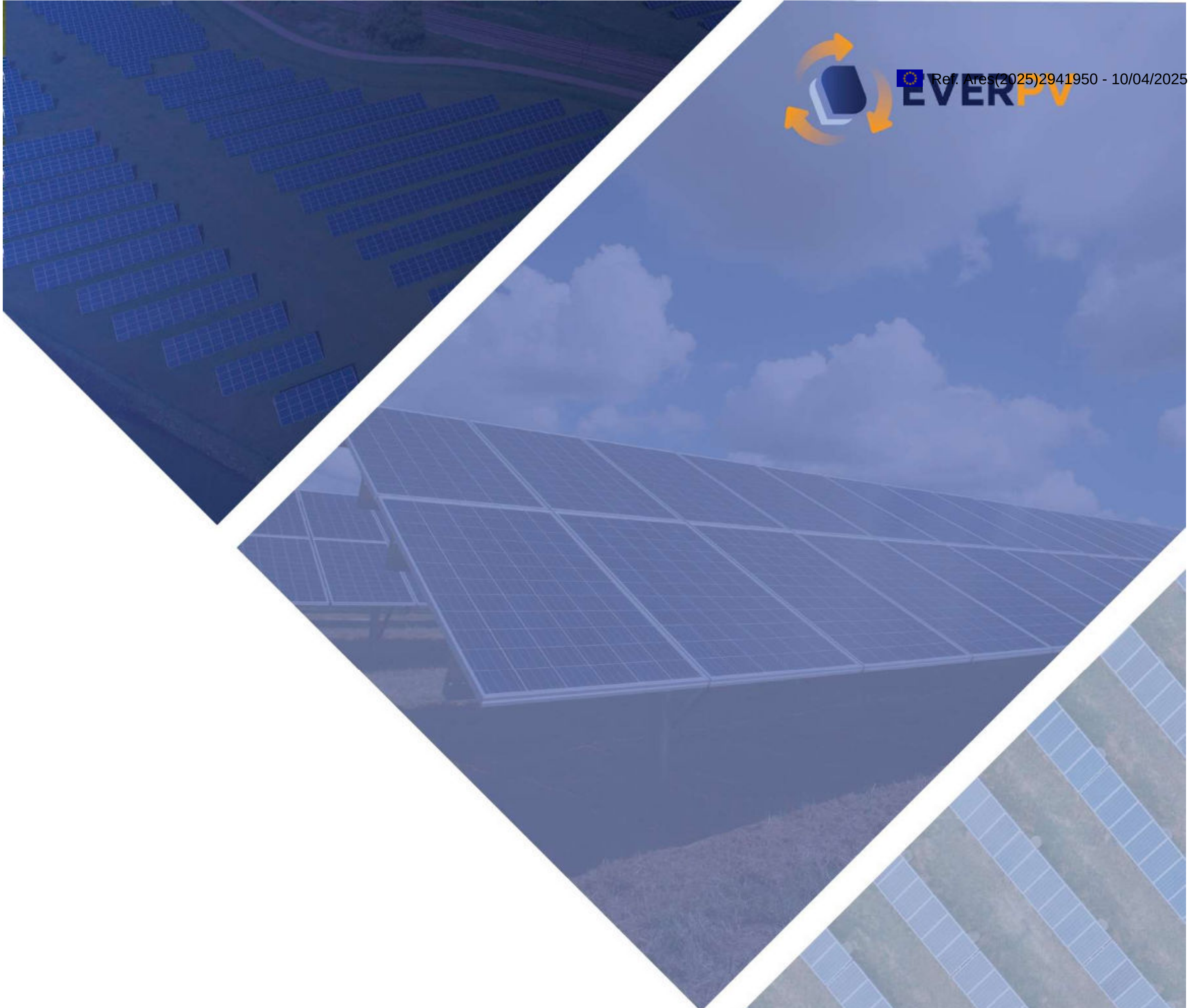

Market assessment of PV and quantification of PV waste and waste streams in EU

Funded by the European Union

Funded by the European Union under Grant Agreement No 101122208. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

TABLE OF CONTENT

LIST OF FIGURES

(Core of the report)

LIST OF TABLES

	EVERPV **GA n°101122208**
Deliverable	Highly efficient delamination technologies to recover and reuse metals, glass, polymers from end-of-life photovoltaic panels

Deliverable ID	**D6.1**
Deliverable name	**Market assessment of PV and quantification of PV waste and waste streams in EU**
Deliverable description	This deliverable presents the methodology and results of the methodology developed to quantify PV POM, PV Stock , PV waste and PV waste streams for all EU27 countries from 2010 to 2030

WP	6	Drivers and requirements to deploy a circular and sustainable PV industry
Task	6.1	Estimate PV market potential and waste generated from 2010 to 2030 (per country and per year) and forecast future PV waste streams

Dissemination level[1]	PU	**Due delivery date**	31 March 2025
Nature[2]	R	**Actual delivery date**	10 April 2025

Lead organization	UNITAR
Main authors	Vanessa Forti (vanessa.forti@unitar.org); Maximilian Schubert (Maximilian.Shubert@unitar.org); Elise Vermeersch (Elise.Vermeersch@unitar.org) (UNITAR)
Contributions	Raffaele Rossi and Christophe Litz (Solar Power Europe), Juan Alzate (Soren), Francesca Fattori (Erion), Nouha Gazbour (CEA)

[1] Dissemination level: **PU** = Public, fully open, **SEN** = Sensitive, limited under the conditions of the Grant Agreement
[2] Nature of the Deliverable: **R** = Report

Version Management			
Filename	EVERPV_D6.1_FINAL.docx		
Author(s)	UNITAR		
Approved by task leader	UNITAR	**Visa**	✓
Approved by WP leader	UNITAR	**Visa**	✓
Approved by Coordinator	Philippe Thony	**Visa**	✓
Authorized by Coordinator	Philippe Thony	**Visa**	✓

Version	Date	Author(s)	Modification[3]
V0	12/02/2025	UNITAR	Creation
V1	24/03/2025	UNITAR, CEA, SolarPower Europe, ERION, Soren	Partners contribution
V2	26/03/2025	"	Revision
V3	07/04/2025	"	Final revision

EC-Grant Agreement	**101122208**
Project acronym	**EVERPV**
Program	HORIZON EUROPE
Client	CINEA
Start date of project	01 September 2023
Duration	36 months
Disclaimer	Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

Coordinator – Administrative information	
Project Coordinator name	Philippe Thony
Project Coordinator organization	CEA
Address	INES campus | F-73375 Le Bourget-du-Lac
Phone Numbers	+33 (0)4 79 79 28 17 +33 (0)7 84 51 52 40
Email	philippe.thony@cea.fr
Project web-sites	everpv.eu

[3] Creation, Modifications, Final version for evaluation, Revised version following evaluation, Final.

ABBREVIATIONS

a-Si	Amorphous silicon technologies
BAU	Business-as-usual
CIGS	Copper Indium Gallium Selenide
EC	European Commission
EoL	End of life
EU	European Union
EVA	Ethylene vinyl acetate
Kt	Kitotonne
kW	Kilowatt
Mono-Si	Monocrystalline Silicon
Multi-Si	Multicrystalline silicon
MW	megawatt
POM	Placed on the market
PV	Photovoltaic
PVs	PV panel
REC	Recovery Scenario
Tdce/PK	Tandem
TF	Thin-film technologies
WP	Work Package

EXECUTIVE SUMMARY

Task 6.1 and Deliverable 6.1 establish a measurement framework for quantifying photovoltaic (PV) waste, covering key indicators like PV panels (PVs) placed on the market (POM), installed capacity, and waste flows. It includes a classification system for consistency and presents PV waste data for the 27 European Union (EU) countries from 2010 to 2030, with waste flows reported at the national level.

