2025 is the basis for determining the stream of waste generated every year since 2021 until 2050.
2. The entire PV waste stream is recycled. Despite the likely diversion of part of the EoL PV modules for reuse, it is difficult to estimate this stream in future years. It seems that the development of technology and the fall in the prices of PV devices will not be conducive to this phenomenon. The transfer of EoL PV panels to recipients in other regions of the world remains an open issue. However, such a scenario has not yet been considered.
3. The input data for the analysis of concerning the installed capacity are expressed in MW. Determination of the mass of generated waste requires the adoption of the mass index of the unit power module. On the basis of [48], the indicators included in Table 4 were adopted.
4. Determination of mass shares of PV waste according to photovoltaic technology is based on the analysis of the Fraunhofer Institute [26] for the years 1996–2021. Predictions for the years 2022–2025 are based on the estimates presented in [51] and the understanding of the PV market. Table 5 contains assumptions for individual technologies.

Table 4. Weight indicators for photovoltaic module technologies.

PV Technology	Weight Indicator [kg/W]
c-Si	0.102
a-Si	0.284
CdTe	0.202
CIGS	0.185

Table 5. Assumptions to the prediction of PV technologies shares in years 2022–2025.

PV Technology	Assumption
Monocrystalline	An annual increase at the level of 2%.
Policrystalline	An annual decrease as a difference of remaining ones.
a-Si	Lack of the a-Si modules installed in years 2022–2025 in the EU.
CdTe	The share was assumed at the level of 4%.
CIGS	The share was assumed at the level of 1%.

3.3. Methodology for the Predicition of PV Waste Streams

The mass streams M of PV waste generated in the EU countries during 2021–2050 were calculated. The calculations are based on the annual data of the cumulated photovoltaic capacity installed in individual EU countries in years 1996–2025.

Calculations for mass are performed by

$$M_y = (C_x - C_{x-1}) \cdot u_{x,t} \cdot w_t \tag{1}$$

where:

C is installed capacity in photovoltaic in a given country of the EU, MW;
t is a type of the photovoltaic technology;
y is a year of EoL photovoltaic waste generation;
x is a year of photovoltaics installation;
u is a share of a given PV technology in x year;
w is a mass indicator for PV panels of different photovoltaic technologies, kg/W.

Annual shares of the photovoltaic technologies are presented in Table 6.

Table 6. Photovoltaic technology shares by annual capacity installed.

t	*x*														
	1996	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
mSi	0.55	0.53	0.49	0.49	0.43	0.39	0.42	0.36	0.32	0.31	0.36	0.34	0.35	0.35	0.29
pSi	0.31	0.35	0.40	0.41	0.47	0.53	0.52	0.60	0.63	0.64	0.57	0.55	0.51	0.48	0.58
aSi	0.11	0.10	0.10	0.09	0.09	0.08	0.06	0.04	0.04	0.04	0.04	0.04	0.05	0.03	0.03
CdTe	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.03	0.06	0.08	0.13	0.08
CIGS	0.03	0.02	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.02
t	*x*														
	2011	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**
mSi	0.24	0.26	0.69	0.25	0.23	0.25	0.34	0.44	0.62	0.80	0.82	0.84	0.85	0.87	0.89
pSi	0.64	0.67	0.22	0.67	0.70	0.69	0.62	0.52	0.33	0.15	0.13	0.11	0.10	0.08	0.06
aSi	0.04	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CdTe	0.06	0.04	0.04	0.04	0.04	0.03	0.02	0.02	0.04	0.04	0.04	0.04	0.04	0.04	0.04
CIGS	0.02	0.01	0.03	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

mSi–monocrystalline; pSi–polycrystalline.

