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Photovoltaic Waste Generation in the Context of Sustainable Energy Transition in EU Member States

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Abstract: The European Union (EU) is witnessing an expansion in solar capacity, aligning with its commitment to achieving climate neutrality by 2050. However, deploying solar capacity introduces significant environmental complexities, such as managing photovoltaic waste when the modules reach their end of life. This study presents an assessment of PV waste mass generation, integrating the latest data from the revised targets of the National Energy and Climate Plans (NECPs) of EU Member States presented in December 2023. Annual and cumulative PV waste mass is presented, analyzing the results in terms of the PV capacity deployment in each country and their recycling needs to face the treatment of the generated PV waste. According to the reviewed targets, the analysis reveals significant variations in PV waste mass generation across EU countries. The revisions show a substantial increase in the amount of waste generated in Europe. Lithuania and Ireland are anticipated to face substantial challenges, particularly under the early-loss scenario, whereas Germany, Italy, France, and Spain continue to be the countries that will generate the most PV waste mass in Europe. These findings emphasize the necessity for formulating and implementing effective waste management strategies to address the increasing generation of PV waste and mitigate its environmental impact. Furthermore, the study underscores the need to reassess projections to accommodate evolving energy policies and targets, ensuring alignment with sustainability objectives in this dynamic field.

Keywords: photovoltaic waste management; end-of-life photovoltaic modules; National Energy and Climate Plans (NECPs); circular economy; PV module recycling; solar PV sustainability; sustainable energy transition

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1. Introduction

Various factors drive the worldwide adoption of solar photovoltaic (PV) energy. These include the upward trend in global electricity prices, countries' increasing commitment to achieving decarbonization targets, and their efforts to boost the proportion of renewable energy in their energy holdings [1].

In 2022, the global increase in newly installed photovoltaic (PV) solar capacity reached 239 GW, establishing a new record with an impressive annual growth rate of 45%, representing the highest observed since 2016. Consequently, the total global installed solar capacity surpassed the terawatt threshold at the beginning of 2022, amounting to approximately

1.2 TW by the end of the year, representing a 25% increase compared to 2021 [2]. This upward trajectory continued in 2023, as evidenced by the IEA report [3], which indicates that the global solar PV capacity added to the grid ranged between 407.3 and 446 GW. This marked another record-breaking year, with an annual growth rate reaching up to 85%, representing the highest rate since 2011. Concurrently, the European Union (EU) exhibited a persistent pattern of expansion in solar capacity, attaining a cumulative installed capacity of 263 GW in 2023 [2]. These developments underscore the EU's unwavering commitment to advancing the deployment of renewable energy technologies in pursuit of its climate neutrality objectives by 2050, as outlined in the European Climate Act [4]. This legislative framework not only reaffirms the EU's goal of achieving a climate-neutral society but also sets ambitious targets, including a mandatory reduction in net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. Such milestones highlight the EU's comprehensive approach to addressing climate change through the accelerated adoption of renewable energy sources and the implementation of rigorous emission reduction policies. To promote the achievement of such targets, each EU Member State is required to develop a comprehensive National Energy and Climate Plan (NECP). This was established under the Regulation (EU) 2018/1999 on the governance of the Energy Union. The main purpose is to provide a comprehensive tool for planning and monitoring the climate and energy policies for the period 2021–2030. This framework stems from the need to meet the commitments of the Paris Agreement and to ensure an orderly and effective energy transition [5]. The NECPs address five interrelated dimensions: decarbonization, energy efficiency, energy security, the internal energy market, and research and innovation. This multi-dimensional approach is designed to ensure coherence between national policies and collective EU targets, such as the 40% reduction in greenhouse gas emissions by 2030 originally set out in the 2014 Energy and Climate package [6]. Although every two years, each country must submit a progress report to the EU Commission according to the Implementing Regulation [7] technological and economic developments since 2019 and an additional geopolitical distinctive situation have justified the revision of the NECPs [8]. Significant cost reductions in renewable energy, energy storage, and electrification technologies have widened the scope for implementing sustainable solutions. Incorporating these developments into the updated plans will allow EU members to maximize the benefits of PV solar technologies and accelerate the energy transition. In 2023, EU members presented updated targets that were more ambitious than those proposed in previous plans. This deployment represents significant progress in reducing greenhouse gas emissions and mitigating climate change. At the same time, however, it introduces significant environmental complexities, particularly in managing and disposing of PV waste streams. With PV modules typically having a 25- to 30-year lifespan, the escalating rate of PV installations raises concerns about the scale and impact of PV waste generation over the coming decades. One management option for this type of waste is recycling. Numerous studies focus on photovoltaic module recycling methods [9–11], primarily calculating the percentage of raw materials that can be effectively recovered. Although a few studies have estimated the total mass of photovoltaic waste generated [12,13], they provide results only for China; the calculation for other countries is still a challenge. For instance, Santos et al. [14], addressed this gap by projecting the generation of PV waste mass for Spain up to 2030 and 2050. A previous study by the authors of this work [15] developed several scenarios for the projection of PV waste mass in China, the USA, Europe as a whole, France, Spain, Italy, Germany, the United Kingdom, Brazil, Chile, and Argentina. Calculations were performed using the methodology described in former publications [16] and were based on historical data of PV deployment in the analyzed countries and regions and the NECPs submitted in 2019. The results highlighted the necessity for effective management strategies for incoming

PV waste. However, the dynamic nature of energy policies and targets compels a new reassessment of these projections for European countries to account for evolving priorities and commitments, considering the revised targets of the countries' NECPs.

This study presents a comprehensive and up-to-date assessment of the mass generation of PV waste in Europe. All European countries are included in the present calculations, integrating the most recent data from the updated NECPs of EU Member States with the revised December 2023 targets. Our analysis extends beyond mere estimation, incorporating the implications of updated and more ambitious deployment goals. Furthermore, it considers both standard and early-loss scenarios, thus accounting for potential variabilities in module lifespans. Furthermore, we examine country-specific trends, highlighting significant differences in projected waste generation among EU nations. This study not only offers insights into the magnitude of the PV waste challenge but also underscores the importance of aligning waste management strategies with the rapidly evolving energy transition landscape. The objective is to inform policymakers and support the implementation of sustainable solutions to mitigate the environmental impact of growing PV waste streams and to make PV solar energy more circular.

2. Methods

The determination of photovoltaic (PV) waste mass is derived from a comprehensive analysis comprising the following procedural steps, which were already described in our previous studies [14,15].

1. Compilation of data concerning the cumulative installed PV capacity across EU countries up to 2023 [8].
2. Gathering of the updated National Energy and Climate Plan (NECP) targets (see Table A1, Appendix A).
3. Projecting the annual installed PV capacity towards 2030 and 2050, considering two different degradation scenarios.
4. Conversion of the projected annual installed PV capacity into corresponding annual installed mass.
5. Estimating PV waste mass through an iterative methodology.

This methodological approach consists of a series of key steps designed to estimate PV waste mass across EU countries. These steps, ranging from data compilation and NECP targets integration to modeling and mass conversion, provide a comprehensive framework for the analysis.

The subsequent subsections delve deeper into the components of this methodology. Section 2.1 examines the updated NECP targets, offering insights into how national policies shape PV capacity growth. Section 2.2 introduces the degradation model, a critical tool for understanding module lifespan and its impact on waste mass generation. Section 2.3 explores the evolution of installed and projected PV capacity, linking policy-driven goals and practical implementation. Finally, Section 2.4 presents the conversion methodology, translating installed capacity projections into PV waste mass estimates.

2.1. NECP Targets

This section presents the National Energy and Climate targets for each of the 27 European countries, comparing the current targets to the previous ones in 2019.

Figure 1 represents the percentage increase calculated as the difference between the final value and the initial value divided by the initial value. Figure 1 shows differences between the updated NECP and the 2019 submission targets. Austria and Latvia have been omitted from the representation, as these countries did not submit an updated NECP prior to July 2024 with the rest of the EU members.