PV classification

The EVERPV classification developed in task 6.1 categorizes PV systems into Residential, Commercial, Industrial, and Utility-scale applications, and considers multiple technologies, including monocrystalline silicon (Mono-Si), multicrystalline silicon (Multi-Si), and Thin-film (TF) technologies. This approach enhances data harmonization and supports effective waste quantification.

Methodological framework

Building on the EU's e-waste methodology, the standardized measurement framework emphasizes installed capacity data over trade statistics for accuracy and includes steps such as estimating stock and lifetimes, calculating waste, and tracking both collected and undocumented PV waste. It integrates key variables like technology shares, conversion factors, and lifetime distributions, validated through multiple sources.

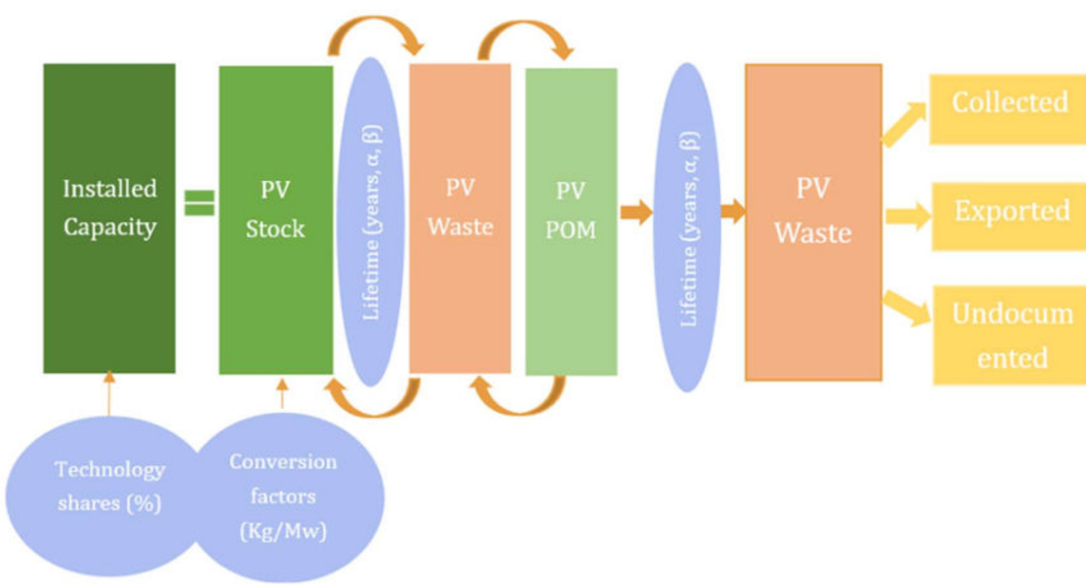

Figure S1: Key variables governing the methodological framework for measuring PV waste statistics

The framework also models three scenarios—Low, Mid, and High—to reflect uncertainties in capacity growth and disposal behavior, offering a nuanced understanding of future PV waste dynamics shaped by policy and technological trends. This approach provides a comprehensive view of the uncertainty in future PV POM and waste projections, influenced by policy and disposal trends

Main results and discussion

Installed capacity

The Mid Scenario serves as middle-of-the-road scenario and utilizes moderate inputs and parameters to create likely outputs. It provides the main guidance and therefore its results are primarily presented, while the additional scenarios establish threshold results as they use more extreme assumptions.

The Mid Scenario projects the cumulative capacity of PV panels to be 816 GW in 2030, ±21% deviation compared to the Low Scenario (644 GW) and High Scenario (983 GW) in the EU27 region.

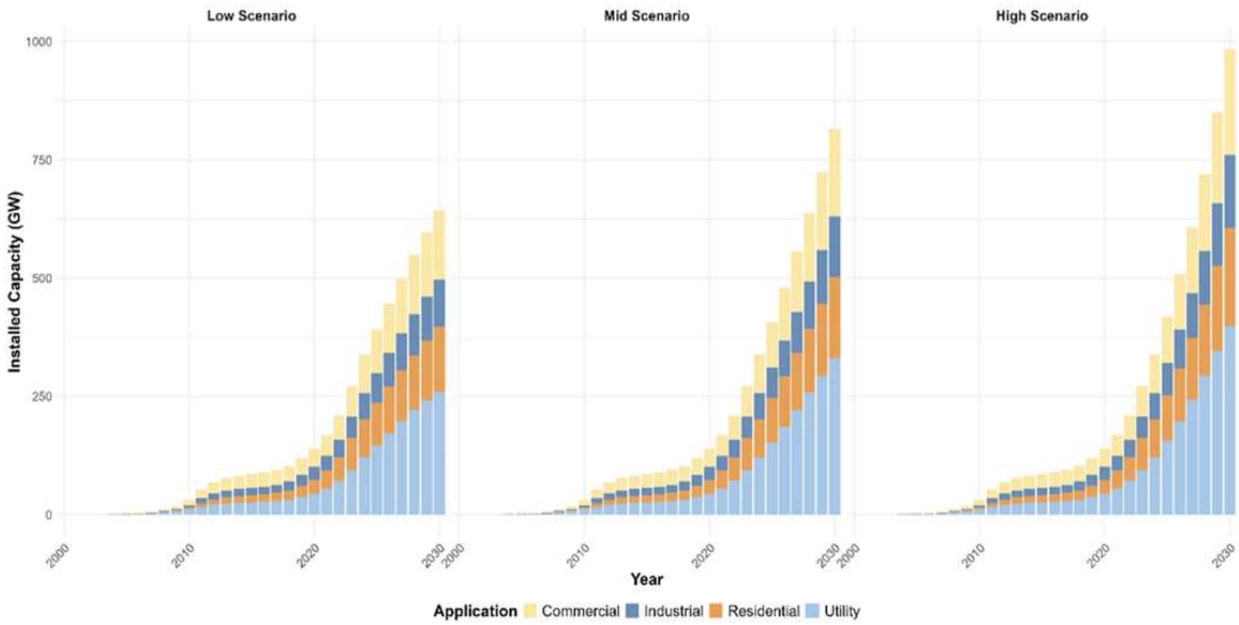

Figure S2: Evolution over time of installed capacity by application in the EU27 in GW.

In terms of applications, in the Mid-scenario, Utility-scale PV panels are the largest growth contributor, increasing by 115% in 2030 (330 GW) compared to 2024. This is followed by Commercial-scale (185 GW), Industrial-scale (173 GW), and Residential-scale (127 GW) in 2030.

In terms of technology, EVERPV estimates that silicon and Thin-film technologies currently account for 94% and 6% of the market respectively. By 2030, it is expected that silicon technology will decrease to 92% (with Multi-Si and Mono-Si reaching 64 GW and 687 GW respectively) and Thin-film to 4% (33 GW), while the Tandem-PK/Si technology is projected to capture a total of 4% market share (32 GW).