Mass indicators allow one to indicate the mass streams of photovoltaic modules for each country. They are listed in the following formula:

$$w_t = \begin{cases} 0.102, & for\ cSi \\ 0.284, & for\ aSi \\ 0.202, & for\ CdTe \\ 0.185, & for\ CIGS \end{cases} \tag{2}$$

For each year, mass streams of photovoltaic panels withdrawn from use of PV technologies were determined. The results for the PV technologies are presented as I- and II-generation PV waste. The reasons for this are primarily the current processing capacity of the test recycling installations for EoL PV panels and the economics of recycling, which is conducive to processing the largest possible streams of PV waste.

4. Results and Discussion

Based on the data and adopted assumptions, the cumulated mass stream of PV waste in selected years in all EU countries was estimated. The results are presented in Table 7.

Table 7. Cumulated mass streams of PV waste in European countries.

Mass Streams of PV Waste in Selected Years in EU Countries [Mg]													
Country	**2030**	**2030**	**2040**	**2040**	**2050**	**2050**	**Country**	**2030**	**2030**	**2040**	**2040**	**2050**	**2050**
	C	**TF**	**C**	**TF**	**C**	**TF**		**C**	**TF**	**C**	**TF**	**C**	**TF**
Austria	2037	281	89.658	11.834	559.152	57.300	Italy	3295	455	1.808.372	238.682	2.882.255	295.364
Belgium	194	27	299.619	39.546	1.003.980	102.885	Latvia	0	0	144	19	1541	158
Bulgaria	0	0	98.451	12.994	328.332	33.646	Lithuania	0	0	6994	923	65.123	6674
Croatia	48	7	4286	566	21.001	2152	Luxembourg	2326	321	11.127	1469	40.268	4127
Cyprus	48	7	4937	652	60.884	6239	Malta	10	2	7080	935	37.764	3870
Czechia	57	8	198.518	26.202	408.311	41.842	Netherlands	4942	682	146.002	19.270	3160.302	323.858
Denmark	291	40	74.829	9877	624.125	63.958	Poland	0	0	10.312	1361	1.433.374	146.888
Estonia	0	0	679	90	79.766	8174	Portugal	194	27	42.767	5645	750.512	76.910
Finland	388	54	1435	189	77.839	7977	Romania	0	0	126.866	16.745	269.265	27.593
France	1260	174	682.889	90.133	3.055.308	313.098	Slovakia	0	0	50.995	6731	103.079	10.563
Germany	199.226	27.509	3.752.604	495.295	10.256.687	1.051.072	Slovenia	19	3	22.876	3019	70.710	7246
Greece	97	13	249.140	32.883	685.940	70.293	Spain	5039	696	450.060	59.402	2.742.414	281.034
Hungary	0	0	16.456	2172	442.638	45.360	Sweden	388	54	9950	1313	538.453	55.179
Ireland	29	4	201	27	308.712	31.635	Total	219.886	30.362	8.167.248	1.077.972	30.007.735	3.075.096

C—crystalline technologies (I generation); TF—thin film-technologies (II generation).

As it can be observed, there are large differences in the PV waste stream generated across the community. This is a result of previous investments in PV. Germany is clearly the leader, both in terms of the size of the streams generated in the years under consideration and the timing of significant PV waste streams. The stream is expected to reach almost 200,000 Mg as early as 2030 in this country. It is also concluded that the mass of first-generation PV waste significantly exceeds the EoL mass of second-generation panels. This is an important issue, since the profitability of recycling is strongly dependent on the size of the waste stream. Currently, second-generation PV waste must be recycled in a separate process line. The small volume of this waste will require a flexible system and higher surcharges. The annual increase in waste PV modules (first- and second-generation combined) for selected years is shown in Figure 6.