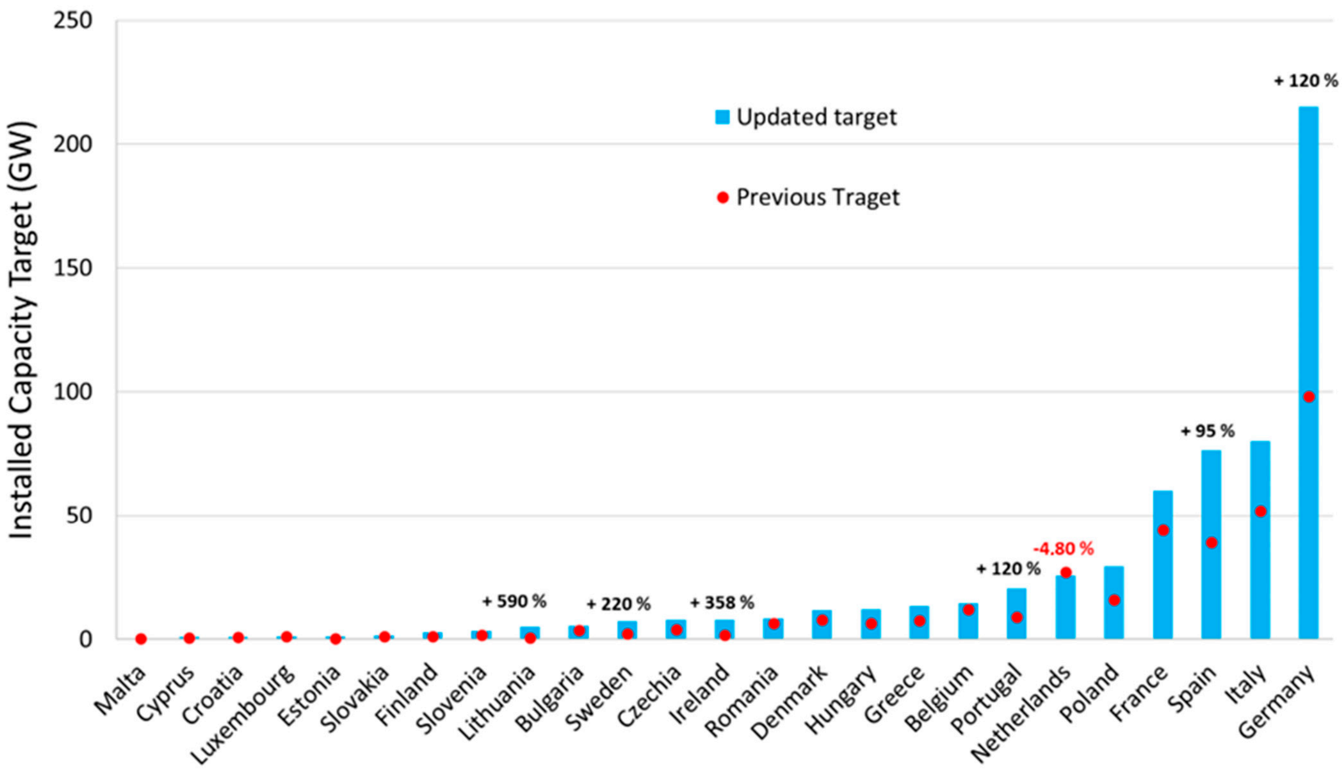


Figure 1. Comparison between updated NECP objectives and previous objectives.

In the context of the present study, Austria is a unique case for consideration due to two factors. Firstly, the submission of its National Energy and Climate Plan (NECP) [17] to the EU Commission was made only in December 2024. Secondly, the NECP contains no updated specific PV targets. In this instance, the NECP is oriented towards formulating a strategy to reach 100% coverage of domestic electricity consumption from renewable sources by 2030 with an anticipated generation of 17 TWh from photovoltaics. An estimation of the installed PV capacity through 2030 is 17 GW, and therefore, the results presented in Section 3 are preliminary. On the other hand, Latvia submitted its NECP in July 2024, which states that, under the target scenario, the share of renewable electricity is projected to rise from around 51% in 2021 to 100% in 2030. This is supported by a significant increase in PV capacity, estimated at 297, resulting in a predicted capacity of 2127 GW [18].

As can be seen, most EU countries have revised their projections for PV capacity up to 2030 in the new plans submitted. Ireland and Lithuania have presented markedly elevated targets, with increases of 358% and 590%, respectively. This implies a significant strategic shift in the focus of their energy matrix. Also, Sweden presents a robust commitment with an increase of 220% on the NECP target, while Estonia has demonstrated a notable shift in policy, setting an increase of 190%. In the case of Spain, the country has set a significant milestone with the revision of its NECP, increasing its targets by 95%. Portugal has shown even greater ambition, with a 120% increase. Although Germany remains the European leader in PV capacity, it has also significantly increased its targets, doubling them compared to 2019. For Belgium, it is relevant to note that in the most recent version of the NECP, no clear targets for PV capacity have been set for each region of the country. Instead, targets have been set for electricity generation and renewable generation. Consequently, the updated calculations also constitute an estimate. The current projections for the PV waste mass in Belgium have not changed significantly compared to our previous calculations. The NECP submitted in 2019 lacked a defined target for PV capacity. This was because each region of the country proposed different strategies for the development of its energy mix in order to meet the decarbonization targets of the energy system.

On the other hand, the Netherlands has been forced to reduce its targets by 4.8% due to growing domestic opposition to solar farm projects. This adjustment highlights the challenges facing energy and climate transition policies in the context of social controversy.

These developments, except for the Netherlands, indicate a strategic commitment to greater reliance on solar PV energy. The revisions indicate a collective and robust determination to enhance solar energy capacity by 2030.

2.2. Degradation Model for Solar PV Modules

Performance degradation of photovoltaic (PV) modules influences several parameters crucial for their operation. A faulty assessment of this degradation leads to inaccurate power predictions and waste generation. Therefore, for a reliable estimation of the lifespan of PV modules, it is essential to develop a precise statistical model that depicts their degradation process effectively.

Although contemporary reliability studies aim to achieve module lifespans of up to 50 years [19], current assessment tools lack precision in evaluating degradation processes and potential failure modes over prolonged periods. It is argued that there is a pressing need to expedite the established learning cycle for PV reliability to align with the rapid technological progress and heightened expectations placed on PV systems during the global energy transition [20].

Numerous studies have focused on modeling PV module degradation, addressing aspects such as distribution parameters and lifetime. Kumar et al. and Lai et al. [21,22] have made significant contributions to this field with complementary approaches.

Kumar et al. analyze the performance of gamma and Gaussian distribution models and calibrate them using maximum likelihood estimation and particle swarm optimization. The authors state that their results show a significant improvement in model accuracy, highlighting the superiority of the constant σ Gaussian distribution model.

Meanwhile, Lai et al. take a more integrated approach to PV module reliability, placing it in the product design and development context. Using a Design for Reliability (DFR) approach, they compare the reliability of two module designs, integrating considerations throughout the product lifecycle. The authors criticize the exclusive use of simple statistical measures, such as the sample mean, to assess reliability. Instead, they propose more sophisticated methods, such as Weibull analysis and linear regression, which allow a more accurate characterization of the reliability distribution of the modules evaluated.

These contributions not only extend the understanding of degradation models but also highlight the importance of advanced statistical methods to address the inherent complexities of PV module reliability analysis. On the other hand, the Weibull probability function has proven suitable for PV degradation evolution [23,24]. Both studies demonstrate the suitability of the Weibull distribution for modeling the degradation and reliability of photovoltaic (PV) modules.

Kuitche's study focuses on crystalline silicon photovoltaic (PV) modules in Phoenix, Arizona's hot and dry climate. The Weibull distribution is employed in the study's time-to-failure analysis. This research effectively models non-linear degradation patterns and incorporates critical environmental factors such as insolation and ambient temperature, thereby providing a robust framework for predicting PV module lifetime. Furthermore, Laronde's work further substantiates the utility of the Weibull distribution through its application in accelerated life testing (ALT) under severe temperature conditions. By combining the Weibull distribution with the Arrhenius model, Laronde is able to account for the differing lifecycle stages of PV modules, as well as translate ALT results back to nominal conditions. Moreover, he considers the stochastic nature of environmental variables in order to provide a more realistic assessment. Collectively, these studies demonstrate the versatility and robustness of the Weibull distribution, underscoring its pivotal role in the reliability assessment and lifetime prediction of PV technologies.

Therefore, the Weibull distribution as defined in *The Handbook* by Dodson [25] has been chosen for the present calculations, as in our previous work [15].

The Weibull probability density function is given at the instant time t by

$$f(t) = \frac{\alpha}{T}\left(\frac{t}{T}\right)^{\alpha-1} e^{-(t/T)^{\alpha}} \tag{1}$$

where α is the form factor and T the scale factor.

The study's calculations considered the regular-loss and early-loss scenarios established by the IEA-PVPS/IRENA [26]. Table 1 presents the corresponding parameters for the Weibull distribution. In both scenarios, a characteristic lifetime of 30 years was employed.

Table 1. Parameters of the Weibull distribution.

Scenario	A	T (Years)
Regular	5.3759	30
Early	2.4928	30

2.3. Annual Installed and Projected PV Capacity

The projected installed capacity in 2050 was determined by linear extrapolation, using both the total installed cumulative capacity in 2030, as outlined in each updated NECP, and the total installed cumulative capacity in 2023. This process assumes a constant annual installation rate from 2023 to 2030 to achieve the NECP targets, with the same slope used to extrapolate the values up to 2050. However, this linear extrapolation does not consider the progressive power loss affecting PV plants, which would result in a slower increase in cumulative capacity than was initially anticipated. To address this power loss, we propose a strategy involving the replacement of discarded modules in older PV plants and the development of new PV installations. This entails factoring in the annual repowering needs up to 2050 when projecting the annual installed PV power.

Figure 2, divided into three separate graphs for visualization purposes, shows the evolution of the annual installed PV power for the 27 EU Member States, considering the repowering requirements that will be implemented under the regular-loss scenario to meet their targets.

2.4. Conversion from Installed PV Power to Mass

The conversion process involves applying the updated exponential decay function equation [15], which is also presented here:

$$\text{Mass to power ratio} = A\, e^{-i/B} \tag{2}$$

This exponential decay function gives the mass-to-power ratio of PV modules installed in the year i, where A is the conversion factor in t MW^{-1}, and B is a time constant, and their values are A: 2.72×10^{25} t MW^{-1} and B: 37.11. This equation was first introduced by IEA-PVPS/IRENA, which, using technical data from solar panels for specific years, suggests that an exponential decay model effectively represents the correlation between PV mass per unit capacity t MW^{-1} and time in years. In a previous paper, we updated the parameters in Equation (2) to account for the advancements in the state-of-the-art module technology. Building upon this, the study incorporated actual data rather than projected values to achieve a more representative fit. Specifically, the power-to-weight ratio of the most commercially dominant PV panels was analyzed, focusing on models with 21% and higher efficiencies, which currently hold the largest market share. To ensure accuracy, the best-selling modules from each manufacturer were identified, and their power-to-weight ratios were derived from the corresponding technical datasheets. This ratio, calculated as the average of the nominal power and weight values, was subsequently integrated into the IEA curve as the reference value.