PV placed on the market

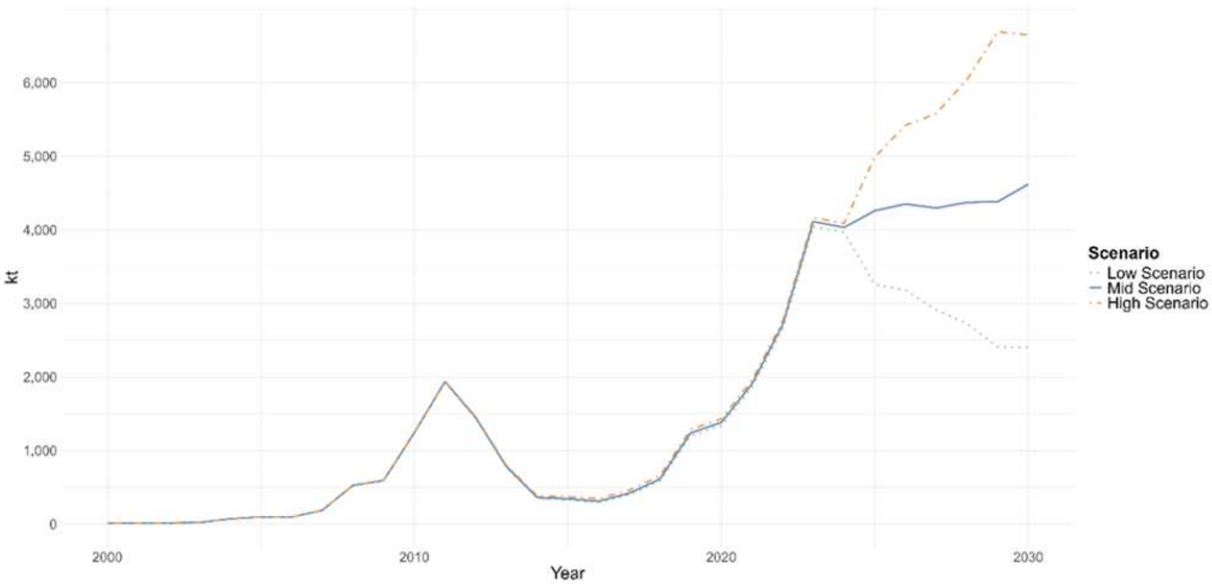

Figure S3: Evolution of PV POM over time for the EU27 in kt.

PV POM varies strongly across scenarios: the Low Scenario (longer lifetimes) leads to declining PV installations, reaching 2,500 kt per year by 2030, while the High Scenario (shorter lifetimes, higher capacity) sees continuous growth, surpassing 6,600 kt. The Mid Scenario shows moderate growth, peaking at 4,500 kt in 2030.

PV waste generated

By 2030, EVERPV projects 207 kt in the Low Scenario, 454 kt in the High Scenario, and 326 kt in the Mid Scenario, with deviations of +37% to 39% due to varying shape values that shift waste timing.

Utility-scale PV waste dominates In the High and Mid Scenarios, Utility-scale PV waste is the largest contributor due to higher replacement rates from repowering, though its relative share declines until 2030 before a potential future rise; Commercial-scale PV waste remains stable but lower in share, while Industrial and Residential waste steadily increase. Instead, the Low Scenario distributes waste more evenly between Utility and Commercial and between Industrial and Residential applications and sees the relative share of Commercial-scale PV panels waste decline till 2030.

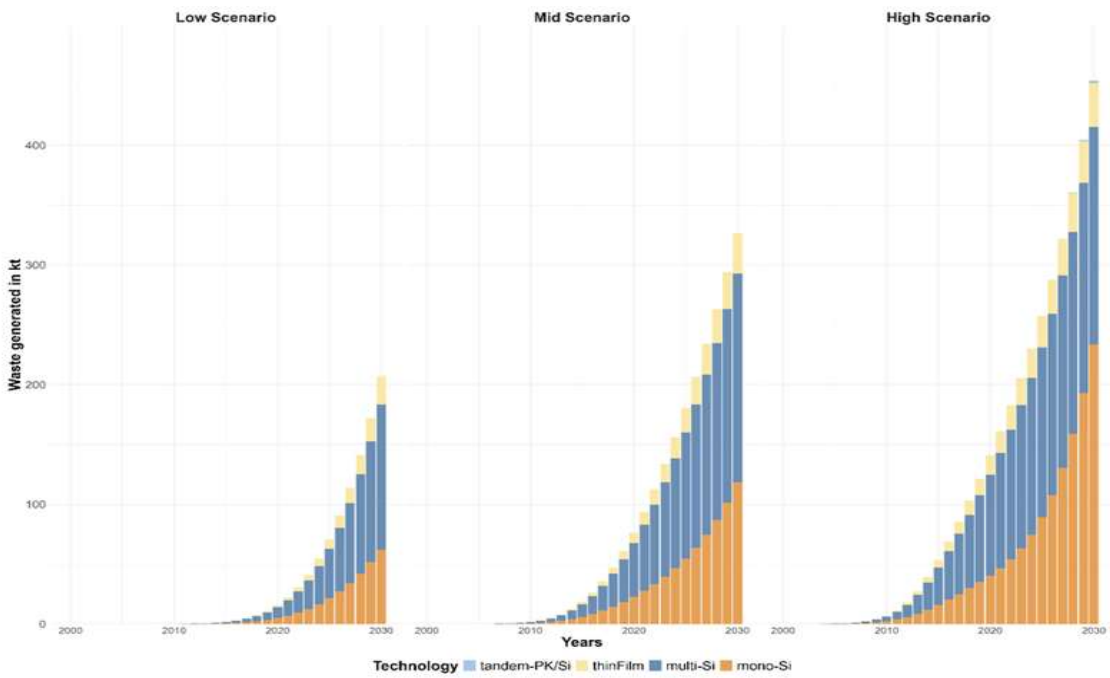

Figure S4: PV waste evolution for the EU27 by application in kt.

PV waste flows by technology show distinct trends across scenarios. In the High Scenario, Tandem-PK/Si panels enter the waste stream in notable quantities due to shorter lifespans and faster disposal. Multi-Si panels dominate waste in the Low and Mid Scenarios, reflecting their early market dominance before Mono-Si became the leading technology after 2018. Multi-Si remains the main waste contributor in the Low Scenario beyond 2030, while Mono-Si becomes dominant just after 2030 in the Mid Scenario and as early as 2028 in the High Scenario due to faster turnover. Thin-film technology follows a similar pattern, with its share declining more rapidly in more aggressive scenarios.

PV waste flows

PV waste collection (calculated for the Mid Scenario) is lagging behind its increasing generation, with the EU-27 average collection rate reaching 40% in 2022, well below the 85% WEEE Directive target. While large markets like France and Italy drive relatively high collection rates, smaller economies show particularly low rates. Data on PV waste exports is limited, with only 2015-2022 data available from Eurostat, and not all countries reporting. France is the main exporter within the EU, accounting for nearly 60% of exports, followed by Italy and the Netherlands. Insignificant amounts were reported exported outside the EU by Germany in 2016 and 2017. Literature suggests a significant portion of PV waste is exported for reuse or recycling outside the EU, sometimes illegally, with estimates ranging from 30% to 90%.

