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State and prospects of photovoltaic module waste generation in China, USA, and selected countries in Europe and South America

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Photovoltaic (PV) waste mass presents an environmental challenge while the PV installation rate is growing globally. Therefore, the assessment of PV waste mass generation is important for managing PV recycling and the refurbishment of wear-out modules. In this study, PV waste mass generation is projected for 2030 and 2050 based on the historical data of cumulative PV capacity and the targets of National Energy and Climate Plans (NECPs) for China, USA, Spain, Germany, France, Italy, the EU as a whole, the United Kingdom and some South American countries such as Brazil, Chile and Argentina. A projection for the cumulative installed power was calculated and compared to NECP targets, and this analysis shows that Germany accomplished 60% of its goal in 2021, followed by Argentina and China with 50% of their planned target achieved, while the furthest from its goal is the USA with 14%. For PV waste mass calculations, an updated equation is introduced for the power-to-mass conversion relation, and different reliability levels of the PV technology are taken into account by considering two degradation scenarios. Our results indicate that the European Union would generate more than 710 000 tonnes of cumulative PV waste mass in 2030, followed by China with around 265 000 tonnes, and the USA with 147 000 tonnes. This implies that in order to treat waste and also provide raw materials for the PV industry, the EU needs to become a stakeholder in the deployment of a solid recycling industry that is capable of managing a large mass of PV WEEE.

1. Introduction

Solar photovoltaic (PV) energy is growing globally due to the increase in electricity prices around the world, and also due to the intentions of countries to meet the objectives of decarbonisation and increase the percentage of renewable energies in their energy matrix.[1] In 2021, the total global operating solar capacity passed the 1 TW threshold, given 167.8 GW of new solar capacity was installed, representing a 21% growth over the 139.2 GW added in 2020.[2] In the European Union (EU), this growth trend was also maintained, and in 2021 its installed capacity grew by 7.9 GW to reach 31.8 GW of total installed capacity. This growth is related to the commitment the EU has made to the search for a climate-neutral society by 2050, which implies the non-release of more greenhouse gases than can be absorbed, and this commitment is embodied in the European Climate Law.[3] The main objective set out in this law is that in less than 8 years, the EU must reduce the net greenhouse gas emissions by at least 55% as compared to the existing levels in 1990. The EU requires each member state to draw up an Integrated National Energy and Climate Plan (NECP) 2021–2030, which will be in contrast to the degree of progress and in concordance with the global balance of the Paris Agreement.[4] In 2023 the European Commission will evaluate the coherence of the measures adopted in order to trace a direct and simple trajectory that optimally achieves the objectives.

With the increase in the installed PV capacity, it will be necessary to properly manage PV electronic waste at the end-of-life of the installed PV panels. In 2012, the EU established a directive for the management of Waste of Electrical, Electronic Equipment (WEEE) with a specific regulation for PV recycling.[5]

This directive includes the principle of extended producer responsibility (EPR) and indicates that the producer of photovoltaic panels is responsible for their treatment at the end of their life. In addition, the regulation prohibits the mixed collection of photovoltaic panels with other waste, such as demolition materials, and requires the separation of silicon panels from those of different technologies. The latest update of the directive in 2019 enforced 85% recovery and 80% preparation for the recycling of PV panels. In addition to this European

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directive, other major countries such as the United Kingdom, Germany, China, and the USA have also revised their WEEE regulations for appropriate end-of-life PV waste management.[6]

The recycling of PV modules is important from an environmental point of view to approach circularity, and the growth of the related industry is linked to the amount of PV modules that reach the end of their life. Other studies[7,8] assessed the environmental contributions from retired modules and their recycling process. The concept of the "wear out" module used in this work refers to two situations: on the one hand, wear-out modules before 2021, cover retired modules from PV installations, regardless of the module's operating status. On the other hand, from 2021 and for the future, wear out modules refers to solar PV modules that do not work properly as estimated by the degradation scenarios proposed and the probability density function used. This last concept will not include PV modules retired for economical or other reasons than the ones stated here, *i.e.*, PV modules that have not reached their end-of-life. Therefore, an assessment of the mass of PV waste that will be generated in the near future from the installed power year after year is useful since recovered raw materials from solar PV waste can satisfy installation demands and mitigate price fluctuations in PV manufacturing.[9] Furthermore, the recycling of PV waste mass can lead to a reduction of the environmental impacts associated with the mining and processing of valuable and limited virgin natural resources and energy savings.[10] These objectives are reasonable if recycling techniques can cost-effectively separate the components of the modules and recover glass, silicon, and metal to conserve resources and reduce landfilling costs.[11] Other reports[12] have assessed the economic sustainability of PV modules recycling, and they concluded that recycling becomes economically profitable for high volumes of waste PV mass.

This study is key since in the case of the EU, the absence of raw materials makes recycling a vital issue for the survival of the PV industry, contrary to what happens in China or South America.[13]

In this work, a projection to 2030 and 2050 of the possible generation of PV waste mass linked to installed capacity is carried out for China, the USA, Australia, Spain, Germany, France, Italy, the EU as a whole, the United Kingdom, and some South American countries such as Brazil, Chile and Argentina. These projections are based on the historical data of cumulative PV capacity provided by the International Renewable Energy Agency, IRENA,[14] until the end of 2021, and the targets of the National Energy and Climate Plan of each country. Furthermore, two degradation scenarios proposed by IEA-PVPS/IRENA[15] are included: the regular-loss (RL) scenario and the early-loss (EL) scenario, which refer to different end-of-life stages. As for the power-to-mass conversion equation, other works, (Santos *et al.*), were based on the exponential decay proposed by IRENA (IRENA and IEA-PVPS, 2016). For our calculations, that equation was updated to take into account new data for the most installed photovoltaic modules on the market in 2020.[16]

This work is organized as follows. Firstly, in Section 2, official data for cumulative installed PV power to 2021 in different countries is presented, as well as 2030 NECPs goals for 27 EU members and other selected countries. A projection for the cumulative PV power to 2050 for ten countries is also proposed based on their national energy plans. Additionally, an assessment of the most representative PV modules of the market in 2021 has been carried out, these being the ones that currently cover the largest market share with efficiencies of over 21%, as indicated in their datasheets. Then, the projections for 2030 and 2050 of the wear-out PV capacity are calculated, considering different degradation scenarios linked to the lifetimes of different PV modules. In Section 3 the calculation of the mass of photovoltaic generated waste is presented and analysed from the estimated projections on the installed capacity for 2050 for the selected countries. Finally, Section 4 presents the conclusions of the work.

2. Materials and methods

2.1 Projected installed capacity

According to the report, State of the Energy Union 2021,[17] renewable energies overtook fossil fuels as the main source of energy in the EU in 2020. For the first time, it generated 38% of electricity, while fossil fuels amounted to 37%, at the time of writing this paper and before the Russia–Ukraine war. So far, nine EU Member States have already phased out coal, thirteen others have committed to phase-out and four other countries are considering possible dates and deadlines. However, trends still fall short of what is needed to drive the required transformation to achieve the objectives of the Energy Union. Therefore, a modification of the goals of European countries will need to be reconsidered.

The national energy plans of the 27 EU countries have been analysed, and countries of special interest within the European Union, and also outside it, have been selected for discussion, such as Spain, France, Germany, Italy, China, USA and Australia; and from South America: Brazil, Chile and Argentina. Data on installed power and the objectives of NECPs of all 27 EU members, China, the USA and selected South American countries are presented in Table 14 in the Appendix. It has to be taken into account that although the target is expected in 2030 for most of the countries, in some of them it is for another year.