For illustrative purposes, Figure 3 depicts the annual installed PV module mass as projected by our methodology for countries with PV mass exceeding 100 k tons, while the same parameter for those countries that would install smaller amounts can be found in Figures A1 and A2 in Appendix A.

Except for the Netherlands, the updated projections demonstrate an increase over the previous calculations. The Netherlands' original NECP proposed a solar PV capacity of 27 GW by 2030, which has since been reduced to 25.7 GW in the revised version.

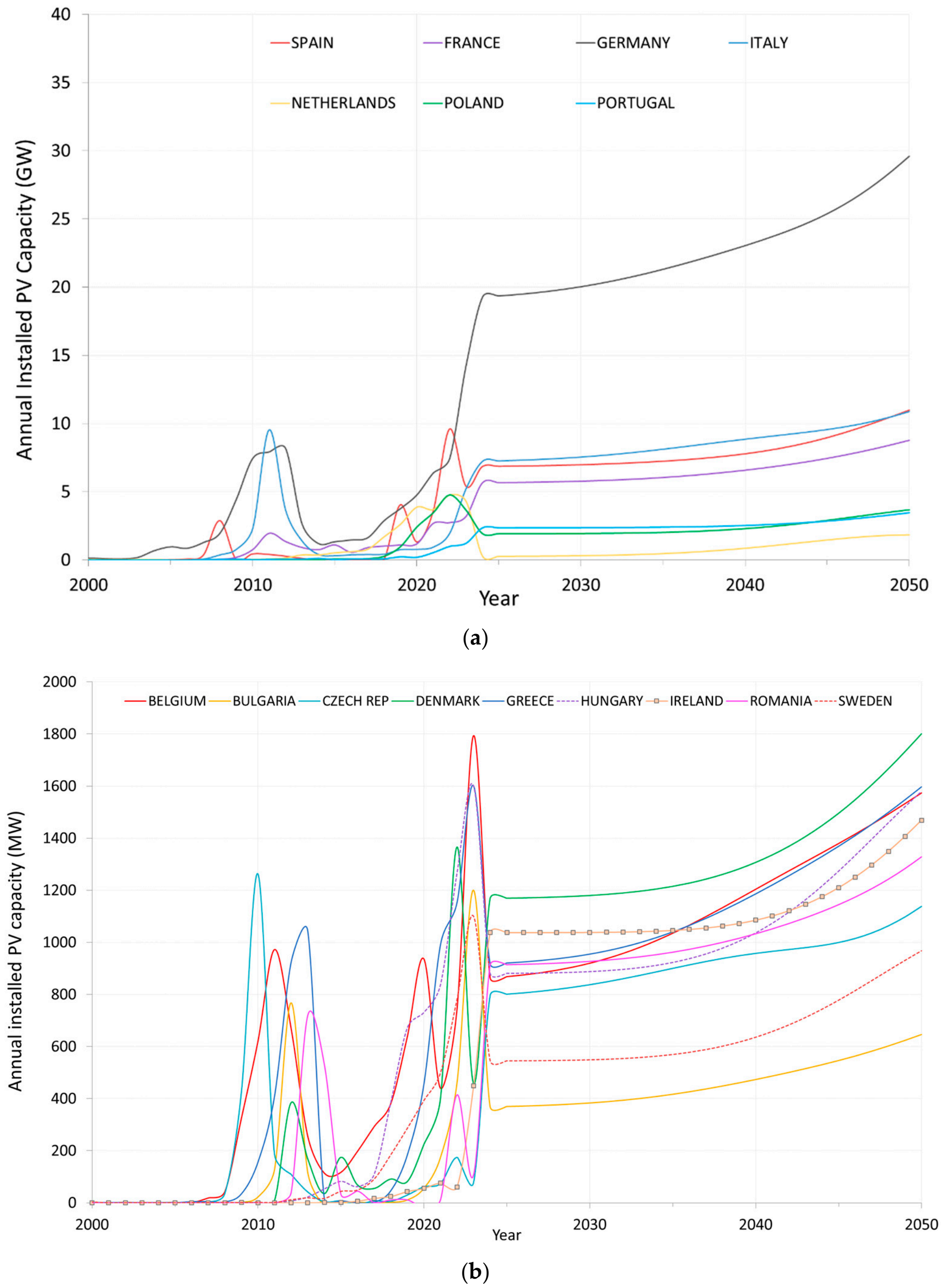
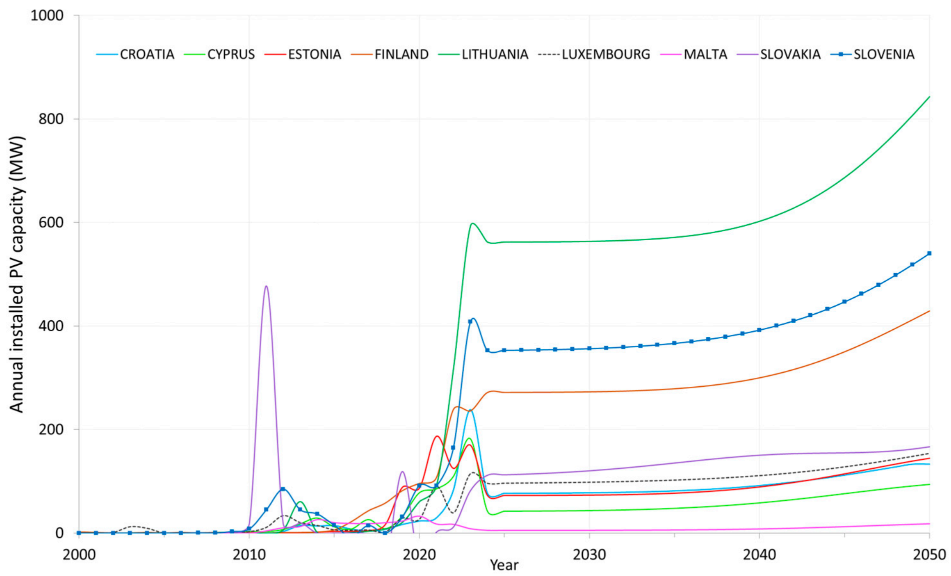


Figure 2. *Cont.*



(**c**)

Figure 2. (**a**) Projected annual installed capacity for countries with targets of less than 5 GW in 2030. (**b**) Projected annual installed capacity for countries with targets between 5 GW and 20 GW. (**c**) Projected annual installed capacity for countries with targets greater than 20 GW in 2030.

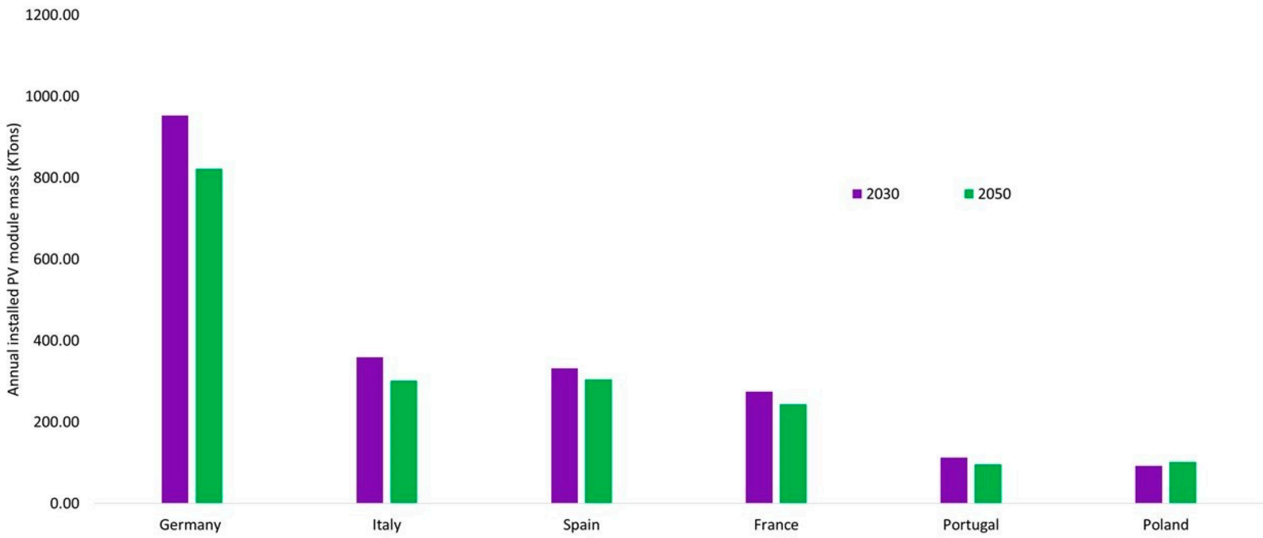


Figure 3. Projected annual PV installed mass up to 2030 and 2050 for EU members who submitted NECPs with updated targets for the regular-loss scenario: countries projected to install more than 100 k tons of PV modules.

3. Results and Discussion

3.1. Calculation of the Cumulative PV WEEE Mass

This analysis involves a crucial step—evaluating the annual mass of PV waste for each degradation scenario by assessing the corresponding annual installed module mass. From these data, we derive the cumulative PV mass.