The report recommends improving data transparency, mandating detailed reporting, and expanding research into long-term waste trends and recycling strategies to ensure sustainable resource recovery and reduce environmental risks.

1 INTRODUCTION

1.1 Purpose of the deliverable

The objective of Deliverable 6.1 is to establish a comprehensive measurement framework for quantifying photovoltaic waste statistics. This methodological framework outlines the approach for calculating key indicators, including PV panels) placed on the market, installed PV capacity, PV waste generation, and PV waste flows. PV waste flows are categorized into three main streams: formally collected PV waste, estimated uncollected PV waste, estimated PV waste exports, and the PV waste gap (i.e., undocumented waste).

A classification system was developed as the foundation of the measurement framework, encompassing the primary PV technologies and applications. This classification ensures consistency in data collection and facilitates reliable quantification of PV waste.

This deliverable provides a detailed presentation of the classification system, the methodological framework, and the results derived from the modelled indicators. Specifically, it reports on the POM, installed PV capacity, and PV waste generation from 2010 to 2030 across the EU-27 countries, disaggregated by technology and application. Conversely, PV waste flows are presented at the national level and by year, without a breakdown by technology or application due to the lack of data availability in official statistics.

1.2 Structure of the deliverable

This deliverable begins with a detailed description of the PV classification system (Chapter 2), outlining the key features and criteria considered in its development.

Chapter 3 presents the methodological framework and system boundaries for calculating the model indicators, including PV panels POM, installed PV capacity, PV waste generation, and PV waste flows. Additionally, it provides an in-depth explanation of the variables governing the model, such as installed PV capacity, applications, PV technologies, conversion factors (kg/MW), and average lifetime.

Chapter 4 summarizes the results for each model indicator. Given the extensive dataset, only the most relevant and representative results are presented, with key outcomes highlighted. This section also includes a discussion of the most significant findings.

Finally, Chapter 5 provides a summary of the main conclusions from Task 6.1, outlining current limitations and offering recommendations for future improvements to the measurement framework.

1.3 Relation with other activities in the project

The work carried out in Task 6.1 is closely linked to the activities planned in Task 6.2, which will focus on assessing the recyclability of PVs. In particular, Task 6.2 will evaluate the potential for improving the recovery rates of key materials, specifically glass, silver, and ethylene vinyl acetate (EVA), which are the primary materials targeted in the EVERPV project. These advancements in material recovery will be integrated with the quantified PV waste formally collected across the EU-27 countries, as determined in Task 6.1. By combining these datasets, it will be possible to estimate the overall recovery potential at the EU level under a scenario in which the technological processes developed within the EVERPV project are widely implemented across European countries. This approach aims to provide a more comprehensive understanding of how improved recycling technologies can contribute to the circular economy and resource efficiency in the PV sector.

Furthermore, a thorough analysis of both historical and projected trends in PV waste generation is essential not only for evaluating future waste management strategies but also for providing critical contextual information to all project partners. By examining past and future PV waste volumes, stakeholders can better understand the evolution of the PV market and its implications for waste generation, material recovery, and sustainability goals. This broader perspective ensures that the findings from Task 6.1 , Task 6.2 and Task 6.3 are effectively contextualized within the larger framework of EU PV market developments and waste management policies.

2 PV CLASSIFICATION

2.1 Background

One of the primary tasks of WP6 was to develop a robust classification system to serve as the foundation for the measurement framework of PV statistics. A well-defined classification system is essential throughout all phases of the model, from data collection and modelling to the final presentation of results. The selected classification must facilitate accurate data input (e.g., installed capacity) while ensuring compatibility with available data sources and governing factors such as conversion efficiencies and average lifetime.

As an initial step, a comprehensive review of existing classification systems was conducted. This review aimed to compile an inventory of all relevant applications and technologies to be incorporated into the measurement framework for PV statistics. The review was based on scientific reports from EVERPV project partners (including Solar Power Europe), international agencies such as IRENA, and other peer-reviewed scientific publications.

The literature reveals that PV applications are classified using various approaches. These include:

- **By usage**: Utility-scale solar farms, remote locations, stand-alone systems, space applications, etc.
- **By design features**: Rigid vs. flexible solar panels.
- **By photovoltaic technology**: Silicon-based monocrystalline and polycrystalline, Thin-film technologies, etc.
- **By application (commonly referred as market segment)**: Residential, Commercial, Industrial, and Utility-scale.

The heterogeneity of classification systems reflects the diverse applications of PV technologies across different scales and sectors, influenced by regulatory frameworks, technological advancements, and sustainability objectives. However, for effective harmonization of PV waste measurement and the development of internationally comparable indicators, specific classification criteria must be met.

A well-structured PV waste classification system should:

1. **Avoid excessive granularity**: Defining categories too specifically based on chemical variations of PV technologies complicates tracking and monitoring.
2. **Ensure meaningful differentiation**: Overly generic categories fail to capture the nuances of PV waste generation and its evolution over time.
3. **Group products by similar application and material composition**: This includes considerations of hazardous substances and valuable materials.
4. **Account for end-of-life attributes**: Products within the same category should exhibit homogeneous average weight and lifetime distribution, facilitating reliable quantitative assessments.

By adhering to these principles, the proposed classification system enables an accurate and standardized approach to PV waste quantification, supporting policy development and sustainability goals at an international level.

2.2 Classification system

In alignment with the key principles outlined in Section 2.1 for defining a PV classification system, the classification system presented in Figure 1 was developed in close collaboration with project partners. This classification framework does not imply a direct correspondence between specific applications and technologies. Instead, it acknowledges that within each application category, whether Commercial, Industrial, Residential, or Utility-scale, multiple technologies are employed. These technologies include (1) Silicon technologies which include monocrystalline silicon (Mono-Si), multicrystalline silicon (Multi-Si), (2) Thin-film (TF) technologies, which encompass Copper Indium Gallium sSlenide (CIGS), Cadmium Telluride (Cdte) and Amorphous silicon (a-Si) technologies and (3) Tandem Perovskite technologies. Each of these technologies offers distinct characteristics suited to different application contexts.

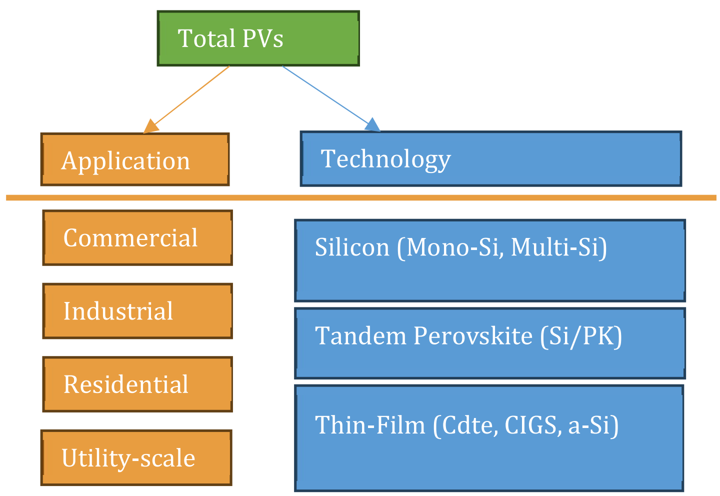

Figure 1 PV classification used in the EVERPV project

The classification system was developed based on the granularity of available data on installed capacity, ensuring alignment with the input parameters required for the calculation model. The classification was designed to account for temporal variations in both application types and technological advancements. The proposed framework was thoroughly reviewed, discussed, and validated in collaboration with project partners to ensure its robustness and applicability.