With the installed power in 2021 and the power target to be installed in or around 2030 obtained from the NECP, a linear projection between these two points has been calculated. The slope obtained has been used to project the installed power towards the year 2050. In this way, the power that should be installed annually to meet the 2050 target is obtained. Keep in mind that this would be the theoretical value based on the accumulated capacity in 2021, but part of that power is lost due to the modules that fail annually. These quantities must be added to the annual value to achieve the target power and perform, from this, the calculation of the PV waste mass. The calculation procedure was explained in detail in a previous article.[18]

An analysis of the objectives set out in the NECPs of the selected countries chosen to calculate PV waste is presented in

Table 1 Cumulated installed capacity and NECP goals in selected countries for calculations

Installed capacity and NECP goals	
Spain	Target: 39.18 GW to 2030 (ref. 19) Achieved: 13.65 GW – 34.83% Installation rate to reach the goal: 2.8 GW per year
Germany	Target: 98 GW to 2030 (ref. 20) Achieved: 58.46 GW – 59.65% Installation rate to reach the goal: 4.39 GW per year
France	Target: 35.1–44 GW to 2028 (ref. 21) Achieved: 14.71 GW – 33.43% Installation rate to reach the goal: 4.18 GW per year The projections to 2050 calculated in this work, presented in Table 3, have been calculated with the highest target, that is, 44 GW, since with this objective the largest amount of PV waste mass will be generated
Italy	Target: 52 GW to 2030 (ref. 22) Achieved: 22.70 GW – 43.64% Installation rate to reach the goal: 3.25 GW per year
European Union	Target: 533 GW to 2030 (ref. 23) Achieved: 158.06 GW – 29.65% Installation rate to reach the goal: 46.88 GW per year At the time of writing this paper, the EU's 2030 goals are being modified, but those outlined in the published NECP propose to reach 533 GW by 2030, and this target is expected to increase
United Kingdom	Target: 70 GW to 2035 (ref. 24) Achieved: 13.70 GW – 19.60% Installation rate to reach the goal: 4.33 GW per year
China	Target: 600 GW to 2030 (ref. 25) Achieved: 300 GW – 50% Installation rate to reach the goal: 33.34 GW per year. Under its ongoing 14th Five-Year Plan (FYP) aiming for renewables to provide 33% electricity consumption between 2021 and 2025, no individual targets were given for solar and wind power capacity or generation, but it indicates they will increase their cumulative solar plus wind energy installed capacity to 1.2 TW by 2030, as part of its updated Nationally Determined Contribution (NDC) For the calculations in this work, the assumption has been made that the installation ratios of solar PV and wind energy will be maintained which will lead to reach 600 GW of PV installed capacity in 2030
USA	Target: 670 GW in 2050 (ref. 26) Achieved: 93.7 GW – 13.98% Installation rate to reach the goal: 19.87 GW per year
Brazil	Target: 21.78–48.59 GW in 2022–2026 (ref. 27) Achieved: 13.10 GW – 26.86% Installation rate to reach the goal: 6 GW per year For calculations in this article, the largest installed capacity has been considered since it is the one that will generate the most waste PV mass in 2026
Chile	Target: 9.36 – 14.36 GW in 2022–2025 (ref. 28) Achieved: 4.36 GW – 30.36% Installation rate to reach the goal: 1.11 GW per year For the calculations the most ambitious target to 2025 of 14.36 GW has been taken because it is the one that will generate the most PV waste mass
Argentina	Target: 2.48 GW in 2030 (ref. 29) Achieved: 1.07 GW – 43.15% Installation rate to reach the goal: 0.15 GW per year Argentina's national energy efficiency plan does not specify a target for PV power towards 2030, however, it projects the percentage that renewable energies will represent of the total energy matrix and indicates that it will be 25%. Thus, for calculations in this work, it is assumed that the percentage of solar photovoltaic energy within renewable energies remains constant at the same value for 2021, which is translated into a goal of 2.48 GW PV installed by 2030

Table 1 together with the actual installed capacity in 2021 and the installation rate to achieve the NECPs goals.

The information presented in Table 1 has been rearranged in Fig. 1 to display a graphical comparison of the considered values.

Table 2 shows the installed photovoltaic capacity in 2021 for selected European countries, the objectives of its national energy plans and the projections towards 2050. As was explained, the projected installed capacity in 2050 was calculated by a linear extrapolation from 2021 to 2030, this is

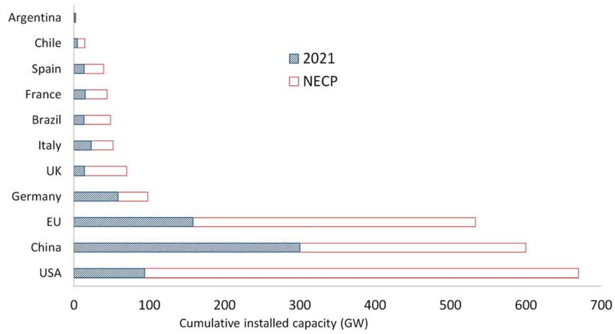

Fig. 1 A comparison of the cumulative installed capacity in GW between installed capacities in 2021 and NECP targets, according to Table 1 for selected countries.

Table 2 Cumulative installed PV capacity in 2021 in selected EU countries from IRENA,[14] estimated capacity in 2030 according to NECPs and projection to 2050 for Spain, France, Germany, and Italy. The superscript refers to the reference year of the target when it is different from 2030

Country	Cumulative capacity (GW) 2021	Goal plan 2030 (GW)	Projection to 2050 (GW)
Spain	13.65	39.18	90.90
France	14.71	35.10–44.00$^{(2028)}$	136.11
Germany	58.46	98.00	185.87
Italy	22.69	52.00	117.13

assuming a constant annual installation rate and the same slope is used to extrapolate values through to 2050.

A similar analysis for the EU countries presented in Table 2 was carried out for other countries outside the EU, such as China, the USA, the United Kingdom, Brazil, Chile and Argentina. Their cumulative installed capacities in 2021, and 2030 targets and respective projections are presented in Table 3.

Globally, the leader in photovoltaic installation continues to be China, with a growth of 23.8% in 2021 compared to the previous year, which implies 2.7 GW of PV capacity installed that year.

Regarding the projections of installed power in the USA, the values used in this work have been taken from ref. 26 for 2035

Table 3 Cumulative installed PV capacity in 2021 from IRENA,[14] projections to 2022–2030 according to national plans or published targets and extrapolation to 2050 for China, USA, UK, Brazil, Chile and Argentina. The superscript refers to the reference year when it is different from the target 2030

Country	Cumulative capacity (GW) 2021	Goal plan 2030 (GW)	Projection to 2050 (GW)
China	306.40	1048.78	2696.16
USA	93.71	375$^{(2035)}$	670^{a}
UK	13.70	70.00$^{(2035)}$	130.33
Brazil	13.05	21.78–48.59$^{(2022–2026)}$	219.22
Chile	4.36	9.36–14.36$^{(2022–2025)}$	76.86
Argentina	1.07	2.48	5.60

^{a} Projected value by ref. 26.

Table 4 PV module degradation scenarios defined as a function of the Weibull parameters used. These parameters are extracted from[15]

Scenario	α	T (years)
Regular-(1)	5.3759	30
Early-(1)	2.4928	30

and 2050. In Table 4, the projection to 2050 is not a result obtained by our calculations, but a target set up in one of the scenarios proposed by the USA Department of Energy aiming to reach 100% decarbonisation by 2050.