Tables 2 and 3 illustrate the results of the calculation procedure for years 2030 and 2050, whilst Figures 4–6 present the yearly evolution from 2010 to 2050. For legibility reasons, some countries, Cyprus, Latvia, and Romania, have been excluded from the representation due to overlapping curves. The comprehensive methodology is first presented by Santos and Alonso-García, 2018.

Table 2. Projections of annual installed PV module mass, annual PV waste mass, and cumulative PV waste mass in 2030 and 2050 for the regular-loss scenario.

Country	Annual Installed PV Module Mass (t)		Annual PV Waste Mass (t)		Cumulative PV Waste Mass (t)	
	2030	2050	2030	2050	2030	2050
Austria *	70,063	26,743	1436	51,288	6306	393,272
Belgium	43,778	43,698	5458	41,173	22,195	522,231
Bulgaria	18,278	17,971	1368	15,585	6508	167,781
Croatia	3705	3708	54	3103	172	22,940
Cyprus	2070	2611	108	2997	381	27,062
Czech Rep	39,879	31,627	4234	18,535	18,954	261,109
Denmark	56,186	50,015	951	34,073	3433	258,496
Estonia	3500	4020	42	4071	102	30,521
Finlandia	12,991	11,922	106	8537	457	58,074
France	274,729	243,381	10,255	169,979	39,814	1,560,949
Germany	953,367	821,840	81,450	571,458	376,516	6,482,177
Greece	45,445	44,347	3420	38,416	13,172	420,968
Hungary	42,272	43,866	472	39,010	1275	290,006
Italy	359,121	302,129	30,517	200,648	126,144	2,528,001
Ireland	49,426	40,806	47	22,185	113	122,107
Latvia *	12,070	10,271	9	6,043	16	33,700
Lithuania	26,834	23,413	103	14,778	320	90,210
Luxembourg	4693	4284	265	3206	1413	28,849
Malta	322	551	86	891	303	12,585
The Netherlands	14,383	51,251	3222	96,361	11,322	943,482
Poland	92,358	102,000	794	97,891	1866	704,754
Portugal	112,925	96,331	865	58,097	3401	369,795
Romania	44,167	36,940	1173	22,275	5106	201,826
Slovakia	5746	4840	856	3572	3473	60,566
Slovenia	16,969	15,016	313	10,064	1651	76,113
Spain	332,237	304,846	14,008	225,589	65,094	1,837,772
Sweden	26,144	26,882	316	23,529	1073	172,754

* Preliminary results calculated from targets on NECPs submitted after July 2024.

Table 3. Projections of annual installed PV module mass, annual PV waste mass, and cumulative PV waste mass in 2030 and 2050 for the early-loss scenario.

Country	Annual Installed PV Module Mass (t)		Annual PV Waste Mass (t)		Cumulative PV Waste Mass (t)	
	2030	2050	2030	2050	2030	2050
Austria *	74,739	69,577	7350	50,609	36,732	614,082
Belgium	49,153	45,632	12,804	40,395	90,151	651,734
Bulgaria	20,089	18,853	3809	15,569	25,485	226,137
Croatia	3996	3799	422	2898	1837	35,379
Cyprus	2431	2464	578	2394	2931	34,988

Table 3. *Cont.*

Country	Annual Installed PV Module Mass (t)		Annual PV Waste Mass (t)		Cumulative PV Waste Mass (t)	
	2030	**2050**	**2030**	**2050**	**2030**	**2050**
Czech Rep	41,590	36,210	6585	24,947	56,420	365,923
Denmark	59,130	53,750	4717	36,355	23,664	422,920
Estonia	3928	3879	581	3327	2304	43,275
Finlandia	13,697	12,591	978	8617	4005	97,519
France	291,439	263,246	32,383	184,240	197,455	2,336,669
Germany	1,007,577	901,448	151,829	650,748	1,160,677	9,155,049
Greece	50,064	46,552	9677	38,205	62,745	558,974
Hungary	46,160	44,093	5391	34,567	22,151	430,690
Italy	380,998	337,771	60,838	243,101	461,882	3,493,715
Ireland	50,652	45,124	1484	26,782	4207	261,861
Latvia *	12,431	11,211	432	6913	1185	69,290
Lithuania	27,849	25,296	1328	16,211	4,685	170,504
Luxembourg	4973	4551	605	3299	4078	42,937
Malta	485	493	315	681	1968	13,353
The Netherlands	28,169	37,491	21,298	60,891	105,150	1,062,752
Poland	102,111	99,879	12,985	82,324	49,314	1,036,826
Portugal	116,862	105,095	5657	65,955	23,870	696,002
Romania	46,254	41,049	3997	26,663	25,159	319,759
Slovakia	6257	5493	1598	4428	12,763	74,976
Slovenia	17,802	16,189	1372	10,895	7545	126,350
Spain	236,356	218,042	36,697	230,067	224,636	2,862,638
Sweden	28,425	27,127	3182	21,072	13,216	260,252

* Preliminary results calculated from targets on NECPs submitted after July 2024.

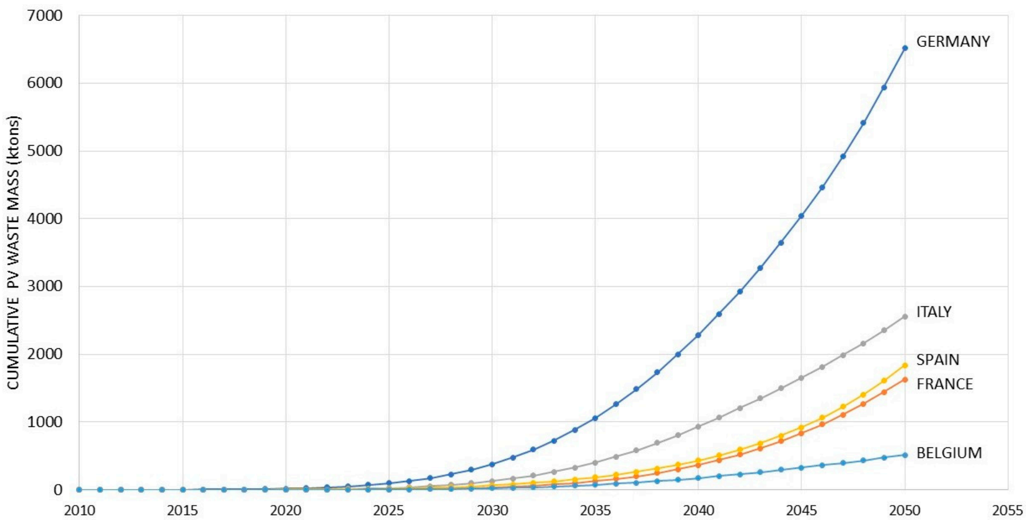


Figure 4. Estimation of the evolution of the cumulative PV waste mass considering the regular-loss scenario for Germany, Italy, Spain, France, and Belgium.

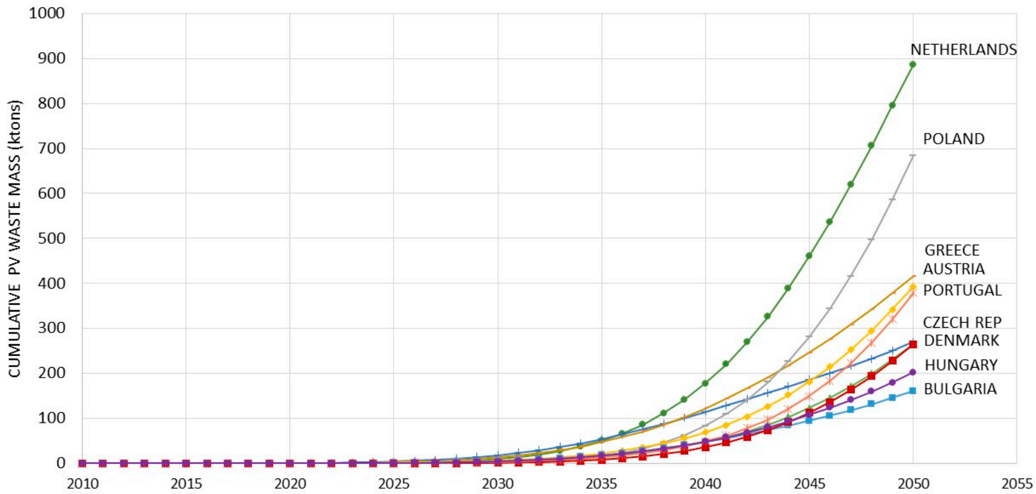


Figure 5. Estimation of the evolution of the cumulative PV waste mass considering the regular-loss scenario for the Netherlands, Poland, Austria, Greece, Portugal, Czech Republic, Denmark, Hungary, and Bulgaria.