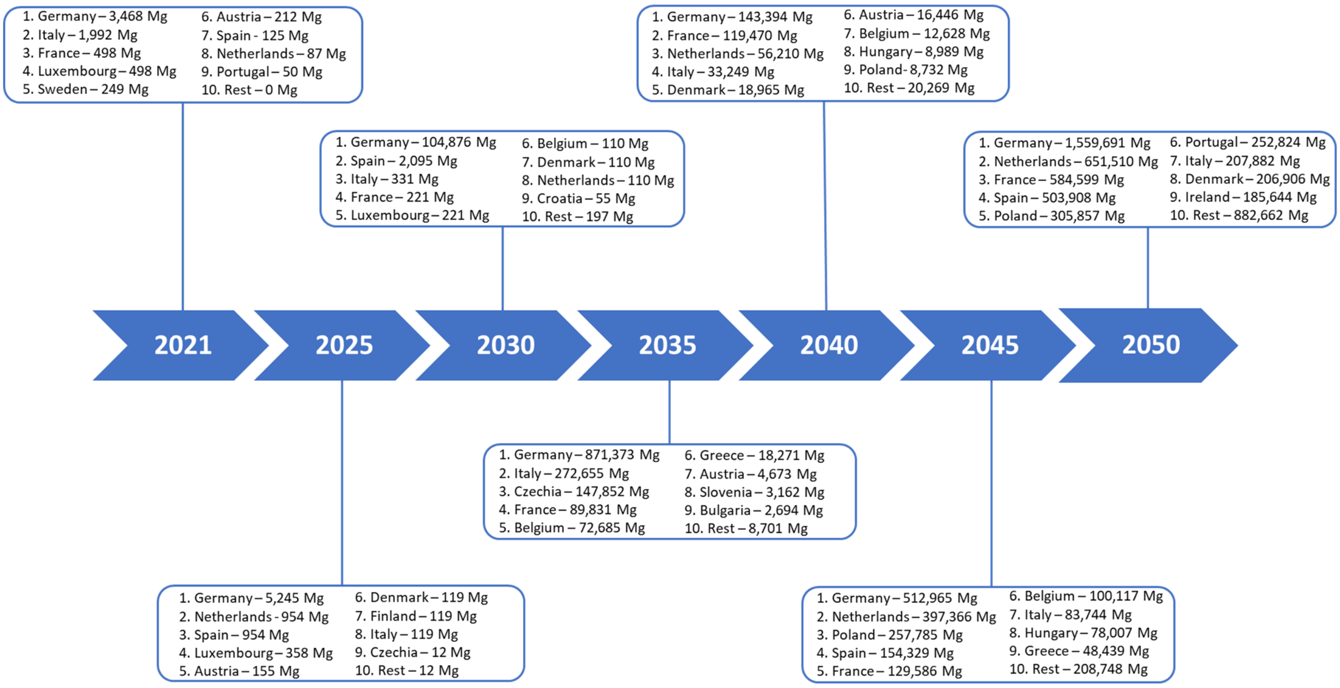


Figure 6. Annual increase in PV waste in selected years in the EU.

Figure 6 summarizes the mass fluxes of PV waste generated for selected years, including the countries with the highest flux values. In each of the considered cases, Germany generates the largest flux of waste annually. The next places of the summary vary for every year. Countries with high installed PV capacities, in addition to Germany, are Italy, France, Spain and the Netherlands. However, the ranking of these countries in terms of PV waste generation over the 2021–2050 period is not same. For example, in 2021, 2025 and 2030, Luxembourg ranked high in the summary of the amount of annual EoL growth of PV panels. This is a country with a relatively early start in investing in PV, hence ranking among the top countries in the early years of the projected waste PV panel market. Subsequent analyzed years did not show significant streams of PV waste generation compared to other EU countries; therefore, Luxembourg was no longer in the lead. In addition, the country's small surface area, which translates into a smaller area for PV investments, resulted in an inability to compete with larger-area countries, which intensified their PV investments in subsequent years. An example of such a country is Poland, which has significantly increased its level of installed PV capacity, starting from 2017. The installed PV capacity was increased by 157 and 58% in 2019/2020 and 2020/21, respectively. This is one of the examples of countries with a significant increase in photovoltaic investments in a short period of time. One of the reasons is the electricity billing system, which is advantageous for the prosumers, as well as the possibility of obtaining subsidies [45]. A similar situation took place in Hungary and Denmark, as well as in the Czech Republic and Belgium. However, in the case of the last two countries mentioned, the growth took place a bit earlier, starting in 2008. A fully predicted case is Ireland, which is expected to significantly increase the amount of installed PV capacity in 2022–2025. The forecast showed that significant amounts of PV waste will be generated in Ireland in 2050.