It can be seen that if the predictions are correct, China will grow by 70.78% in 2021–2030 and 61.10% from 2030 to 2050, while the USA will increase its PV capacity by 0.63% in 2021–2030 and 36.30% from 2030 to 2050, reaching its net-zero emissions in 2050.

In South America, Brazil and Chile constitute the most prominent markets, with Brazil being comparable to Germany and Europe in terms of the level of installation per year, according to the Solar Power Europe 2021 report.[30]

As for Argentina, its plan[29] does not specify a PV target towards 2030 but it does project the percentage that renewable energies will reach in that year, and indicates that they will be 25% of the total energy matrix. For the calculations in this work, it is assumed that the percentage of solar PV energy within renewable energies will remain constant at 11%[29] of the value of 2021, which is translated into a goal of 2.48 GW installed in 2030.

To evaluate the effects of variations in the prediction of annual installed power and PV waste mass, four different scenarios have been projected. These scenarios are representative of the possible photovoltaic penetrations in the electricity mix and as a forecasting analysis methodology considered also by other works.[31] In this way, the possibilities of growth assumptions and their consequent generation of waste are analysed. In this regard, we varied the annual installed power projections in 2050 by applying different increment factors from the year 2021. The first scenario was to consider the annual installed PV power 25% lower, and then three more optimistic scenarios were assumed, proposing increases of 25%, 50% and 100% of the annually installed PV power from 2021. This allows us to study how the annual PV waste mass would be modified. The four projections were applied to the two PV module degradation scenarios: Early (1) and Regular (1). These Early (1) and Regular (1) scenarios correspond to the early-loss and the regular-loss scenario proposed by ref. 15. In each case, the annual wear-out power needs were calculated to correct the annual installed PV power projection. Then, the annual PV WEEE mass was determined.

2.2 Degradation model for solar PV modules

The time in which a PV module will fail can be evaluated using the Weibull probability function. Similar work has shown its suitability for this evaluation.[18,32–34]

This probability density function is given at the instant of 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 is the scale factor.[35]

In eqn (1) the form factor α indicates whether the failures are due to a failure of the material, in which case the value will be <1 and is considered an early failure, if the failures are due to the ageing of the equipment, with which the α will take a value >1, or if the failures are due to random causes, in which case this factor will take the value of 1.[36]

The scale factor T offers the time at which 63.2% of the installed power will fail, and is also known as the characteristic lifetime.[37]

In this work, the failures due to the wear-out of the panels are analyzed, that is, the scenario in which the failure corresponds to a decrease in the power of the panel caused by its degradation, which is equivalent to saying that $\alpha > 1$. The IEA-PVPS/IRENA report[15] proposes two degradation scenarios, taking into account the moment at which the failure of the PV module is produced, and calculates its corresponding Weibull parameters accordingly. In this work, the same scenarios and parameters, presented in Table 4, have been used.

In Spain, 25% of the current cumulative PV capacity installed was connected in 2008, coinciding with the transformation of the PV industry when the Asian manufacturers quickly gained market. There were problems regarding the quality of the modules.[38] This situation caused a decrease in the reliability of the PV modules fabricated in that period and led to their early degradation.[39,40,41] In 2008, Spain beat installation PV power records at the European level, but between 2009 and 2012, Germany far exceeded Spain's rates, as did Italy from 2010 to 2012, as shown in Fig. 2.

To help with analysing the effect of loss reliability on the PV waste mass projection, two new degradation scenarios have been proposed here for the Spanish, German and Italian special cases, namely, Regular (2) and Early (2), which take into account these peculiarities by a shorter characteristic lifetime T of 20 years for 2007 and 2008, and T of 30 years for any other year.

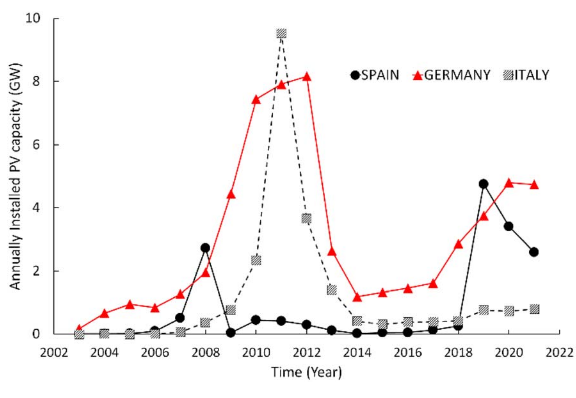

Fig. 2 Annually installed PV capacity *vs.* time for Spain, Germany and Italy.

2.3 Conversion from installed PV power to mass PV waste

To evaluate the total mass of PV waste it is necessary to estimate, in addition to the annually installed power, the modules that will fail annually and must be replaced. To do this, the conversion of power to mass was first carried out using the following exponential decay function:

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

Eqn (2) 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. This equation was proposed by IEA-PVPS/IRENA,[15] which suggest, based on technical data of solar panel for specific years, that exponential decay represents a good fit for correlation between the mass of PV per unit capacity (t MW^{-1}) *vs.* time in years. The work is a review of the average data of the nominal power and weight of PV modules from leading producers from 1980 to 2013. From 2015 to 2050 they make a projection based on the future relationship between power and weight, which is expected to be optimized as there is a reduction in total weight (due to a decrease in the thickness of frames, glass layers and wafers) and an increase in power.

In this study, to obtain a more representative adjustment, real data, not projected, for the year 2020 has been included, in which the power/weight ratio of the most representative panels of the market has been analysed. These are the ones that currently cover the largest market share with efficiencies of 21% and above, according to ref. 42.

The best-selling modules of each manufacturer in Table 5 were obtained, and from the technical datasheet, the weight-to-power ratio was obtained as an average of nominal power and weight, which was then used as a replacement for the 2020 value in the IEA curve.

The IRENA report gives a projected ratio of 65 t MW^{-1} for 2020, and our calculations, based on real data, set this value to

Table 5 PV modules with efficiencies higher than 21% for manufacturers according to ref. 42 selected for the calculation of the value of the power/weight ratio in 2020

Manufacturers	
LONGi green energy technology	China
Tongwei	China
JA solar	China
Aiko solar	China
Trina solar	China
Jinko solar	China
Canadian solar	China/Canada
Zhongli	China
Suntech	China
First solar	USA
LG solar	China
Chint	China
GCL	China
Maxeon	Singapore
Risen	China
Yingli	China

Table 6 Fitting parameters for the mass-to-power ratio function (eqn (2)). An exponential dependence with time is assumed. B corresponds to the exponential time constant. R^2 corresponds to the coefficient of determination of the fitting

A (t MW^{-1})	B (year)	R^2
2.72×10^{25}	37.11	0.937

56.54 t MW^{-1}. This implies a faster-than-expected reduction in module weight.

Therefore, the parameters that fit eqn (2) are presented in Table 6. For years after 2020, the same data from the IEA-PVPS/IRENA report were taken.

3. Results

In this section, the calculation of the mass of photovoltaic generated waste is presented and analysed from the estimated projections in installed capacity to 2050 for the selected countries.

The installed power during those years could be affected by lower reliability in the long term, reducing its expected lifetime.[43]

Once the NECP goal of 39.18 GW has been reached, our projections indicate that in 2050, Spain will have an installed photovoltaic capacity of 90.90 GW if the same growth rate is considered (see Table 2).