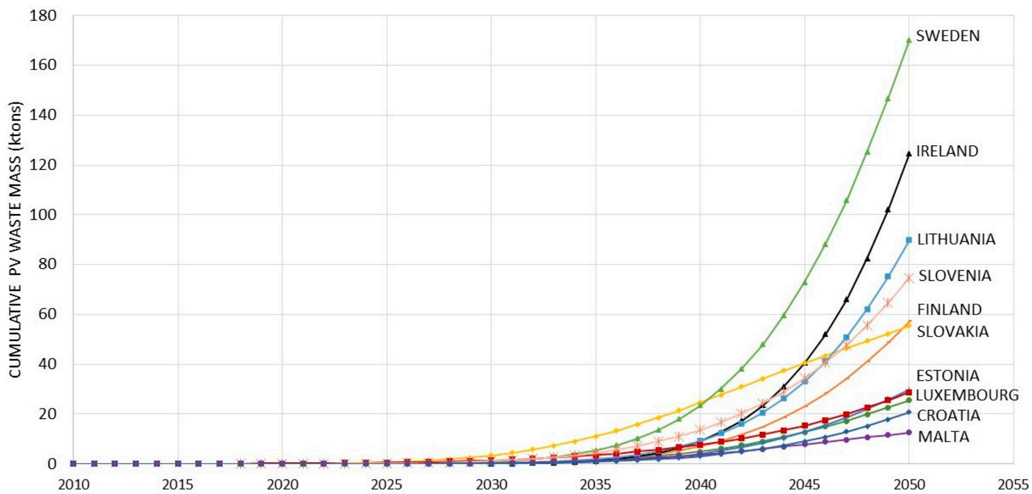


Figure 6. Estimation of the evolution of the cumulative PV waste mass considering the regular-loss scenario for Sweden, Ireland, Lithuania, Slovenia, Finland, Slovakia, Estonia, Luxembourg, Croatia, and Malta.

Figure 4 illustrates Europe's countries with the highest projected cumulative waste generation. The countries in question are Germany, Italy, Spain, France, and Belgium. In this group, Germany is the clear main producer with a projected waste generation of 6500 ktons by 2050, making it the country with the most significant management challenge. This volume is a direct reflection of the country's historic installed capacity, driven by national initiatives such as the Energiewende, which encouraged a significant increase in the deployment of solar energy. Similarly, Italy and Spain, with projected figures of 2600 and 1900 ktons, respectively, also face considerable challenges, given their favorable climates and policies that have encouraged the installation of photovoltaic systems. France, with a projected volume of 1900 ktons, demonstrates a relatively moderate growth trajectory, potentially attributable to its historical reliance on nuclear power. Conversely, Belgium anticipates a considerably lower volume, with less than 500 ktons, reflecting its geographical and climatic constraints with regard to the adoption of this technology. The projections indicate that, although the rate of growth may vary, the volume of waste generated is set to increase significantly from 2040 onwards. This is linked to the end of life of the systems installed between 2010 and 2020. This scenario emphasizes the necessity for the development of robust recycling infrastructures and advanced circular economy strategies, particularly in countries with high projected volumes.

Figure 5 provides supplementary insight by focusing on another group of European countries, led by the Netherlands and Poland. The Netherlands is projected to experience the highest accumulation of waste in this group, reaching approximately 900 ktons by 2050. This figure reflects a substantial deployment of PV systems in recent decades. Poland, with an estimated 700 ktons, follows closely behind, driven by national policies that have significantly encouraged the installation of solar systems.

The projections for Greece and Portugal indicate a more moderate growth in installed capacity, while the volumes registered in Austria, Bulgaria, Hungary, the Czech Republic, and Denmark are significantly lower, remaining below 250 ktons by 2050. In contrast to countries such as the Netherlands or Poland, which demonstrate a consistent and more pronounced growth in their cumulative waste projections, the Czech Republic exhibits a relatively flat trajectory during the initial decades of the period analyzed, followed by a more pronounced increase towards the later decades (2040–2050). This evolution can be explained by factors related to the initial deployment of photovoltaic (PV) technology, the regulatory framework, and the specific characteristics of the Czech Republic's energy system. In terms of installed capacity, the Czech Republic exhibited a comparatively gradual initial development of PV compared to countries such as the Netherlands, reflecting a more conservative adoption of these technologies during the 2010s. This may be linked to a lower availability of government incentives during the early stages of the energy transition in Eastern Europe, as well as a lower level of priority given to solar power in its energy matrix, which has historically relied more on resources such as coal and nuclear power. These differences reflect both the installed capacity and the political and economic priorities of each country.

Figure 6 provides an overview of countries with more limited PV capacities, including Sweden, Ireland, Lithuania, Slovenia, Finland, Slovakia, Estonia, Luxembourg, Croatia, and Malta. In this group, Sweden is projected to have the highest amount of waste by 2050, at approximately 180 ktons, followed by Ireland with 130 ktons and Lithuania with 90 ktons. The relatively high growth within the group can be attributed to recent efforts to integrate solar technologies into their energy matrices, which are aligned with European climate targets. The intermediate volumes are observed in countries such as Slovenia, Finland, and Slovakia, while the lowest projections are seen in Estonia, Luxembourg, Croatia, and Malta, with values remaining below 30 ktons. On initial examination, Slovakia appears to exhibit a divergent trajectory in comparison to the other countries within the group. While all countries exhibit exponential growth patterns towards 2050, the case of Slovakia is distinctive in that its growth is initially less pronounced, followed by a more accelerated and flattened increase from 2040 onwards. This behavior can be explained by specific factors related to the country's energy context, national policies, and technology adoption dynamics. The Slovakian energy matrix has been predominantly dominated by nuclear power, which has limited the early deployment of PV systems. This is in contrast to countries such as Sweden and Ireland, which have integrated solar more aggressively into their energy strategies since earlier years. Furthermore, the installed capacity in Slovakia during the period 2010–2020 was considerably lower, which accounts for the relatively low accumulation of waste during the initial decades of Figure 6. However, from 2040 onwards, Slovakia demonstrates a more rapid increase in PV waste generation. This shift in the growth trajectory may be associated with a recent surge in the adoption of solar technologies, driven by the necessity to diversify its energy mix and fulfill the climate targets set by the European Union. The revised NECP targets have been pivotal in establishing more rigorous objectives for the adoption of solar energy, leading to a notable surge in the deployment of PV systems.

Another point of view we would like to draw attention to is the difference in waste that will be produced according to the new capacity targets set out in the national plans submitted to the EU Commission. This waste is compared to the waste that would have been generated if the plans' targets had remained unchanged. This analysis, illustrated in Figure 7, demonstrates the potential impact of these new targets on PV waste production towards 2050.

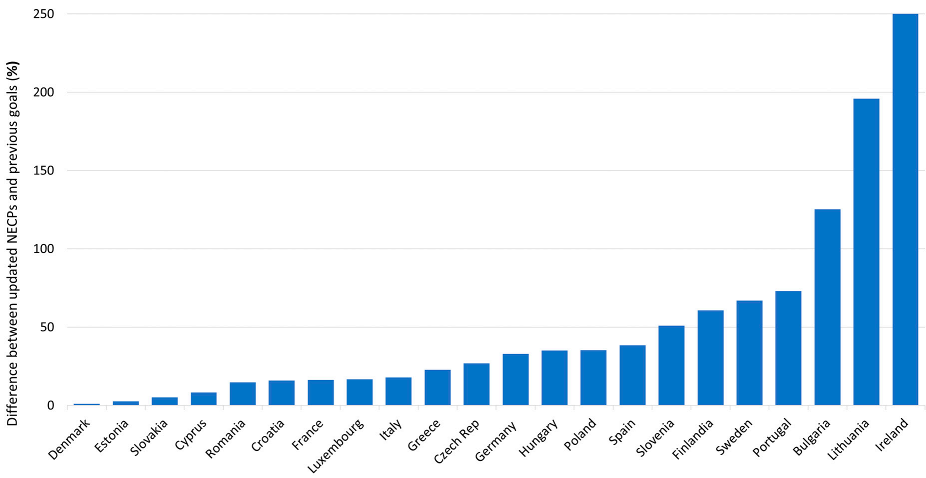


Figure 7. Cumulative PV waste mass in 2050 as a difference between updated NECPs and previous goals for countries that show a difference above 0.5%.

It should be noted that some countries have been omitted from Figure 7 for the sake of enhanced clarity and legibility. One such example is the Netherlands. As the country recently formulated its NECP, the findings presented herein are particularly relevant. The NECP, presented in 2019, projected a solar PV capacity of 27 GW by 2030, underscoring the country's commitment to sustainability. Despite its leadership in renewable energy adoption, the country has experienced opposition to solar farm projects in certain areas, creating challenges in integrating climate and energy transition policies. As outlined in Section 2.1, the updated NECP projects an installed capacity of 25.7 GW, representing a 4.80% reduction in installed capacity by 2030 and achieving a cumulative PV waste mass reduction of 1.85%, equivalent to 17,805 tons less than the previous NECP. The projected mass of waste generated in the year 2050 is expected to decrease from 99,837.22 to 96,361 tons. Although not included in Figure 7, Malta has shown a marginal increase in PV waste mass of 16 tons, equivalent to a growth of 0.13%. This increase can be attributed to the fact that the country has increased its installed capacity target in its updated NECP. Although relatively modest, Malta's projected installed capacity of 270 MW by 2030 indicates a positive trend in PV uptake and the associated increase in waste generation if met. Figure A4 in Appendix shows Cumulative PV waste mass up to 2030 for EU members who submitted NECPs with updated targets for the regular-loss scenario.

Upon closer examination of the results shown, it becomes evident that Lithuania and Ireland may encounter significant internal challenges regarding PV waste mass generation. These countries show notable variations in cumulative mass generation under updated targets through 2030 with differences around 200% compared to others. Considering these findings, developing and implementing medium- and long-term strategies are imperative and warrant serious consideration.

Analyzing the updated targets of each NECP, another issue for consideration is the contribution of waste mass generation in the European Union as a whole, as shown in Figure 8 below.