An important aspect of recycling PV waste is cost effectiveness. Currently, it is one of the factors hampering industrial investments in this area. In the future, when the waste stream increases, it should result in increased investments in this area. According to [44], the profitability threshold for the installation of recycling of waste photovoltaic panels is the waste stream of 19,000 Mg/year. Taking this assumption into account, there are several types of countries:

- Starting from a given year, those with a waste stream well above the threshold value. They include Germany, France, Italy, Netherlands, Ireland, Sweden, Romania, Poland and Portugal.
- Starting from a given year, those achieving a waste stream close to the threshold value, with the stream then fluctuating significantly, including a relevant reduction as well as a significant increase with respect to the profitability threshold. They include Spain, Hungary, Greece, Denmark, Czech Republic, Bulgaria, Belgium and Austria.
- In a given year or several years, those where the amount of generated waste exceeds the profitability threshold, while not exceeding it in the following years. They include Slovakia and Estonia.
- Those where the stream of generated PV waste does not exceed the profitability threshold in any year. They include Croatia, Cyprus, Finland, Latvia, Lithuania, Luxembourg, Malta and Slovenia.

Table 8 shows the dates of achieving the stream of generated PV waste according to the profitability criterion of photovoltaic waste recycling installations [44] by individual EU countries.

Table 8. Dates of achieving profitability criterion for PV waste recycling installation.

2028	2032	2033	2034	2035	2037	2038	2043	2046	2047
Germany	Spain	Italy	Belgium Czechia France	Greece	Austria Bulgaria Denmark	Netherlands	Hungary Poland Sweden	Estonia	Ireland Romania

5. Conclusions

The climate policy of the European Union focuses on the development of renewable energy sources, which has been a trend in the Member States in recent years. One of the most frequently used technologies is photovoltaics. It is in line with the SDG sustainable development goals. There has been a significant development of PV technology recently, and it has spreaded to a large extent in Europe. The prediction for PV technology indicates its further development and an increase in its share in electricity production. Consequently, there will be the need to manage PV waste after its useful life (average 20–35 years). The guidelines on the method of management are included in the EU legislation. Accordingly, PV panels have been classified as WEEE waste, and therefore they are subject to the requirements regarding recovery levels. The recommended method, in line with the idea of the circular economy, is recycling. It enables the high-efficiency recovery of materials.

The method of recycling EoL photovoltaic panels with a high recovery rate is called upcycling. It includes various mechanical, chemical and thermal processes that allow for highly efficient recovery. This method of management of photovoltaic waste is positively assessed in terms of environmental impact compared to other ones, despite the use of chemicals or high energy consumption. Nevertheless, the currently existing installations for recycling PV panels are indicative. The small streams of generated waste translate into a lack of profitability. However, this situation is estimated to change in the coming years, requiring immediate action. The prediction of the amount of PV waste generated in the EU in the 2021–2050 perspective indicates that the need to manage a significant stream of PV waste will take place already at the end of the 2020s. It will appear the earliest in Germany, the largest market for EoL photovoltaic panels in the EU. In 2030, the stream of PV waste generated in this European country will amount to over 100,000 Mg, and in 2050, it will be almost 16 times higher. The prospect of a significant increase in this type of waste for other EU countries will come later, depending on the specific implementation of photovoltaic technology in recent years. In total, the community will be generating over 1 million Mg of PV waste annually in the years 2035–2037 and 2044–2050. In 2050, the annual growth will amount to 5.34 million Mg, while the accumulated amount of PV waste generated in the EU by 2050 will be over 33 million Mg.