As was settled in Section 2.3, waste mass generated by this installed power varies with wear-out modules.

In this work, the same four possible scenarios proposed by Santos are considered, but the key difference is that we provide a new focus for calculations, given that we used a projection based on the objectives of the National Energy Climate Plan for Spain (NECP),[19] new real data of installed capacity, and a new mass-to-power ratio (eqn (2)) based on real data, which brings more accuracy.

In an updated article,[44] the calculations were based on two different power estimations, the European Network of Transmission System Operators for Electricity (ENTSO-E), which assumes an installed capacity of 47 GW in 2030, and the one predicted by the Committee of Experts on Energy Transition report[45] which considers that Spain would have an installed capacity of 26 GW by the same year. The results in this work show that in the period 2020–2035, the PV WEEE mass is determined by the failure of the 2007–2008 PV plants. Therefore, the annual PV WEEE mass is independent of the chosen PV capacity projection. In 2050, the influence of the degradation scenario becomes less relevant.

Table 7 Total wear-out power in MW for NECP target projection for Spain in Regular (1), (2) and Early (1), (2) refers to shorter characteristic lifetime degradation scenarios

Total annual wear-out power (MW)		
	Year	
Scenario	2030	2050
Regular (1)	2756.55	4693.10
Early (1)	3012.50	4811.55
Regular (2)	2903.95	4780.30
Early (2)	3054.50	4804.10

Our PV power projections were based on the NECP target, which is 39.18 GW for 2030, as stated before. The total wear-out power calculated with this target is presented in Table 7.

The total wear-out power shows an increase with time due to new PV installations. However, it is possible to observe that in the year 2030, the difference in power between type 1 scenarios reaches 9%, and in type 2 scenarios the difference is 5%. These differences become less relevant by 2050, being 2.5% for type 1 scenarios and only 0.5% for type 2 scenarios. Power losses in 2030 and type 1 scenarios are linked to the end-of-life of PV installations developed in 2007–2008, and scenarios with a shorter characteristic lifetime, Regular (2) and Early (2), present higher total wear-out power. In the year 2050 the degradation is less relevant, but the trend of greater power losses in Early-EL than in the Regular-RL continues, both in type 1 and type 2 degradation scenarios.

3.1 Analysis of selected countries

The assessment of the photovoltaic waste up to 2050 for selected countries requires a projection of the cumulative installed PV capacity. Previous works have estimated the projection of PV waste in different countries with special emphasis on some EU state members.[46–48] Calculations were made previously[46] for Italy by considering that the lifetime of PV modules is 25 years, not taking into account any probability distribution function and, consequently, not all possible degradation scenarios were considered. Another report[47] used Weibull probability distribution but calculated PV waste mass just for Germany. Another group[48] modeled the bathtub-shaped lifetime distribution and restricted calculations to Flanders, a region of Belgium.

Herein, we have used the Weibull probability distribution to calculate the effects of the PV plant wear-out power needs for Europe, China and some South American countries using an iterative process.

As in the case of Spain, for the rest of the countries, this wear-out capacity has been calculated since it causes a progressive power loss in PV plants, which means that the installation rates calculated without this consideration in previous works are insufficient to achieve the objectives proposed by their national plans.

In Table 8 the projections of the total wear-out power calculated in the Regular (1) and Early (1) scenarios for the selected countries are presented.

The results show a progressive increase in wear-out power with time for both degradation scenarios in all selected countries. There are differences between the Regular (1) and the Early (1) scenario behaviours, and for a clearer analysis of the

Table 8 Annual wear-out power in MW for NECP target projection for selected countries

Annual wear-out power (MW)			
		Year	
Country	Scenario	2030	2050
Germany	Regular (1)	5 373	8 588
	Early (1)	6 125	9 362
	Regular (2)	7 470	8 894
	Early (2)	6 699	9 229
Italy	Regular (1)	2 058	3 107
	Early (1)	2 387	3 571
	Regular (2)	3 263	3 240
	Early (2)	2 721	3 492
France	Regular (1)	4 320	6 936
	Early (1)	4 670	7 348
European Union	Regular (1)	4 3671	6 8913
	Early (1)	46 999	73 548
United Kingdom	Regular (1)	4 146	6 582
	Early (1)	4 509	7 043
USA	Regular (1)	20 956	34 656
	Early (1)	22 998	35 531
China	Regular (1)	74 603	127 672
	Early (1)	81 747	130 962
Brazil	Regular (1)	7 135	11 512
	Early (1)	7 561	12 024
Chile	Regular (1)	2 516	4 005
	Early (1)	2 669	4 218
Argentina	Regular (1)	158	305
	Early (1)	178	296

evolution, the wear-out power evolution with time is presented in the following figures for these countries.

Our calculated projections in Fig. 3 show the different behaviours between the two degradation scenarios in Spain, Germany and Italy. The Regular (1) scenario graphs present relative maximum points around the interval 2040–2042. It presents a change in the speed of growth around the interval.

2040–2042, reaching a maximum in the slope for Germany in 2040 and for Italy in 2042, then the velocity of growth decreases

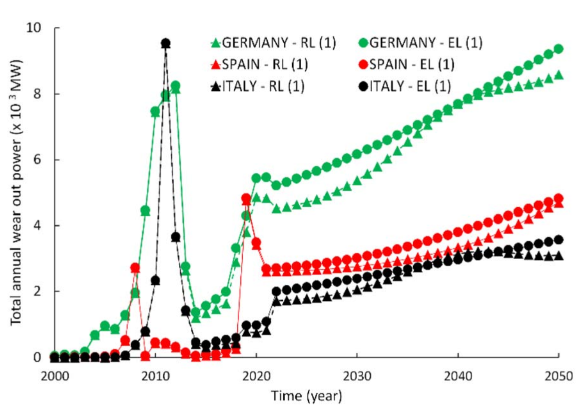

Fig. 3 Annual wear out comparison between the Regular (1) and the Early (1) degradation scenarios for Spain, Germany and Italy.

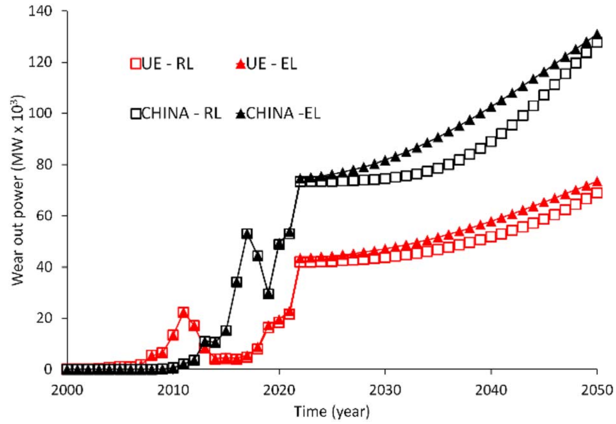

Fig. 4 Annual wear-out comparison between the Regular (1) and the Early (1) degradation scenario for the European Union and China.

and resumes the rate of growth prior to the interval 2040–2042. These relative maximum peaks are due to oscillations produced in PV power installations and their maximums occurred 30 years earlier.

Continuing with the analysis of the results of Table 8, Fig. 4 is presented, which shows the comparison of the evolution of the wear-out power in the two degradation scenarios for the European Union and China.

Wear-out power curves increase earlier in the Early (1) scenarios than in the Regular (1) scenarios, linked to the early life stage failure probability of PV modules considered in the Early degradation scenario. The same behaviour is observed in the wear-out capacity evolution projected for South America presented in Fig. 5.