The segmentation of PV capacity into four application categories – Residential, Commercial, Industrial, Utility-scale – is based on PV system size and application and follows the standard approach used in the sector and by leading international organisations (e.g., IEA, IRENA) and consultancies (BNEF, S&P Global). In the EU, however, national regulatory authorities sometimes use different approaches for PV capacity reporting.

In this analysis, segmentation is based on the following system size:

- Residential: <10 kW;
- Commercial: <250 kW;
- Industrial: <1,000 kW;
- Utility-scale: >1,000 kW, ground-mounted.

It is acknowledged that this approach allows for a minor degree of overlapping because of the dual approach that takes into account both system size and application. For example, Residential PV systems can sometimes be larger than 10 kW, and similarly, Industrial PV systems can exceed 1 MW, while certain ground-mounted applications are smaller than 1 MW. Despite these minor inconsistencies, this approach is preferred because of clear advantages in terms of harmonisation and comparability across different geographies.

The distribution of technologies was determined based on an assessment of the current market landscape. It is estimated that thin-film technologies account for 5% of the market, while silicon-based technologies dominate with a 95% share. Among silicon-based technologies, monocrystalline silicon contributes 90%, while multicrystalline silicon represents 5% (Fraunhofer ISE, 2024).

The thin-film segment is primarily dominated by CdTe, with CIGS and amorphous silicon contributing less than 0.5%. According to ITRPV projections, the introduction of silicon-perovskite tandem technology is expected to gain market penetration, reaching a share of over 10% by 2030 (ITRPV, 2025).

3 METHODOLOGICAL FRAMEWORK

3.1 Structure of the methodological framework

Task 6.1 developed a comprehensive measurement framework for assessing PV Installed Capacity, PV placed on market, and PV waste generated in the EU27 region. The primary objective was to produce harmonized data on PV waste statistics to enhance monitoring over time and facilitate comparability across member states. The implementation of a standardized calculation method is fundamental to ensuring consistency and accuracy in data collection, thus supporting effective policymaking and resource management in the green energy sector.

The measurement framework originates from the EU methodology outlined in Article 7 (Magalini et al., 2014), developed by the SCYCLE team in 2012 and which guides Member States in calculating collection targets based on POMs and e-waste. The methodology for measuring e-waste statistics has been published in 2018 in the Guidelines for Measuring E-waste Statistics (Forti et al., 2018).

In the EVERPV project, this framework has been refined and adapted to calculate PV waste generation from PV installed capacity other than from POM as suggested by the methodological framework mentioned before.

This adaptation was driven by the greater reliability of installed capacity data compared to PV trade statistics, which are often less robust. Installed capacity data is systematically collected to monitor advancements in renewable energy deployment, making it a more suitable foundation for the framework.

The framework follows a structured approach, as illustrated in Figure 2. The key steps include:

1. **PV Installed Capacity**: The process begins with gathering data on PV installed capacity per country, measured in megawatts (MW) per year. In this project, SolarPower Europe has provided the necessary data. Installed capacity is synonymous with "stock"—the cumulative amount of PV modules in operation within a country.
2. **Stock and Lifetime**: PV modules remain in Residential buildings, solar farms, and in use by the industry and public sector for a certain period before disposal. This duration, termed "lifetime," includes active use, storage, and second-hand transfers within the country. The stock represents the "urban mine," a future source of secondary raw materials.
3. **PV Waste Generation**: After reaching the end of their "lifetime," PV modules are discarded, becoming PV waste. "PV waste generated" represents the total volume of domestically produced PV waste before formal collection and excludes imports of externally generated PV waste. This metric is crucial for PV waste statistics and informs waste management strategies.
4. **PV POM**: PV Waste Generation and PV Stock are used in the model to calculate PV POM. Please refer to the sub-chapter 3.2 for a more detailed description of the approach and calculation steps.
5. **PV Waste Generation** is then recalculated adopting a sales-lifetime approach by combining PV POM with PV lifetimes. The PV Waste Generation calculated with this approach is then

consolidated using the results obtained from the previous steps. This conversion enables the estimation of PV waste at the national level by country and year.

6. **PV Waste Collected**: PV waste collection occurs through formal channels mandated by national e-waste legislation. Collection mechanisms include retailers, municipal collection points, and pickup services operated by designated organizations, producers, or government entities. The collected PV waste is directed to state-of-the-art treatment facilities for environmentally sound material recovery.
7. **PV Waste Exported**: PV waste exports can include both legal and illegal exports. According to international Convention, such as the Basel Convention, the export of PV waste is allowed only under certain circumstances (e.g. if it is destined to an authorized recycling facility). Should the PV waste similar to other e-waste products be exported without the necessary supporting documentation, the export is to be considered illegal. In parallel, legal exports may also include second-hand functioning PV modules, they are to be considered PV waste in the country of origin because their "lifetime" ends, and they enter the stock phase in a new country. This movement must be accounted for to accurately estimate domestic PV waste generation.
8. **PV Waste Undocumented:** This represents the quantity of PV waste that is not officially reported as collected and recycled in national statistics or documented as exported, whether legally or illegally. Monitoring this unaccounted waste is essential, as the ideal scenario is to minimize it to zero. If discrepancies persist, member states or national Producer Responsibility Organizations may need to investigate underlying causes. Potential factors contributing to this gap include inaccuracies or omissions in data reporting, inefficiencies or leakages within the formal collection system, the involvement of informal sectors in waste collection and processing and illegal exports to other countries, typically lower income countries.

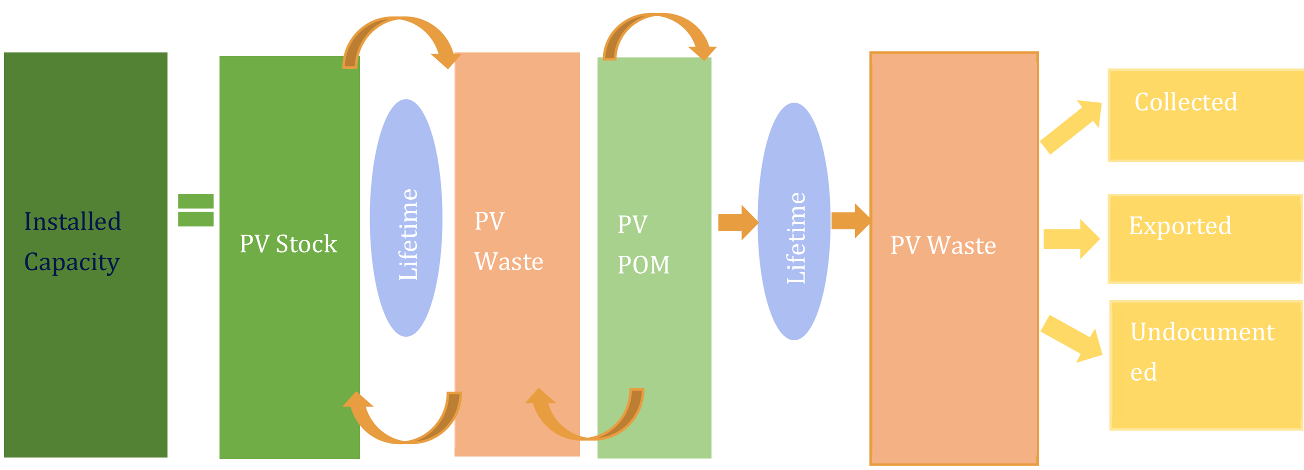

Figure 2 Methodological framework for measuring PV waste statistics

In the present deliverable, the indicators provide insights into the stock, waste generation, and management of PVs across the EU27 countries from 2010 to 2030. The data is categorized by application and technology where applicable.