A characteristic feature of the European market of used photovoltaic modules is a significant diversification of the amount of waste generated in the analyzed period. This diversification is important in the economic assessment of photovoltaic waste recycling plants. The rule applicable in this case is as follows: the larger the stream of processed waste, the more profitable it is to recycle. The demand of the EU countries for full-scale installations of high-efficiency recycling of PV waste was determined on the basis of the assumed cost-effectiveness condition. Dates have been set for some of the countries to become profitable. Not all of them will generate significant amounts of photovoltaic waste. In 2028, it will take place in Germany; in the 30s, it will take place in Spain, Italy, Belgium, the Czech Republic, France, Greece, Austria, Bulgaria, Denmark and the Netherlands; and in the 40s it will take place in Hungary, Poland, Sweden, Estonia, Ireland and Romania.

By analyzing the obtained PV waste streams in individual EU countries in the years 2021–2050 from the economic point of view, possible management systems for EoL PV panels can be specified. Depending on the size of the annual waste streams, they can be defined as follows: a profitable system of recycling plants with stable supplies of input material (among others in Germany, France and Italy); a conditionally profitable system of recycling plants without ensuring a stable supply of input material (among others in Spain, Hungary and Greece); an unprofitable central recycling plant without ensuring stable supplies of waste (among others in Slovakia, Estonia and Croatia). Profitability is one of the evaluation criteria here. One should be reminded of the EPR system, which is established to ensure financing of the PV waste management system, even in the case of unprofitability. However, for some markets, management of EoL photovoltaic panels will require much more funding from producers and distributors. Therefore, it seems reasonable to create a common market for waste of photovoltaic panels as an alternative scenario to the management of this type of waste by each Member State on its own.

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References

1. *The Paris Agreement*; United Nations Climate Change: Paris, France, 2015.
2. United Nations Sustainable Development Goals. Available online: https://sdgs.un.org/goals (accessed on 28 November 2022).
3. Czajkowski, A.; Poranek, N.; Remiorz, L. Renewable Energy Sources as an Element of European Green Deal and Sustainable Development Goals (SDG). In *Proceedings of the 21st International Multidisciplinary Scientific GeoConference SGEM, Sofia, Bulgaria, 7–10 December 2021*; Trofymchuk, O., Baiba, R., Eds.; SGEM International Multidisciplinary Scientific GeoConference: Sofia, Bulgaria, 2021; Volume 21, pp. 187–196. [CrossRef]
4. Poranek, N.; Łaźniewska-Piekarczyk, B.; Lombardi, L.; Czajkowski, A.; Bogacka, M.; Pikoń, K. Green Deal and circular economy of bottom ash waste management in building industry—Alkali (NaOH) pre-treatment. *Materials* **2022**, *15*, 3487. [CrossRef]