Bogdanov *et al.*[49] assessed that the cumulative PV capacity in South America must reach 424 GW in 2030 and this appears a very long way away, taking into account that there are cases such as Argentina, which have been experimenting with delays in PV power installation. In this regard, despite the success of

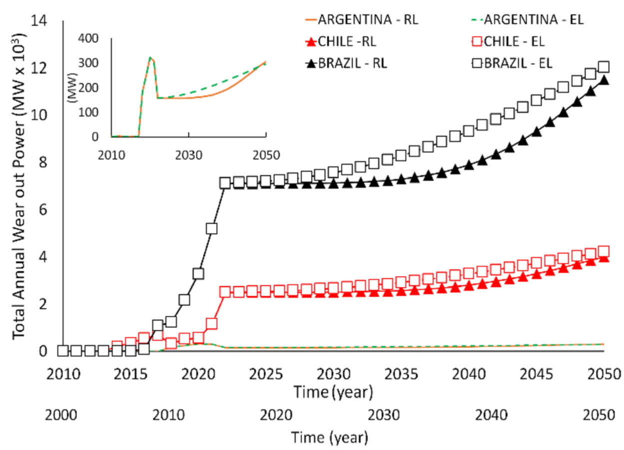

Fig. 5 Annual wear-out comparison between the Regular (1) and the Early (1) degradation scenario for the European Union and China.

energy auctions to expand renewable capacity in Argentina, the sector faces macroeconomic challenges that are still holding back growth in many sectors, including (i) high interest rates; (ii) the need to hedge against the risk of local currency fluctuations; (iii) limited transmission infrastructure, and (iv) artificially low electricity prices due to subsidies for the net accounting for distributed generation.[2]

3.2 Evolution of the cumulative PV WEEE mass

To calculate the cumulative PV WEEE mass projection, it was necessary first to obtain the annual installed PV module power and convert it to mass using eqn (2). This annual installed PV power was calculated through an iterative process that takes into account the annual power losses that would increase year by year until a maximum is reached around 30 years later. Therefore, the cumulative PV WEEE mass projection results for Spain, Germany and Italy are presented in Table 10, separate from the analysis made for the other countries because of the two additional degradation scenarios considered, as was explained in Section 2.2. The results presented in Table 9 for Spain are analogous in the order of magnitude to those presented by Santos *et al.* based on the Bloomberg New Energy Finance (BNEF) and the European Network of Transmission System Operators for Electricity (ENTSO) projections. The influence of degradation scenarios can be seen in the results obtained in 2030, and they lose relevance in projections obtained in 2050. Type 2 degradation scenarios present higher values in 2030 due to the failure of the 2007–2008 PV plants. In 2050, the cumulated PV WEEE mass increases roughly to 1 300 000 tonnes for the Regular (1) and (2) scenarios and 33.24% higher for the Early (1) and (2) than the Regular (1) degradation scenarios.

Comparative analyses of the cumulative PV WEEE mass as a function of time for the selected countries are presented in Fig. 6–8. Large-territory countries (*e.g.* China, Australia, and the USA) face uneven PV development patterns by region.[31,50,51] These countries will require a spatial-temporal analysis of solar waste as the initial step for effective waste management, which is not carried out in this work.

The results have been grouped into three graphs due to the different orders of magnitude of the variables that are represented, and to facilitate the analysis.

Fig. 6 shows the evolution of the cumulative PV WEEE mass. As can be seen, the generation of PV WEEE is related to the projected development of the PV market; as a result, Italy shows a PV waste generation greater than the rest of the countries presented in this graph, such as the United Kingdom or France. Fig. 7 shows the comparison of PV WEEE masses for China, Germany and the European Union for the Regular – RL scenario. These projections are presented together due to the similarities in the orders of magnitude. As can be observed, the European Union leads the cumulative waste generation until 2040, when China takes the lead throughout 2050.

Table 9 Cumulative PV WEEE mass (*t*) projections for Spain, Germany and Italy

Cumulative PV WEEE mass (*t*)			
		Year	
Country	Scenario	2030	2050
Spain	Regular-1	66 189	1 262 084
	Early-1	209 378	1 672 074
	Regular-2	246 250	1 300 307
	Early-2	312 386	1 742 067
Germany	Regular-1	377 500	4 689 566
	Early-1	1 103 448	5 348 656
	Regular-2	1 433 512	49 164 416
	Early-2	1 832 862	5 952 004
Italy	Regular-1	126 413	1 898 452
	Early-1	443 518	2 118 562
	Regular-2	671 900	2 017 718
	Early-2	836 329	2 453 832

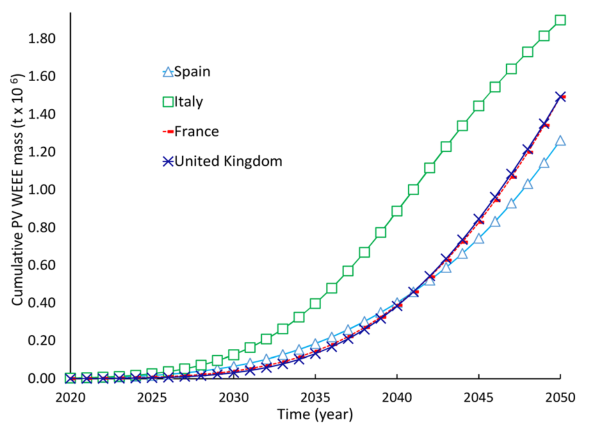

Fig. 6 Cumulative PV WEEE mass for Spain, Italy, France and the United Kingdom, considering the Regular (1) scenario.

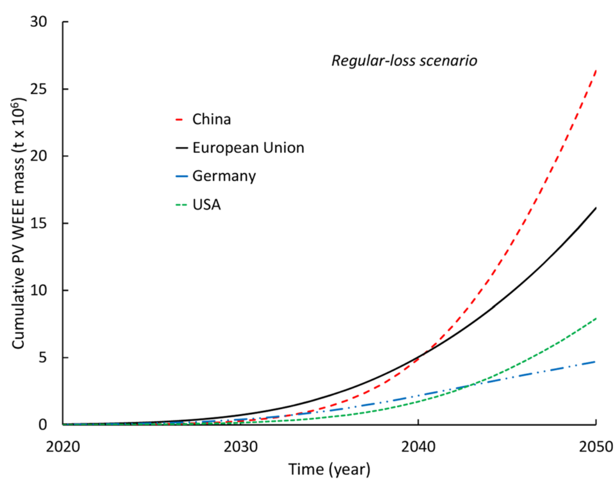

Fig. 7 Cumulative PV WEEE mass for China, Germany, the European Union and the USA, considering the Regular (1) scenario.

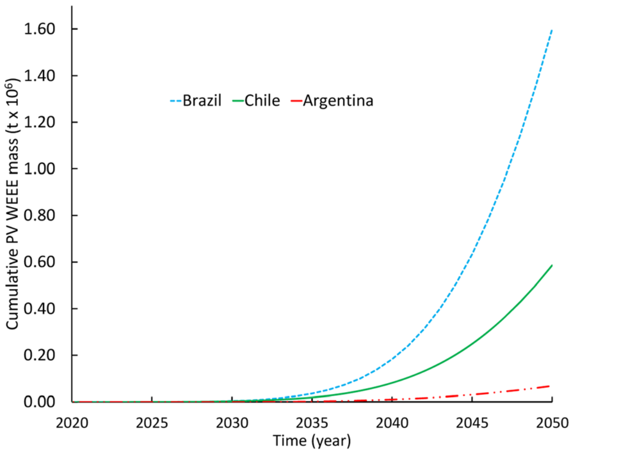

Fig. 8 Cumulative PV WEEE mass for some South American countries, considering the Regular (1) scenario.