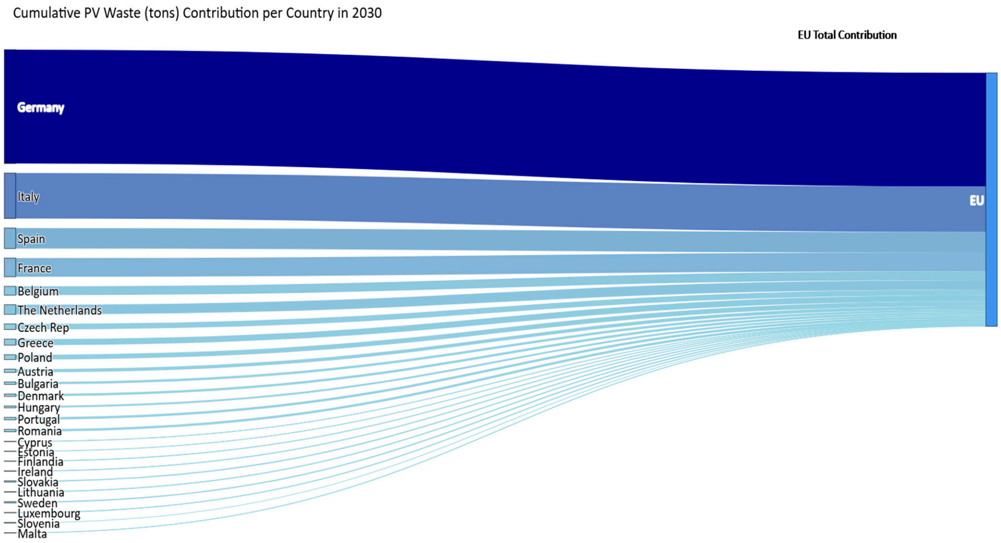


Figure 8. Cumulative PV waste mass contribution per country in 2030 for the early-loss scenario in tons.

As expected, the mass of waste generated in all cases is higher in the early-loss scenario than in the regular-loss scenario. This situation corresponds to the evolution of the annual installed mass over time and can be seen in the results presented in Tables 2 and 3. PV plants will be affected by a progressive power loss, which, in the case of the early-loss scenario, will be markedly faster than in the regular loss due to the variation in the form factor, which has a smaller value [27]. The replacement of decommissioned modules due to early-life-stage power losses will result in a greater final installed mass in the early-loss scenario than in the regular-loss scenario. In both assessed degradation scenarios, the same countries are observed as the primary contributors to the generation of PV waste mass: Germany, Italy, France, and Spain.

The discrepancies between the early-loss and regular-loss scenarios demonstrate the urgent need for proactive measures in PV waste management. Investment in technologies designed to extend the lifespan of PV modules is essential to mitigate the risks associated with the early-loss scenario and reduce overall waste generation.

3.2. Calculation of the Annual PV WEEE Mass

While the results of the projection of the accumulated waste mass are of great interest, it is equally relevant to analyze the mass of waste that will be generated annually. This approach would allow us not only to anticipate logistical needs, such as waste collection, transport, and storage, but also to plan the industrial capacities required for recycling, repair, and reuse more efficiently. An annual analysis could also facilitate the identification of periods of high PV waste mass generation, which would be crucial to designing flexible strategies to ensure the sustainability of management systems. This includes the assessment of existing infrastructure, investment in advanced technologies for handling this PV waste mass, and the implementation of adaptive regulations to ensure proper management in line with the objectives of the sustainable energy transition. Figures 9–11 present the evolution of annual PV waste mass generation while Figure A3 in Appendix A Annual PV waste mass up to 2030 for EU members who submitted NECPs with updated targets for the early-loss scenario.

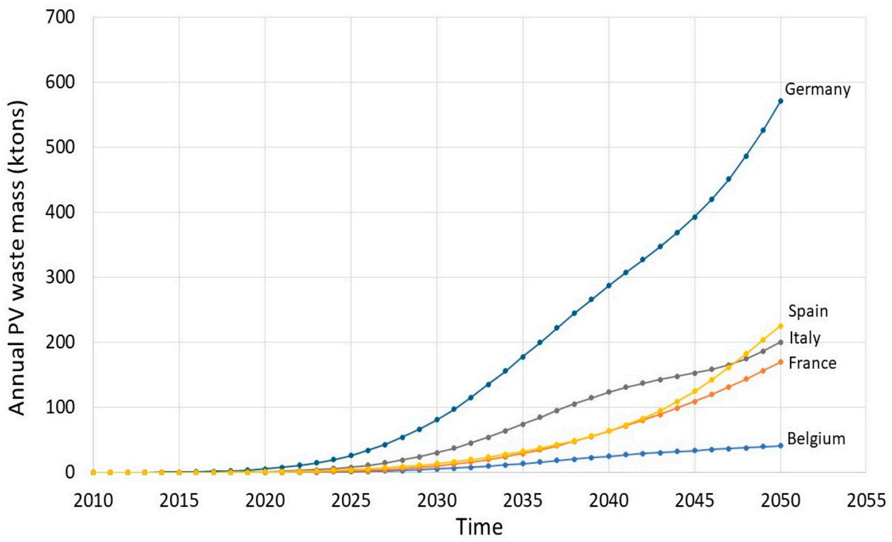


Figure 9. Estimation of the evolution of the annual PV waste mass considering the regular-loss scenario for Germany, Spain, Italy, France, and Belgium.

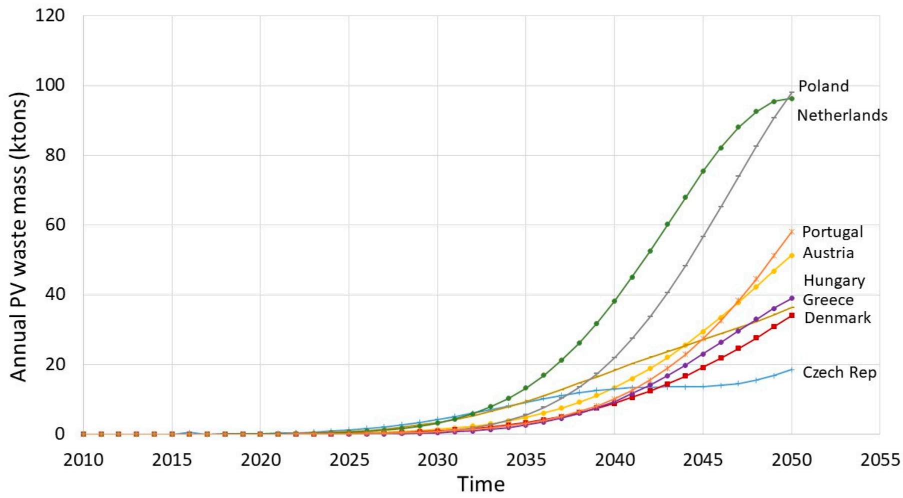


Figure 10. Estimation of the evolution of the annual PV waste mass considering the regular-loss scenario for Poland, the Netherlands, Portugal, Austria, Hungary, Greece, Denmark, and the Czech Republic.

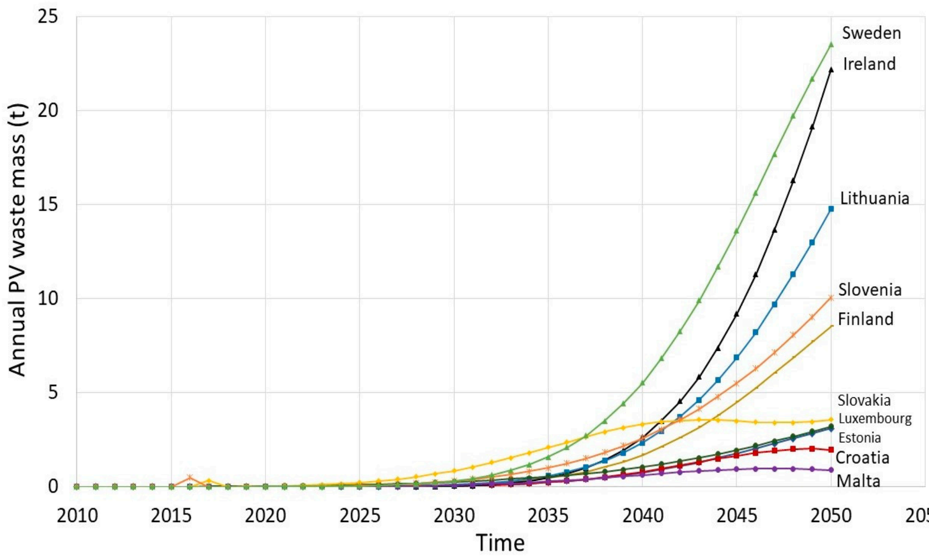


Figure 11. Estimation of the evolution of the annual PV waste mass considering the regular-loss scenario for Sweden, Ireland, Lithuania, Slovenia, Finland, Slovakia, Luxembourg, Estonia, Croatia, and Malta.

When analyzing these curves, it is evident that, while they all demonstrate an upward trend to a greater or lesser extent, certain countries such as Italy, Greece, the Czech Republic, and Slovakia exhibit turning points in the annual waste mass generation curves. These fluctuations indicate uneven rhythms in PV capacity installation in different periods over time, leading to a reduction in PV waste generation projections during specific periods.

3.3. Discussion on Photovoltaic Waste Management

This section will analyze some of the critical aspects of the treatment of photovoltaic waste, with a focus on the groups identified in Section 3.1. The first group is defined as those whose difference in waste generation is less than 0.5% (Figure 7), while the second group comprises the countries shown Figure 8.