5. *Future of Solar Photovoltaic: Deployment, Investment, Technology, Grid Integration and Socio-Economic Aspects (A Global Energy Transformation: Paper)*; International Renewable Energy Agency, IRENA: Abu Dhabi, United Arab Emirates, 2019.
6. *Trading Into a New Bright Energy Future*; International Renewable Energy Agency, IRENA: Abu Dhabi, United Arab Emirates, 2021.
7. *Solar PV*; International Energy Agency IEA: Paris, France, 2021.
8. Solar Power Europe—Leading the Energy Transition. Available online: www.solarpowereurope.org (accessed on 30 October 2022).
9. Cerchier, P.; Brunelli, K.; Pezzato, L.; Audoin, C.; Rakotoniaina, J.P.; Sessa, T.; Tammaro, M.; Sabia, G.; Attanasio, A.; Forte, C. Innovative recycling of end of life silicon PV panels: Resielp. *Detritus* **2021**, *16*, 41–47. [CrossRef]
10. Gaska, K.; Generowicz, A. SMART computational solutions for the optimization of selected technology processes as an innovation and progress in improving energy efficiency of smart cities—A case study. *Energies* **2020**, *13*, 3338. [CrossRef]
11. *Directive 2012/19/EU on Waste Electrical and Electronic Equipment*; European Commission: Brussels, Belgium, 2012.
12. Global Cumulative Installed Solar PV Capacity. Statista. Available online: https://www.statista.com/statistics/280220/global-cumulative-installed-solar-pv-capacity (accessed on 29 September 2022).
13. Chen, W.-S.; Chen, Y.-J.; Lee, C.-H.; Cheng, Y.-J.; Chen, Y.-A.; Liu, F.-W.; Wang, Y.-C.; Chueh, Y.-L. Recovery of Valuable Materials from the Waste Crystalline-Silicon Photovoltaic Cell and Ribbon. *Processes* **2021**, *9*, 712. [CrossRef]
14. 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 Rev.* **2020**, *27*, 100431. [CrossRef]
15. Al-Waeli, A.H.; Kazem, H.A.; Chaichan, M.T. Review and design of a standalone PV system performance. *Int. J. Comput. Appl. Sci.* **2016**, *1*, 1.
16. Włodarczyk, R. Analysis of the Photovoltaic Waste-Recycling Process in Polish Conditions—A Short Review. *Sustainability* **2022**, *14*, 4739. [CrossRef]
17. Tan, J.; Jia, S.; Ramakrishna, S. End-of-Life Photovoltaic Modules. *Energies* **2022**, *15*, 5113. [CrossRef]
18. BP. *Statistical Review of World Energy 2022*; BP: London, UK, 2022.
19. *Solar Thermal and Concentrated Solar Power Barometers*; Eur'observer: Paris, France, 2022.
20. Dodd, N.; Espinosa, N. Preparatory Study for Solar Photovoltaic Modules, Inverters and Systems: Options for an EU Ecolabel and Green Public Procurement, European Commission, Joint Research Centre. 2018. Available online: https://susproc.jrc.ec.europa.eu/product-bureau/sites/default/files/contentype/product_group_documents/1581689975/190410_PV_Prep_study_Ecolabel_and_GPP_Preliminary_Consultation_Draft.pdf (accessed on 30 October 2022).
21. Renewable Energy—Recast to 2030 (RED II). Available online: https://joint-research-centre.ec.europa.eu/welcome-jec-website/reference-regulatory-framework/renewable-energy-recast-2030-red-ii_en (accessed on 10 October 2022).