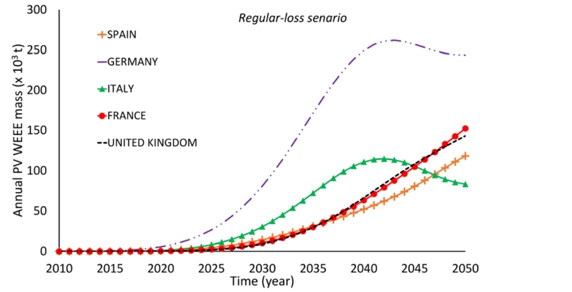

Fig. 9 Annual PV WEEE mass for Spain, Germany, Italy, France and the United Kingdom, considering the Regular (1) scenario.

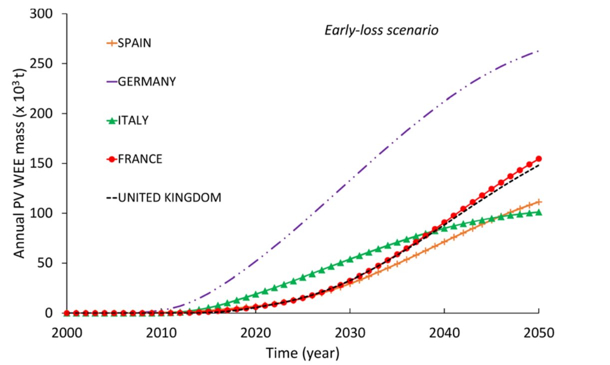

Fig. 10 Annual PV WEEE mass for Spain, Germany, Italy, France and the United Kingdom, considering the Early (1) scenario.

Another point to highlight in this comparison is that within the countries of the European Union, Germany is the one that produces the greatest amount of PV waste, even more than China until 2032, according to our projections.

The results for the comparison of the cumulative PV WEEE masses for the selected countries in South America are presented in Fig. 8. This figure highlights the cumulative PV waste generated by Brazil, which is directly related to the installation capacity rate carried out. It is the only South American country present in the top 10 countries in terms of power installation due to a 74% growth in installed capacity in 2021 over the installed capacity in 2020.[2] However, between 2021 and 2027, Chile will generate a 21% greater cumulative PV waste mass than Brazil, due to the annual installed PV capacity, which is higher in Chile. As for Argentina, the generation of PV waste mass is low due to a very limited installation rate. Projections towards 2050 have been made with data from the IRENA database and its NECP, but Argentina is expected to update its solar power PV growth strategy with the aim of reaching the goals set out in its NECP, as indicated in the document “Lineamientos para un Plan de Transición Energética al 2030”.[29]

The results presented in Fig. 6–8, are useful for estimating an appropriate recycling strategy for wear-out modules, as well as the development of a national industry for PV WEEE recycling.

3.3 Annual PV WEEE mass evolution

The assessment of the annual PV waste mass is useful for preparing the recycling industry to manage the exponential growth expected for the amount of wear-out PV modules.

The annual retired capacity flow from PV plants to the recycling industry is calculated and presented in Fig. 9–11 for the selected countries in the EU and United Kingdom and both scenarios are considered.

Fig. 9 and 10 show the evolution of the annual PV WEEE mass for the Regular – RL and the Early – EL scenarios, respectively. In the first one, a difference in behaviour is observed in the curves of Germany and Italy, which present maximums around the years 2042–2043.

This oscillation is directly related to maximums in the annual power installation that occurred in 2011 and 2012 respectively. In the Early scenario, significant waste mass losses begin in 2008, while in the Regular (1) degradation scenario these losses occur from 2015. As was expected, the annual increase in PV waste presented by the Early (1) scenario in all countries is higher than the resultant in the Regular (1) degradation scenario.

Fig. 11 presents a comparison of the annual PV WEEE mass generated in China and the European Union in both degradation scenarios.

The comparison between China and the European Union shows a monotonically increasing function for annual waste mass generation, related to the continuous growth of PV installations. In the Early scenario, waste generation occurs earlier due to the higher failure probability in the early stages considered. By 2050, the influence of early losses in the annual waste generation in the European Union has nearly disappeared, while in China the Regular – RL scenario produces an 8.25% more PV WEEE mass than the Early degradation scenario.

The annual PV WEEE mass evolution for the same three selected countries in South America is presented in Fig. 12.

Brazil will generate higher amounts of annual PV WEEE mass as a result of its capacity PV installation rate. All curves

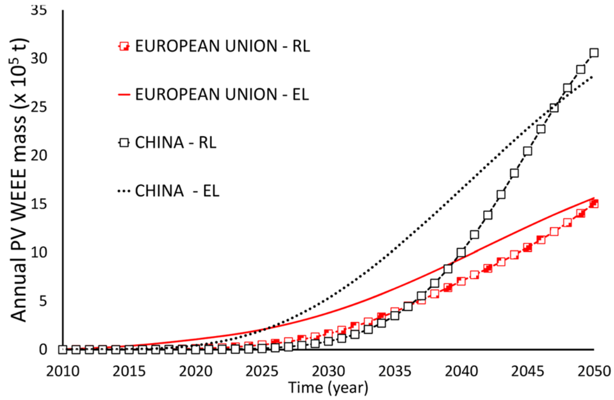

Fig. 11 Annual PV WEEE mass evolution for Regular (1) and the Early (1) scenarios in China and European Union.

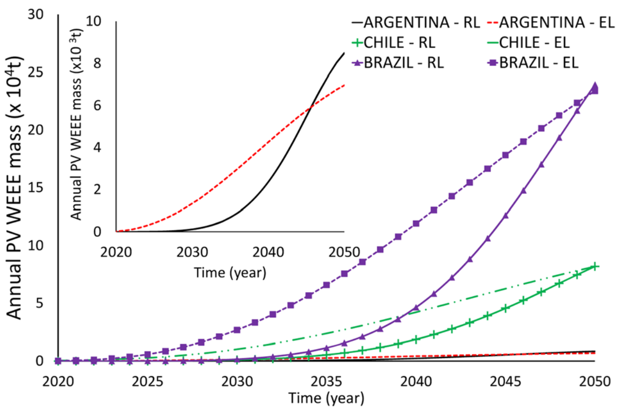

Fig. 12 Annual PV WEEE mass evolution for Regular (1) and the Early (1) scenarios in selected countries in South America.

behave like monotonically increasing functions but the generation rates increase faster in the Early scenario during the first years due to early life stage failure.[52]

To summarize what is stated in this section, the projections for 2030 and 2050 obtained for the countries analyzed are presented and a comparative analysis is shown below.

In addition, the projections for the annual installed PV module mass for the Regular (1) scenario are presented in Table 10 and for the Early (1) scenario in Table 11.