Germany, the foremost PV energy market in Europe, has established a robust framework for the management of its expanding volumes of PV waste. At present, several substantial facilities are in operation, including those managed by the Reiling Company group. These facilities are primarily focused on silicon-based PV panels, with the Reiling plant capable of recycling up to 10,000 tons of panels annually. The current infrastructure in Germany has the capacity to handle approximately 50,000 tons of PV waste per year [28]. Nevertheless, the country's anticipated volume of PV waste will far exceed this capacity. This consequently requires continuous investment in expanding recycling infrastructure and enhancing efficiency in recovering valuable materials, including silicon, silver, and other metals.

In contrast, France is making significant advances in the development of its PV waste management systems, as evidenced by Veolia's facility in Rousset, which is capable of recycling 4000 tons of PV panels annually [1]. This facility, one of the most advanced in Europe, is capable of recovering up to 95% of the materials that comprise a photovoltaic panel. Additionally, Soren (formerly PV Cycle France) plays a pivotal role in coordinating PV waste collection and recycling initiatives at the national level. Notwithstanding these initiatives, France's projected PV waste generation of over 2 million tons by 2050 necessitates a strategic expansion of recycling capacity to accommodate the anticipated surge.

Italy follows a comparable trajectory, with facilities such as Relight Group and S.I.R.E. (Società Italiana Recupero Ecologico) collectively managing a significant portion of the country's PV waste. Additionally, newer facilities, such as Tialpi, are working to enhance recycling processes, and the pilot plant can handle 1000 tons per year [29]. Italy's current recycling capacity is estimated to be between 3000 and 5000 tons per year. Nevertheless, in light of the projected 3 million tons of PV waste that Italy is expected to generate by 2050, it is of the utmost importance that the nation significantly expands its infrastructure. Italy, like other major PV markets, is prioritizing the improvement of material recovery rates and the overall efficiency of its recycling processes.

The recycling practices of PV waste in the Netherlands, Austria, Belgium, Latvia, and Malta reveal both approaches and common strengths, reflecting their commitment to sustainable waste management and alignment with European Union directives. The Netherlands has demonstrated a strong commitment to sustainable waste management practices, supported by a robust regulatory framework and significant investments in infrastructure. Circular economy principles guide these efforts [30] which emphasize resource efficiency and the minimization of environmental impacts. As a result, the existing measures provide the necessary framework to manage PV waste effectively, even in scenarios of increased cumulative generation.

Focusing on Austria, it is worth commenting that the government implements WEEE recycling through the use of existing electronic waste recycling facilities in accordance with EU directives. Nevertheless, it faces difficulties in managing PV waste due to a lack of specialized facilities and the necessity for policy updates. The utilization of general electronic waste facilities results in a reduction in recycling efficiency, highlighting the need for increased investment in dedicated PV recycling infrastructure [31].

On the other hand, Belgium has developed a robust system for managing WEEE, combining manual and automated recycling processes to ensure compliance with EU directives [32]. Although Cesaro et al.'s work warned in 2018 that the country was facing the challenge of scaling up recycling capacity to handle future increases in PV waste while maintaining economic efficiency [33,34], nowadays, despite a minor change in the NECP target, it remains an issue to consider [32]. Among these countries, Malta will face significant challenges in WEEE and PV waste management due to its smaller market size and limited local infrastructure compared to the other EU markets. The country often exports electronic and PV waste to larger EU countries for processing. Malta's reliance on external facilities underscores the need for investment in local recycling capabilities to handle increasing waste volumes effectively [35]. While complying with the EU recycling directives, further development is needed to achieve self-sufficiency in waste management.

Focusing on Figure 7 and analyzing Lithuania and Ireland, to the best of our knowledge, neither of them has highly specialized and advanced facilities dedicated exclusively to solar panel recycling. However, Ireland runs various recycling and collection programs, including WEEE Ireland [36], which manages recycling initiatives without a specific focus on solar panels.

In contrast, although Lithuania follows the same guidelines, it has not achieved noteworthy advancements in this particular field [35].

From a policy perspective, these findings provide a compelling rationale for reviewing EU directives on PV waste management. A reassessment should incorporate mandatory targets for recycling efficiency, reusing standards, material recovery, and circular economy principles. One of the key solutions for PV waste management is enhancing circularity through the repair and reuse of PV modules that are decommissioned prematurely but remain functionally viable. The IEC TR63525 ED1 report is currently being developed, but has not been edited yet, to establish guidelines for assessing the reuse potential of PV modules and ensuring their reliability. Recent studies, such as Rosillo et al.'s, have demonstrated the feasibility of PV repair to extend their lifespan [37]. Additionally, integrating ecodesign and design for recycling principles into PV module manufacturing can significantly improve recyclability, enhance material recovery, and reduce environmental impact. These measures, along with strategic policy adjustments, could mitigate the long-term consequences of PV waste and contribute to a more sustainable European supply chain.

Such measures would reduce the environmental impact and encourage the growth of a secondary market for recovered materials, thereby alleviating supply chain constraints in the production of new modules.

In addition to the logistical challenges associated with managing PV waste, it is imperative to consider the significant environmental and economic implications. From an economic perspective, the increasing PV waste issue presents challenges and opportunities. While managing and recycling large quantities of waste is costly, expanding the PV recycling and reuse sector offers significant potential for economic growth. The establishment of a robust PV recycling industry has the potential to create new employment opportunities, drive technological innovation, and support the EU's goals of resource independence, particularly in relation to critical raw materials such as rare metals.

3.4. Comparison with Other Regions

Although the European Union has been a leader in PV waste management, with regulatory frameworks such as the WEEE Directive, other global players such as China and Australia face unique challenges and opportunities in addressing PV waste.

In China, PV waste management is still in its early stages compared to the EU. The country is projected to generate 6.24 million tons of PV waste by 2050, a significantly higher volume than any European country [38]. However, China lacks a comprehensive regulatory framework for PV waste treatment. Unlike the EU, where the WEEE Directive mandates producer responsibility, China does not yet have an extended producer responsibility (EPR) scheme for PV panels, leading to inadequate funding for recycling initiatives [39]. Another major challenge is the limited infrastructure for material recovery, particularly for high-value elements such as silicon and silver. Despite these limitations, China has been investing in research and pilot projects for PV recycling, focusing on process innovations such as advanced delamination techniques and chemical extraction to improve recovery rates [40].

Australia also faces challenges in PV waste management, but this is different from China's policy approach. Unlike China, Australia has recognized the need for a circular economy model and has started developing EPR schemes similar to those in the EU. However, there are still no national regulations mandating PV panel recycling, leading to inconsistencies in waste treatment across different states [41]. Studies indicate that upcycling technologies could play a crucial role in Australia's transition to a more sustainable PV waste management system. Research suggests that upcycling reduces environmental impact compared to downcycling and could help integrate recovered materials into the domestic supply chain [42].

Australia's key challenges include the high costs of recycling, limited local infrastructure, and reliance on landfill disposal. Unlike the EU, where centralized recycling hubs exist, Australia must invest in developing national-scale facilities. Additionally, while some companies have begun implementing pilot projects, the lack of financial incentives could make large-scale PV recycling economically unfeasible. Despite these challenges, Australia's focus on policy-driven solutions, particularly in EPR and upcycling strategies, represents a step forward in aligning with EU circular economy practices.

4. Conclusions

This study provides a comprehensive assessment of photovoltaic (PV) waste mass generation across European Union (EU) member states, utilizing the most recent data from the updated National Energy and Climate Plans (NECPs) as of December 2023. The findings highlight the dual challenge facing the EU: while the expansion of PV capacity is essential to achieving the 2050 climate neutrality goals, the projected increase in PV waste underscores the pressing need to develop tailored waste management strategies.

Our analysis demonstrates that Germany, Italy, France, and Spain are expected to generate the largest quantities of PV waste, necessitating the development of large-scale, specialized recycling facilities. However, smaller nations such as Lithuania and Ireland will also experience significant increases due to ambitious NECP targets despite lacking adequate recycling infrastructure. These findings emphasize the urgency of establishing either national or regional recycling hubs to prevent bottlenecks in PV waste treatment.

Furthermore, this study highlights the critical challenges associated with solar panel recycling, not only from a technical perspective but also from an economic standpoint, which remains one of the major obstacles to large-scale recycling implementation. Current recycling efforts face significant barriers, including the low market value of recovered materials, high operational costs, and a lack of strong financial incentives. Without targeted policy interventions, many decommissioned solar panels may continue to end up in landfills rather than being effectively recycled. Future efforts should focus on advancing recycling technologies to improve material recovery rates and economic feasibility through supportive policies and business models. Developing secondary markets for recovered PV materials, strengthening extended producer responsibility (EPR) policies to ensure manufacturers contribute to end-of-life management costs, and incentivizing large-scale recycling investments will be key elements in addressing these challenges.

Additionally, establishing regional recycling hubs and enhancing financial incentives and regulatory frameworks will be crucial to supporting the circular economy and minimizing the environmental impact of PV waste. Efforts should also consider investment in research on upcycling processes that contribute to the European supply chain, enhancing the sustainability and value of recovered materials. Moreover, integrating ecodesign principles and design for recycling approaches in the early stages of PV module manufacturing can significantly enhance their recyclability, extend their lifespan, and reduce the overall environmental impact of the solar industry.

Achieving a climate-neutral society by 2050 requires an integrated approach to accelerating renewable energy deployment while ensuring sustainable waste management. The conclusions drawn from this study provide essential guidance for policymakers, industry stakeholders, and researchers, supporting the development of effective PV waste management strategies. By addressing both technical and economic challenges, the EU can establish a more resilient and circular photovoltaic industry, ensuring that solar energy remains a truly sustainable solution for the future.