Table 1 below presents the availability of data related to the results and datasets used in the statistical framework. It summarizes key indicators, their measurement units, geographical scope, temporal coverage, application and technology coverage.

Table 1 Summary of indicators characteristics measured in the statistical framework

Indicator	Measurement unit	Geographical coverage	Temporal coverage	Application coverage
PV POM	GW, weight	*All EU27 countries*	*2010-2030*	*By Application and technology*
PV Stock	GW, weight	*All EU27 countries*	*2010-2030*	*By Application and technology*
PV Waste Generated	GW, weight	*All EU27 countries*	*2010-2030*	*By Application and technology*
PV Waste Formally Collected	weight	*All EU27 countries*	*2010-2030*	*Total*
PV Waste Exported	weight	*All EU27 countries*	*2010-2030*	*Total*
PV Waste Undocumented	weight	*All EU27 countries*	*2010-2030*	*Total*

3.2 Model variables and data sources

Different variables have been used in Task 6.1 for measuring the indicators presented in subchapter 3.1. Figure 3 summarizes the key variables used in the model. It illustrates how these variables govern the model, which indicator they influence and the specific calculation steps in which they are involved. The key variables are: technology shares, conversion factors and lifetime distribution.

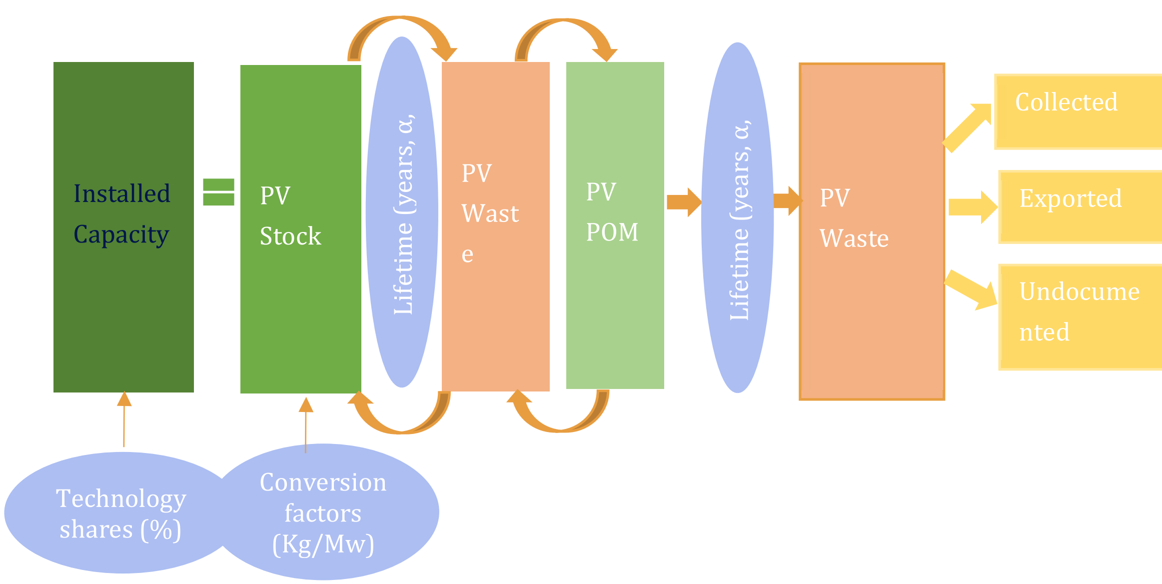

Figure 3 Key variables governing the methodological framework for measuring PV waste statistics

Table 2 below presents the availability of data related to the variables used in the statistical framework. It summarizes key variables, their measurement units, and the granularity of the data used in the model.

Table 2 Summary of variables characteristics measured in the statistical framework

Variable	Measurement unit	Geographical coverage	Temporal coverage	Application and Technology coverage
Technology share	% of the total	*Average for EU27 countries*	*Yearly 2010-2030*	*By technology*
Conversion factors	Kg/Mw	*Average for EU27 countries* *Average for EU27 countries*	*Yearly 2010-2023* *Yearly 2024-2030*	*Total* *By application*
Lifetime	Average lifetime (years) Shape (α) and Scale (β) parameters	*Average for EU27 countries* *Average for EU27 countries*	*Yearly 2010-2030* *Yearly 2010-2030*	*By application (Total and Utility scale* *By application (Total and Utility scale))*

3.2.1 INSTALLED CAPACITY

Installed capacity data – both historical and forecast – has been provided by SolarPower Europe for all EU-27 countries for the time series 2000-2030. The data captures all grid-connected installed solar PV capacity of any size and application in each EU Member State. Data was provided by year, country, and application (i.e. by application/segment).

SolarPower Europe's data reflect the association's best knowledge at the time at its publication. Data is gathered from a wide variety of sources, including national stakeholders, grid operators, industry experts, international organisations, while also considering national and EU solar targets and global market and policy trends. Final evaluations are however fully independent, and figures provided reflect SolarPower Europe's internal analysis. As a result, data may differ from the one provided by external sources, including official reporting.

Across Member States, official statistics are usually gathered from grid operators, which cover a range of different energy generation technologies. For solar PV capacity, this leads to three main challenges. First, this data is occasionally reported in alternating current (AC) terms, which is the relevant aspect for the grid operator. However, for the purpose of this analysis, it is more useful to look at installed capacity in direct current (DC) terms, which gives information on the amount of PV modules deployed. Second, some grid operators do not provide data on distributed generation, leading to incomplete datasets. Third, official statistics tend to be revised upwards as installed PV systems get accounted for in national registries, with a delay that sometimes spans over several years. In practical terms, this means that even official data needs to be weighted up and adapted. This evaluation applies as well to the segmentation data, on which there is no unique reporting method across grid operators and other sources.

For historical installed capacity, segmentation data was available for the years 2016-2024. For the previous years from 2016 backwards, the segmentation split was calculated using the 2016 shares.