Calculation of the annual PV waste module mass is of special interest since it provides a picture of the availability of discarded modules year by year. Hence, this information will be helpful in analysing the balance between the waste stream from wear-out PV modules and the waste flow to the recycling industry. Referring to the annual installed PV module mass presented in Tables 10 and 11, it is observed that the values obtained for the Early (1) scenario are higher than those for the Regular (1) scenario for both years 2030 and 2050, ranging from 5% to 14%. On the other hand, each country will install more modules in 2030 than in 2050 in both scenarios, according to our projections. For the Regular (1) scenario, our results for the USA are similar to the results published by the IEA report[53] and differ from those reported in ref. 51 by 44%. Our first inference about this difference is that ref. 51 doesn't use a probabilistic failure model to calculate the annual PV waste mass; instead, they carry out calculations using a fixed PV market share, which we consider may vary. For the Early (1) scenario, our results are analogous to the IRA report.[53]

3.4 The effects of variation of the annual installed PV power on the annual PV module waste mass

The projections of the future PV waste mass generated have great uncertainty due to oscillations that are introduced in the annual installed PV capacity in each country analysed. As we have seen, most of them have established ambitious objectives in their NECPs but to a greater or lesser extent, they are affected by different variables, and not only technological improvements, some of which have not been possible to predict, for example, the crisis caused by the Covid-19 pandemic, the Russian–Ukraine war, and environmental factors. Therefore, a study of the effects produced by a variation of the annual installed PV power on the projections of the annual PV waste

Table 10 Projections of annual installed PV module mass, cumulative PV waste mass and annual PV waste mass in 2030 and 2050 for the Regular (1) scenario

Country	Annual installed PV module mass (*t*)		Annual PV waste mass (*t*)		Cumulative PV waste mass (*t*)	
	2030	2050	2030	2050	2030	2050
Spain	131 236	130 344	14 193	118 570	66 188	1 262 085
Germany	255 796	238 512	80 985	243 740	377 500	4 689 566
Italy	97 991	86 2845	30 332	83 358	126 416	1 898 453
France	205 666	192 629	10 303	152 355	39 920	1 493 559
EU	2 079 118	1 913 947	161 888	1 503 989	711 597	16 153 332
China	3 551 782	3 545 909	83 910	3 059 470	264 492	26 326 611
USA	997 659	962 511	37 867	864 336	147 114	7 901 705
United Kingdom	197 366	182 814	9 101	143 212	32 167	1 494 108
Brazil	339 682	319 717	1 626	239 338	3 923	1 601 475
Chile	119 773	111 241	1 059	81 941	3 026	585 441
Argentina	7 521	8 454	117	8 486	298	67 769

Table 11 Projections of annual installed PV module mass, cumulative PV waste mass and annual PV waste mass in 2030 and 2050 for the Early (1) scenario

	Annual installed PV module mass (*t*)		Annual PV waste mass (*t*)		Cumulative PV waste mass (*t*)	
Country	2030	2050	2030	2050	2030	2050
Spain	143 420	133 633	29 550	111 364	209 378	1 672 074
Germany	291 565	260 022	129 893	264 117	1 103 448	5 348 656
Italy	113 641	99 184	53 476	101 449	443 517	2 118 562
France	222 270	204 074	32 424	154 669	199 394	2 096 400
EU	2 237 546	2 042 685	370 304	1 566 199	2 579 690	22 248 201
China	3 891 877	3 637 273	530 459	2 826 235	2 625 782	36 993 226
USA	1 094 916	986 819	165 656	800 864	908 472	10 874 454
United Kingdom	214 676	195 612	32 784	148 170	198 595	2 038 572
Brazil	359 984	333 942	26 774	233 884	98 844	2 660 990
Chile	127 048	117 153	10 255	81 857	43 092	949 040
Argentina	8 470	8 213	1 335	6 969	5 696	92 837

Table 12 Effects of the annual installed PV capacity variation in the annual PV waste mass for the Regular (1) scenario for selected countries

Regular (1) scenario	Annual PV waste module mass (t)							
	2030				2050			
Annual installed PV power variation	−25%	+25%	+50%	+100%	−25%	+25%	+50%	+100%
Spain	14 134	14 473	14 311	14 429	99 007	147 032	157 696	196 822
Germany	81 315	81 089	81 523	81 402	226 541	277 329	341 561	387 096
Italy	30 303	30 360	30 389	30 446	71 569	95 147	106 936	130 513
France	10 224	10 460	10 461,	10 619	122 228	184 818	212 607	272 860
EU	161 159	162 617	163 346	164 803	1 209 493	1 798 484	2 092 980	2 681 970
China	75 282	92 537	101 166	118 422	2 349 032	3 769 907	4 480 344	5 901 219
USA	35 944	39 791	41 714	45 561	668 952	1 059 720	1 255 104	1 645 872
UK	9 051	9 151	8 201	9 292	116 652	169 772	196 332	24 8511
Brazil	1 484	1 620	1908	2 190	187 529	282 467	342 955	446 572
Chile	1 016	1101	1143	1 228	64 400	99481	117 021	152 102
Argentina	111	122	127	138	7 149	9 821	11 158	13 831

Table 13 Effects of the annual installed PV capacity variation on the annual PV waste mass for the Early (1) scenario for selected countries

Early (1) scenario	Annual PV waste module mass (*t*)							
	2030				2050			
Annual installed PV power variation	−25%	+25%	+50%	+100%	−25%	+25%	+50%	+100%
Spain	27 745	31 356	33 161	36 771	91 381	131 347	151 331	191 297
Germany	129 924	136 185	145 133	145 578	228 455	296 749	344 319	399 190
Italy	52 923	54 940	55 948	57 964	88 780	113 692	126 147	151 059
France	29 848	35 134	37 778	43 064	123 153	186 122	217 606	280 575
EU	352 263	402 936	428 272	478 944	1 252 375	1 873 143	2 183 527	2 804 295
China	483 087	578 014	625 478	720 404	2 270 630	3 381 751	3 937 312	5 048 433
USA	140 356	190 956	216 257	266 857	620 498	981 230	1 161 596	1 522 328
UK	30 685	34 899	37 006	41 220	119 247	177 087	206 007	263 847
Brazil	22 169	31 379	35 984	45 195	180 050	287 717	341 551	449 218
Chile	8 759	11 752	13 248	16 241	63305	100 409	118 961	156 066
Argentina	1 198	1 472	1 609	1 884	5 675	8 262	9 555	12 142

module mass is an interesting analysis to carry out to cover the cases in which the deployment of PV capacity is higher than the targets of the countries NECPs in three scenarios, and one in which it is lower, and these variations are presented as follows. For the Regular (1) scenario, results are shown in Table 12 and for the Early (1) scenario, in Table 13.

Table 12 shows different behaviours in the results obtained from the variations in the years 2030 and 2050. In 2030, variations in "the annual installed power" produces percentages less than 10% in the annual PV waste mass for all countries except China, Brazil, Chile and Argentina that far exceed these values when 100% variations in the annual installed power are projected. For example, China will generate 41% of PV WEEE mass, Brazil 95%, Chile 48% and Argentina 91%. It could be said that in 2030 the generation of PV WEEE mass does not show great sensitivity to variations in the annual installed power. However, this situation changes in results obtained in projections for 2050 when its correspondence is undeniable.

For the Early (1) scenario, results shown in Table 13 also present a similar pattern of behaviour to the results for the Regular (1) scenario presented in Table 12 for all studied countries. In 2050, the differences obtained in the annual PV waste mass when variations occur in the annual installed PV are greater than those that take place in the year 2030. However, in both 2030 and 2050, these results are greater than those obtained in the Regular (1) scenario because here the degradation of modules in the early stages is taken into account and, therefore, the generation of PV waste mass occurs earlier.