22. Besiou, M.; Van Wassenhove, L.N. Closed-loop supply chains for photovoltaic panels: A case-based approach. *J. Ind. Ecol.* **2016**, *20*, 929–937. [CrossRef]
23. Clyncke, J. Regulatory Developments in Europe—The EU WEEE Directive and the National Implementations. In Proceedings of the 29th European Photovoltaic Solar Energy Conference, Amsterdam, The Netherlands, 22–26 September 2014.
24. Wambach, K. *Life Cycle Inventory of Current Photovoltaic Module Recycling Process in Europe*; The United States Department of Energy and Electric Power Research Institute: Washington, DC, USA, 2017.
25. Markert, E.; Celik, I.; Apul, D. Private and Externality Costs and Benefits of Recycling Crystalline Silicon (c-Si) Photovoltaic Panels. *Energies* **2020**, *13*, 3650. [CrossRef]
26. Fraunhofer Institute for Solar Energy Systems. *Photovoltaics Report*; Fraunhofer Institute for Solar Energy Systems, ISE: Freiburg im Breisgau, Germany, 2022.
27. Muteri, V.; Cellura, M.; Curto, D.; Franzitta, V.; Longo, S.; Mistretta, M.; Parisi, M.L. Review on Life Cycle Assessment of Solar Photovoltaic Panels. *Energies* **2020**, *13*, 252. [CrossRef]
28. Bukowski, M.; Majewski, J.; Sobolewska, A. Macroeconomic Electric Energy Production Efficiency of Photovoltaic Panels in Single-Family Homes in Poland. *Energies* **2021**, *14*, 126. [CrossRef]
29. Sung, K. A Review on Upcycling: Current Body of Literature, Knowledge Gaps and a Way Forward. In Proceedings of the ICECESS 2015 17th International Conference on Environmental, Cultural, Economic and Social Sustainability, Online, 23–16 February 2021; World Academy of Science, Engineering and Technology (WASET): Venice, Italy, 2015.
30. Held, M. LCA screening of a recycling process for silicon based PV modules. Available online: http://www.pvcycle.org.uk/wp-content/uploads/Exec-Summary-LCA-Screening-of-a-Recycling-process-of-silicon-based-PV-modules-2012-07.pdf (accessed on 28 October 2022).
31. Duflou, J.R.; Peeters, J.R.; Altamirano, D.; Bracquene, F.; Dewulf, W. Demanufacturing photovoltaic panels: Comparison of end-of-life treatment strategies for improved resource recovery. *CIRP Ann.* **2018**, *67*, 29–32. [CrossRef]
32. Granata, G.; Pagnanelli, F.; Moscardini, E.; Havlik, T.; Toro, L. Recycling of photovoltaic panels by physical operations. *Sol. Energy Mater. Sol. Cells* **2014**, *123*, 239–248. [CrossRef]
33. Dassisti, M.; Florio, G.; Maddalena, F.; Campana, G.; Howlett, R.J.; Setchi, R.; Cimatti, B. *Cryogenic Delamination and Sustainability: Analysis of an Innovative Recycling Process for Photovoltaic Crystalline Modules BT—Sustainable Design and Manufacturing 2017*; Springer International Publishing: Cham, Switzerland, 2017; pp. 637–646.
34. Wang, S. Method and Device for Decomposing and Recycling Photovoltaic Component. CN102544239A. 2014. Available online: https://patents.google.com/patent/CN102544239B/en (accessed on 24 October 2022).