For forecasted installed capacity, SolarPower Europe's approach presents three scenarios (low, medium, high) until 2030. The Mid Scenario anticipates the most likely development given the current state of play of the market. The Low Scenario forecast assumes that policymakers halt solar support and other issues arise, including interest rate hikes and severe financial crisis situations. Conversely, the High Scenario forecasts the best optimal case in which policy support, financial conditions, and other factors are enhanced. A graphic representation of the scenarios considered in the forecasts of PV installed capacity is presented In Figure 4:

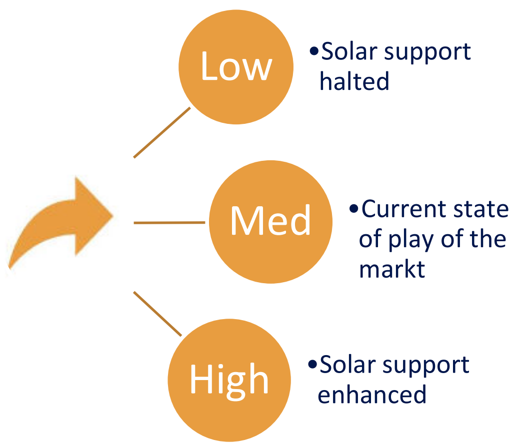

Figure 4 Scenarios considered in the forecasts of PV Installed Capacity

SolarPower Europe's scenario forecasts, including segmentation data, span over 5 years, meaning that data was available until 2028. For years 2029 and 2030, data is based on SolarPower Europe's projections stretching beyond the usual 5-year timespan. Since this data does not include segmentation, country-specific segmentation is assumed to remain stable compared to 2028.

Forecasting PV capacity deployment on the longer term, covering a period longer than 5-10 years, is a difficult exercise that can be subject to very different interpretations, considering the impact of economic, political, policy, market, technology, behavioural and other changes that are hard to evaluate or even unforeseeable today. For this reason, forecasts with time horizons 2040 and 2050 are largely dependent on far-reaching assumptions.

3.2.2 TECHNOLOGY SHARES

The technology distribution in the model was compiled from different sources. For historical values until 2023, the Photovoltaics Report by Fraunhofer (Fraunhofer ISE, 2024) was utilized, which provided a split of the global annual production of PV panels by technology between Thin-film, Multi-Si, and Mono-Si, the three dominant technologies. This data was compiled from multiple data sources, such as Navigant, HIS Markit, and estimates from IEA.

For data not relying on historical numbers, CEA provided a forecast until 2050 which estimated the share of technologies, thereby distinguishing between Multi-Si, Mono-Si and individual Thin-film technologies, such as CdTe, CIGS, and a-Si. Additionally, newer technologies, such as Tandem PK/Si and Tandem CdTe/PK were reflected. The projection was estimated based on the current market landscape and ITRPV forecasts, assuming the continued dominance of monocrystalline silicon technology and the complete phase-out of multi-Si by 2026. Silicon-perovskite tandem technology is expected to start penetrating the market by 2030, gradually replacing monocrystalline silicon and eventually dominating with a 95% market share by 2050. For the thin-film segment, CdTe is expected to maintain a stable market share between 3% and 5%, while CIGS and amorphous silicon technologies are anticipated to disappear.

The model itself only distinguishes between four categories, Multi-Si, Mono-Si, Thin-film, and Tandem-PK/Si. The latter was included due to an estimate high individual market share and a resulting need to showcase the impact per technology category.

The technology categorisation, furthermore, does not vary between different countries or applications. The model assumes a uniform distribution across countries and applications.

The chosen technology shares are presented as share of annual PV POM in Figure 5. A uniform distribution is assumed across different markets and applications.

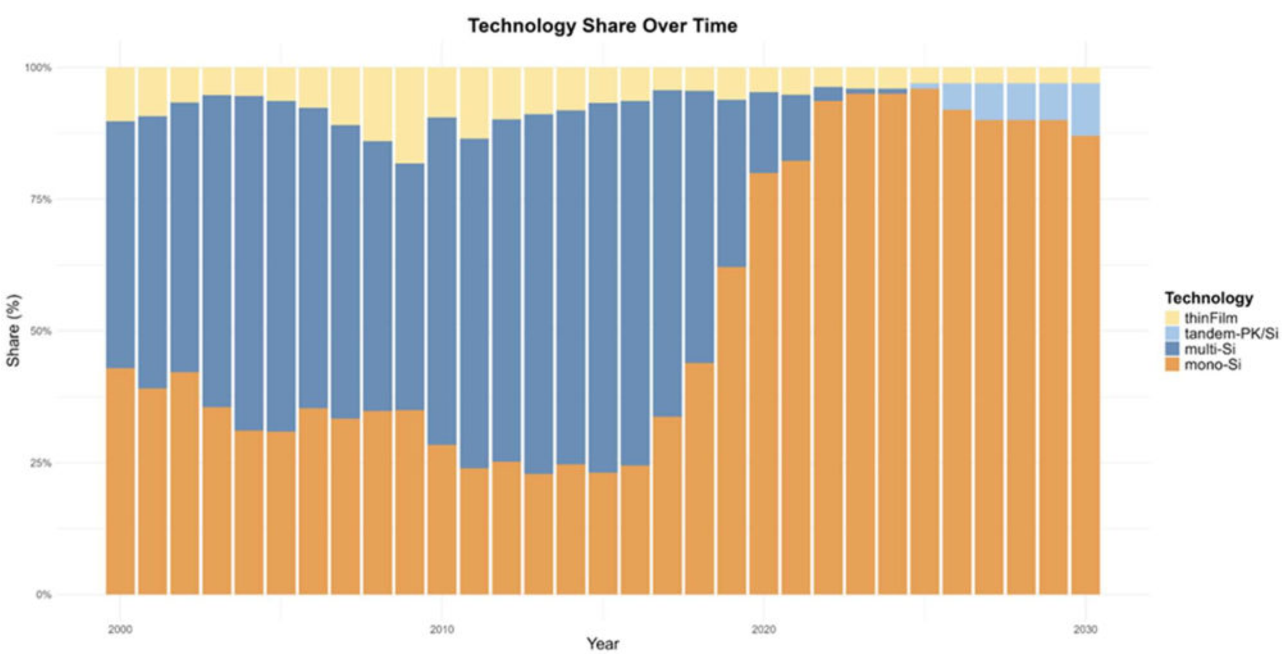

Figure 5 Technology penetration at POM level (EU27 average)

Most notably, the early on dominant technology of Multi-Si is increasingly diminishing and eventually assumed to shrink to neglectable volumes by 2024, being completely substituted by the more efficient and better performing Mono-Si technology, which by then reaches its peak share with 96% of annually installed PV panels. However, with the introduction of the Tandem-PK/Si technology which has been announced for the proximate years, the model assumes increasingly growing shares. Simultaneously, while Thin-film technology continues to struggle on the mainstream market, it retains a niche market share for the years to come due to speciality applications. A summary table of the technology shared used in this project is provided in Annex 1.

3.2.3 CONVERSION FACTORS

As previously described, the model starts with the computation of PV installed capacity in MW, however, to provide a comprehensive overview of the quantities of PV waste flows, a MW to kg conversion was required. Therefore, conversion factors were collected and added as a model variable to allow for a simple translation into results in mass volumes (kt).

MW to mass conversion factors were sourced from SolarPower Europe (SolarPower Europe, 2023 and 2024), which derives an average from multiple references, including SolarPower Europe data, SOREN France, and IRENA. The data provided was one common conversion factor across all technologies and applications until 2023.

The conversion factors were further refined using data from CEA, which provided estimations for each application from 2024 onward in kg/MW. These application-specific conversion factors were subsequently integrated with SolarPower Europe's conversion factor for previous years. As a result, a single conversion factor was applied across all applications from the model's start until 2024 (based on SolarPower Europe data), after which each application adopts a distinct conversion factor (based on CEA data). This improvement accounts for variations in weight-to-capacity ratios among applications, which are captured from 2024 onward due to a lack of earlier data.