To manage the generation of PV waste that will occur in the long term, countries need to develop an organized infrastructure for the recycling of electronic waste generated by solar PV. Gautam *et al.*[54] proposed the development of an organized recycling infrastructure in India through the creation of SMEs but this could be applied to other countries to deal with the strategic management of end-of-life (EOL) solar photovoltaic mass waste. However, recycling facilities face diverse challenges, such as high energy use and liquid consumption in recovery technologies; *e.g.*, thermal, mechanical and chemical recycling methods.[55]

4. Conclusions

Projections for future PV WEEE mass in nine countries and the European Union were carried out to 2030 and 2050, taking into account two different PV degradation scenarios to analyse the effects of PV technology reliability on PV waste generation. Furthermore, two extra degradation scenarios were studied for Spain, Germany and Italy, which consider lower quality standards of PV installed modules during 2007–2008.

A projection for the cumulative installed power was calculated and compared to NECPs targets for selected countries, which gives an idea of the level of progress of each country's energy plans, and the yearly installation goals they need to achieve. From that point of view, Germany is the country that has made the most progress in achieving its target, accomplishing 60% of its goal in 2021. It is followed by Argentina and China with 50% of the objective of their NECP achieved, and the United Kingdom with only 20% is the studied country that has achieved the least of its goal.

The annual PV wear-out power projections depend on the annual installed PV power and the degradation scenario. With these calculations carried out, it is evident that the generation of PV waste represents a significant percentage of the total PV power installed in 2021, depending on the considered scenario. For all cases analysed, almost one in two PV modules would be used to replace wear-out power in 2050. Therefore, an important market could arise linked to PV module recycling.

Our projections indicate that important PV waste quantities could be generated in the near future in the cases studied, linked to high PV installation rates, with China holding the leadership in 2050 followed by the European Union. For the most conservative scenario, China would generate more than 26 million tonnes of cumulative PV waste mass, while the European Union would generate 16 million tonnes in 2050. The European Union will need a powerful PV recycling industry to treat a cumulative PV waste mass of approximately 700 000 tonnes by 2030, considering the most conservative scenario, which implies that it will have to treat 170% more PV waste than China at that time.

As for the annual PV waste mass generation, important differences were observed between the results obtained in the two degradation scenarios by 2030. In 2050, the differences in annual PV waste mass generation are reduced to a minimum, and even less waste is generated in Spain, China, Brazil, Chile and Argentina in the Early (1) scenario than in the Regular (1) scenario because early failures have already occurred.

An assessment of the effects produced by a variation in the annual installed PV power on the projections of the annual PV waste module mass was carried out for both degradation scenarios. As was expected, a higher PV capacity means greater PV WEEE mass. For the Regular (1) scenario, projections to 2030 are independent of PV capacity, while its correspondence is strong in 2050. In the Early scenario, the generation of PV waste mass occurs earlier in both 2030 and 2050.

As a conclusion for the analysis of the results presented, it should be highlighted that the generation of PV waste mass in the two scenarios evaluated, Regular (1) and Early (1), present very large percentage differences between the reference annual installed capacity and its variations of −25%, +25%, +50% and +100%. This could have a high impact on recycling PV planning both at the state and global levels.

As for the South American countries studied in this work, Brazil is the one that will have an annual installed PV capacity that would cause it to be the leader of the region, even surpassing the European leader, Germany, both in 2030 and in 2050.

Appendix

In Table 14, data on installed power and the objectives of the NECPs of all 27 members of the European Union, the United Kingdom, China, the USA, and selected South American countries are presented.

Table 14 Historical data, sources and 2030 NECP goals. The superscripts refer to the reference year when it is different from 2030

Country	Historical data	Source	NECP (GW) 2030	Source
Spain	1990–1999	Eurostat	39.18	NECP Spain[19]
	2000–2021	Irena		
France	1990–1999	Eurostat	35.10–44.00$^{(2028)}$	NECP France[21]
	2000–2021	Irena		
Germany	1990–1999	Eurostat	98.00	NECP Germany[20]
	2000–2021	Irena		
Italy	1990–1999	Eurostat	52.00	NECP Italy[22]
	2000–2021	Irena		
Austria	1992–1999	Eurostat	9.70	NECP Austria[56]
	2000–2021	Irena		
Belgium	2002–2010	Eurostat	20.00	NECP Belgium[57]
	2011–2021	Irena		
Croatia	2009–2021	Eurostat and Irena	0.77	NECP Croatia[58]
Cyprus	2004–2021	Irena	0.75	NECP Cyprus[59]
Czechia	2000–2005	Eurostat	3.98	NECP Czechia[60]
	2006–2021	Irena		
Denmark	1996–1999	Eurostat	7.84	NECP Denmark[61]
	2000–2021	Irena		
Finland	1990–1999	Eurostat	1.20^{a}	NECP Finland[62]
	2000–2021	Irena		
Greece	2000–2021	Eurostat and Irena	7.70	NECP GREECE [X][63]
Hungary	2007–2021	Eurostat and Irena	6.50	NECP Hungary[64]
Ireland	2009–2021	Eurostat and Irena	1.75$^{(2040)}$	NECP Ireland[65]
Latvia	2012–2021	Eurostat and Irena	0.80^{b}	NECP Latvia[66]
Lithuania	2008–2021	Eurostat and Irena	0.74	NECP Lithuania[67]
Luxembourg	2001–2021	Eurostat and Irena	1.11^{c}	NECP Luxembourg[68]
Malta	2005–2021	Eurostat and Irena	0.27	NECP Malta[69]
Netherlands	1990–1999	Eurostat	27.00	NECP Netherlands[70]
	2000–2021	Irena		
Poland	2011–2021	Eurostat and Irena	16.06$^{(2040)}$	NECP Poland[71]
Portugal	1997–1999	Eurostat	9.00	NECP Portugal[72]
	2000–2021	Irena		
Romania	2008–2021	Eurostat and Irena	6.43	NECP Romania[73]
Slovakia	2010–2021	Eurostat and Irena	1.20	NECP Slovakia[74]
Slovenia	2000–2021	Eurostat and Irena	1.65	NECP Slovenia[75]
Sweden	1992–1999	Eurostat	2.24	NECP Sweden[76]
	2000–2021	Irena		
Bulgaria	2007–2021	Eurostat and Irena	3.67	NECP Bulgaria[77]
UK	1997–2021	Irena	70.00$^{(2035)}$	NECP UK[24]
China	2000–2021	Irena	1048.78^{d}	14th FYP[25]
USA	2000–2021	Irena	670$^{(2050)}$	Solar futures USA[26]
Brazil	2001–2021	Irena	21.78–48.59$^{(2022–2026)}$	NECP Brazil[27]
Chile	2012–2021	Irena	9.36–14.36$^{(2022–2025)}$	NECP Chile[28]
Argentina	2000–2021	Irena	2.48^{d}	NECP Argentina[29]

^{a} Not an objective but a projection Finland made in its NECP. ^{b} Wind + solar. ^{c} GW h. ^{d} For further explanation see Table 1.

Author contributions

M. B. N.-M.: conceptualization, data-curation, formal analysis, investigation, methodology, validation, writing; M. C. A.-G.: conceptualization, data-curation, formal analysis, funding acquisition, investigation, methodology, project administration, supervision, validation, visualization, writing; F. G.-R.: conceptualization, data-curation, formal analysis, funding acquisition, investigation, methodology, supervision, validation, visualization, writing; J. D. S.: formal analysis, investigation, methodology, validation, visualization, writing-review and editing; M. A. M.-G.: conceptualization, funding acquisition, investigation, methodology, supervision, validation, writing-review and editing.

Conflicts of interest

There are no conflicts of interest to declare.

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