35. Klugmann-Radziemska, E.; Ostrowski, P.; Drabczyk, K.; Panek, P.; Szkodo, M. Experimental validation of crystalline silicon solar cells recycling by thermal and chemical methods. *Sol. Energy Mater. Sol. Cells* **2010**, *94*, 2275–2282. [CrossRef]
36. PV Cycle. Available online: http://www.pvcycle.org/homepage/ (accessed on 30 October 2022).
37. Veolia. Recycling Photovoltaic Panels, a Technology Unique in France. Available online: https://www.veolia.com/en/solution/recycling-photovoltaic-panels-technology-unique-france (accessed on 20 October 2022).
38. Recycling of Solar Panels: A New Challenge for Going Green. Available online: https://techinformed.com/recycling-solar-panels-a-new-challenge-for-going-green/ (accessed on 25 October 2022).
39. Loser Chemie. Available online: https://lc-freiberg.de/products-and-services/non-destructive-processing-of-pv-modules/?lang=en (accessed on 28 October 2022).
40. Solar World. Available online: https://www.technologyreview.com/2021/08/19/1032215/solar-panels-recycling/ (accessed on 15 October 2022).
41. Pagnanelli, F.; Moscardini, E.; Granata, G.; Abo Atia, T.; Altimari, P.; Havlik, T. Physical and chemical treatment of end of life panels: An integrated automatic approach viable for different photovoltaic technologies. *Waste Manag.* **2017**, *59*, 422–431. [CrossRef]
42. Latunussa, C.E.L.L.; Ardente, F.; Blengini, G.A.; Mancini, L. Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels. *Sol. Energy Mater. Sol. Cells* **2016**, *156*, 101–111. [CrossRef]
43. Shin, J.; Park, J.; Park, N. A method to recycle silicon wafer from end-of-life photovoltaic module and solar panels by using recycled silicon wafers. *Sol. Energy Mater. Sol. Cells* **2017**, *162*, 1–6. [CrossRef]
44. Azeumo, M.F.; Conte, G.; Ippolito, N.M.; Medici, F.; Piga, I.; Santilli, S. Photovoltaic module recycling, a physical and a chemical recovery process. *Sol. Energy Mater Sol. Cells* **2019**, *193*, 314–319. [CrossRef]
45. Lee, C.-H.; Chang, Y.-W.; Popuri, S.R.; Hung, C.-E.; Liao, C.-H.; Chang, J.-E. Recovery of silicon, copper and aluminium from scrap silicon wafers by leaching and precipitation. *Environ. Eng. Manag. J.* **2018**, *17*, 561–568.
46. Dias, P.; Javimczik, S.; Benevit, M.; Veit, H.; Bernardes, A.M. Recycling WEEE: Extraction and concentration of silver from waste crystalline silicon photovoltaic modules. *Waste Manag.* **2016**, *57*, 9242–9250. [CrossRef] [PubMed]
47. Lee, C.H.; Hung, C.-E.; Tsai, S.-L.; Popuri, S.R.; Liao, C.-H. Resource recovery of scrap silicon solar battery cell. *Waste Manage. Res.* **2013**, *31*, 518–524. [CrossRef] [PubMed]
48. Paiano, A. Photovoltaic waste assessment in Italy. *Renew. Sustain. Energy Rev.* **2015**, *41*, 99–112. [CrossRef]
49. Jung, B.; Park, J.; Seo, D.; Park, N. Sustainable system for raw-metal recovery from crystalline silicon solar panels: From noble-metal extraction to lead removal. *ACS Sustain. Chem. Eng.* **2016**, *4*, 4079–4083. [CrossRef]
50. SolarPower Europe. *EU Market Outlook for Solar Power 2021–2025*; SolarPower Europe: Brussels, Belgium, 2021.
51. Choi, J.K.; Fthenakis, V. Crystalline silicon photovoltaic recycling planning: Macro and micro perspectives. *J. Clean. Prod.* **2014**, *66*, 443–449. [CrossRef]
52. Dykas, S.; Szymański, A.; Cai, X. Real prospects for the development of power technologies based on renewable energy sources in Poland. *Front. Energy* **2017**, *11*, 168–174. [CrossRef]
53. Muller, A.; Wambach, K.; Alsema, E. Life cycle analysis of solar module recycling process. *MRS Proc.* **2005**, *895*, 307. [CrossRef]
54. Vellini, M.; Gambini, M.; Prattella, V. Environmental impacts of PV technology throughout the life cycle: Importance of the end-of-life management for Si-panels and CdTe-panels. *Energy* **2017**, *138*, 1099–1111. [CrossRef]
55. Huang, B.; Zhao, J.; Chai, J.; Xue, B.; Zhao, F.; Wang, X. Environmental influence assessment of China's multicrystalline silicon (multi-Si) photovoltaic modules considering recycling process. *Sol. Energy* **2017**, *143*, 132–141. [CrossRef]
56. Stolz, P.; Frischknecht, R.; Wambach, K.; Sinha, P.; Heath, G. *Life Cycle Assessment of Photovoltaic Module Recycling*; CH Treeze Ltd.: Uster, Switzerland, 2016.
57. Lunardi, M.; Alvarez-Gaitan, J.; Bilbao, J.; Corkish, R. Comparative life cycle assessment of end-of-life silicon photovoltaic modules. *Appl. Sci.* **2018**, *8*, 1396. [CrossRef]
58. D'Adamo, I.; Miliacca, M.; Rosa, P.; Rosa, P. Economic feasibility for recycling of waste crystalline silicon photovoltaic modules. *Int. J. Photoenergy* **2017**, *2017*, 1–6. [CrossRef]

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