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Data Availability Statement: These data were derived from the following resources available in the public domain: https://www.irena.org/Data/Downloads/IRENASTAT (accessed on 27 November 2024).

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Conflicts of Interest: There are no conflicts of interest to declare.

Appendix A

Updated targets from the NECP of each country.

Table A1. The 2030 NECP goals for EU countries.

Country	Updated NECP 2030 Target (GW)
Austria [17]	17.00 *
Belgium [43]	14.50
Bulgaria [44]	5.50

Table A1. *Cont.*

Country	Updated NECP 2030 Target (GW)
Croatia [45]	1.00
Cyprus [46]	0.90
Czechia [47]	10.10
Denmark [48]	11.70
Estonia [49]	1.20
Finland [50]	2.80
France [51]	54.00
Germany [52]	215.00
Greece [53]	13.00
Hungary [54]	12.00
Ireland [55]	8.00
Italy [56]	79.90
Latvia [57]	2.13 *
Lithuania [58]	5.10
Luxembourg [59]	1.10
Malta [60]	0.27
Netherlands [61]	25.80
Poland [62]	30.00
Portugal [63]	20.40
Romania [64]	8.00
Slovakia [65]	1.40
Slovenia [66]	3.50
Spain [67]	76.40
Sweden [68]	6.50

* Target estimated from electricity generation information obtained from NECPs submitted after July 2024.

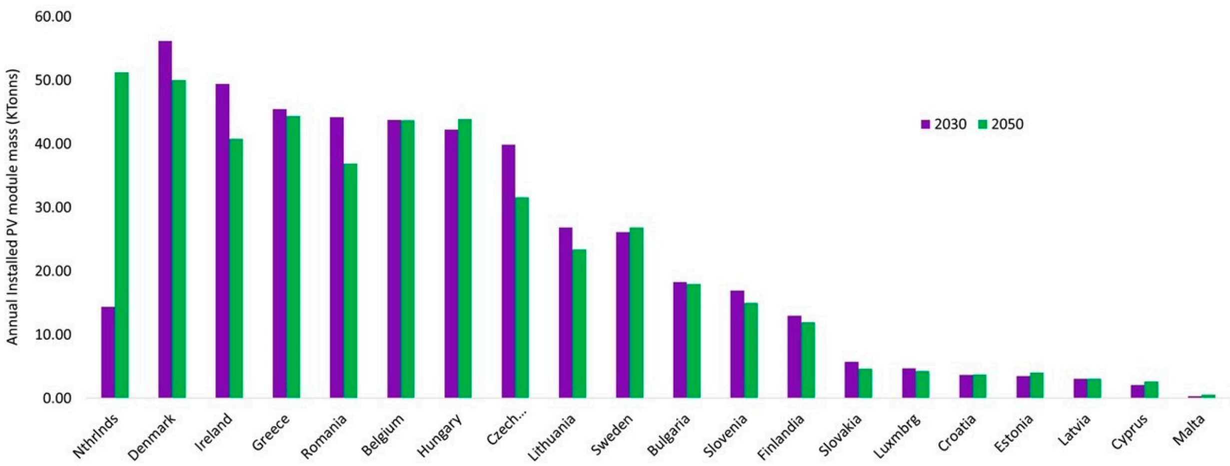

Figure A1. Projected annual PV installed mass up to 2030 and 2050 for EU members who submitted NECPs with updated targets for the regular-loss scenario: countries projected to install less than 100 k tons of PV modules.

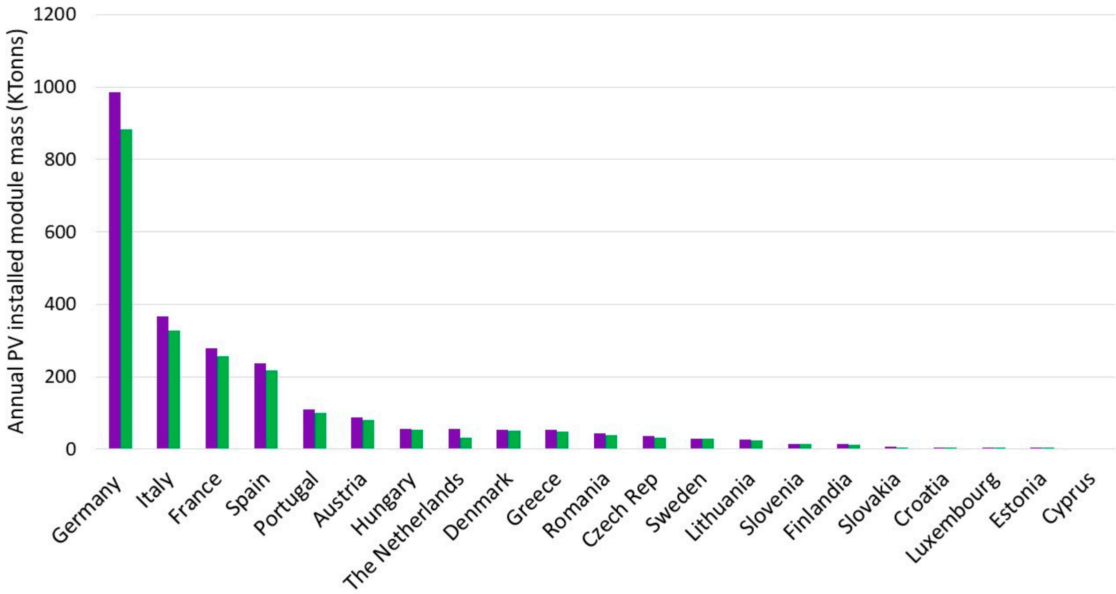

Figure A2. Projected annual PV installed mass up to 2030 and 2050 for EU members who submitted NECPs with updated targets for the early-loss scenario.

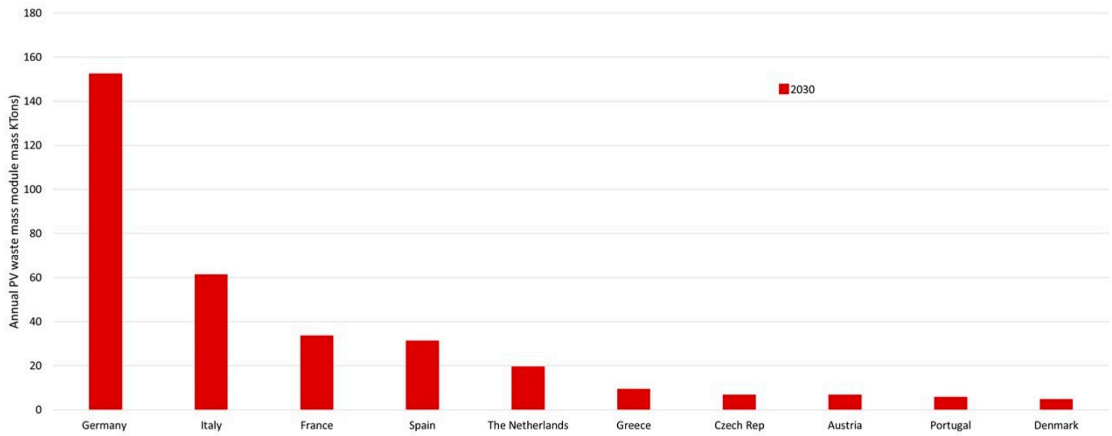

Figure A3. Annual PV waste mass up to 2030 for EU members who submitted NECPs with updated targets for the early-loss scenario. For visualization reasons, countries with less than 0.5 ktons of annual PV waste mass generation are omitted.

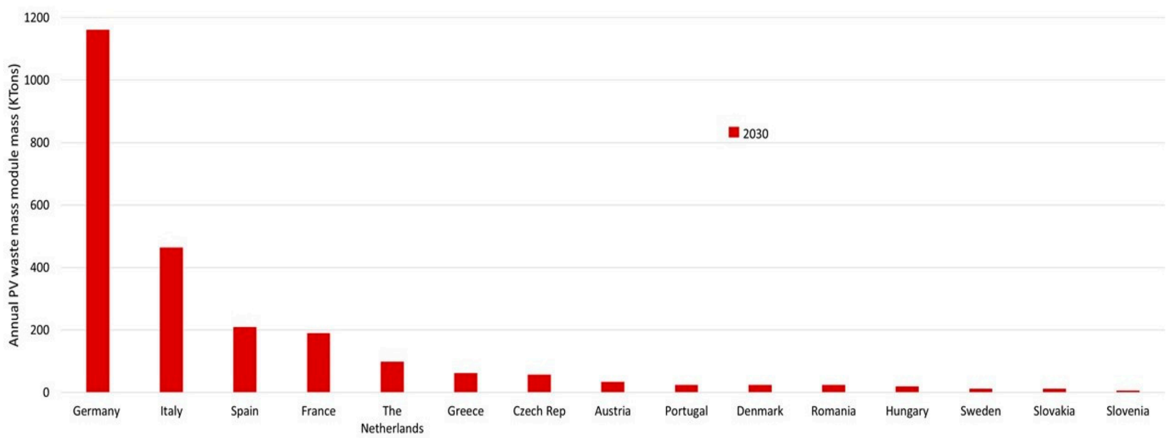

Figure A4. Cumulative PV waste mass up to 2030 for EU members who submitted NECPs with updated targets for the regular-loss scenario. For visualization reasons, countries with less than 0.5 ktons of annual PV waste mass generation are omitted.

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