To estimate the conversion factors, technical parameters of the modules were extracted by application segment, including weight, power, surface area, and efficiency, based on data from the top 10 manufacturers. These parameters vary according to the application segment. Higher efficiency is observed in residential installations due to the need for high-performance modules, whereas utility-scale solar plants can operate with lower-efficiency modules (Table 3)

Table 3 Benchmark of technical parameters for the TOP10 PV module manufacturer

Benchmark 2023 -2024	Technoogies	Performances	Utility scale	C&I segment		Residential
				C&I Utility	C&I Rooftop	
JinKO Solar	Mono-Si technologies	Wafer size	M10 (TOPCON)	M10 (TOPCON)	M10 (TOPCON)	
		Module Weight	30,6 kg	28 kg	24,2 kg	
		Module Power	630 Wp	590 Wp	485 Wp	
		Module Area	2.79 m²	2.58 m²	2.1 m²	
		Module efficiency	22,6%	22,9%	23,10%	
risen	Mono-Si technologies	Wafer size	G12 (HJT)	G12 (HJT)		-
		Module weight	30,6 kg	34 kg		
		Module Power	733 Wp	585 Wp		
		Module Area	3.06 m²	2.57 m²		-
		Module efficiency	23,95%	22,8%		
AIKO	Mono-Si technologies	Wafer size		M10 (ABC)	M10 (ABC)	
		Module Area	2,64 m²	2.58 m²	1.95 m²	
		Module weight	30,5 kg	28,2 kg	20,5 kg	
		Module power	625 Wp	620 Wp	465 Wp	
		Module efficiency	23,70%	24%	23,80%	
LONGi	Mono-Si technologies	Wafer size	M10 (TOPCON)		-	-
		Module Area	2.58 m²		-	-
		Module weight	31,7 kg	27,5 kg	-	-
		Module power	590 Wp	600 Wp	-	-
		Module efficiency	22,9%	23,3%	-	-
HUASUN	Mono-Si technologies	Wafer size	G12 (HJT)	M10 (HJT)	M10 (HJT)	
		Module Area	3.1 m²	2.17 m²	1.82m²	
		Module weight	31,7 kg	27,5 kg	23,5 kg	
		Module power	720 Wp	480 Wp	400 Wp	
		Module efficiency	23,2%	22,1%	21,98%	
ASTRONERGY A CHINT COMPANY	Mono-Si technologies	Wafer size	G12 (TOPCON)	M10 (TOPCON)	M10 (TOPCON)	
		Module Area	3.1 m²	2.79 m²	1.95m²	
		Module weight	31,7 kg	33,5 kg	21,3 kg	
		Module power	665 Wp	585 Wp	435 Wp	
		Module efficiency	21,40%	22,65%	22,30%	
CanadianSolar	Mono-Si technologies	Wafer size	G12 (TOPCON)	M10 (TOPCON)	M10 (TOPCON)	
		Module Area	2,70m²	2.58 m²	2.04 m²	
		Module weight	32,8 kg	24,6 kg	22,7 kg	
		Module power	625 Wp	455 Wp	460 Wp	
		Module efficiency	23,1%	22,80%	22,5%	
JA SOLAR	Mono-Si technologies	Module Area	2.79 m²	2,58m²	1,95m²	-
		Module weight	33,4 kg	31,2 kg	21,5 kg	
		Module power	625 Wp	575 Wp	435 Wp	
		Module efficiency	22,40%	22,30%	22,30%	

For the projection up to 2050, all parameters are assumed to remain nearly constant, except for efficiency, which is expected to reach between 30% and 33%, depending on the application segment

The applied conversion factor starts with 120 tons/MW and gradually improves by around 2% per year to 64 tons/MW in 2023. Starting in 2024, Utility panels show the slowest improvement in their weight ratio until 45 tons/MW in 2050, whereas Commercial and Industrial panels share a conversion factor of 40 tons/MW in 2050. The lowest conversion factor is available for Residential with 36 tons/MW for the same year.

A summary of the conversion factors used in Task 6.2 is provided in Annex 2.

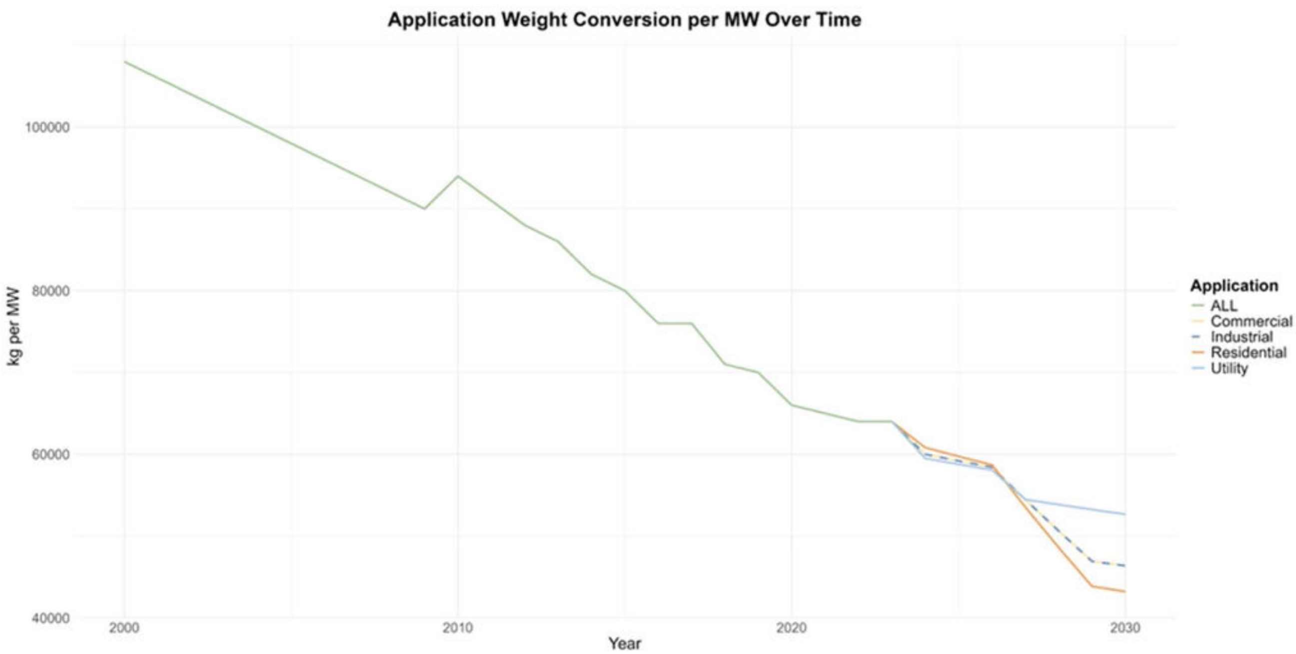

Figure 6 Application weight (kg) conversion per MW over time

3.2.4 LIFETIME

Average lifetime as a parameter in the model

The lifetime parameter represents the duration between the market introduction of one individual panel to the time when its user decides to dispose it off. The period includes active use, storage, and second-hand transfers within the country. The lifetime defined in the methodological framework is different than the technical lifetimes usually communicated by the producers because the model aims at mapping real trends in waste volumes that reflect the consumer's discarding behaviour. In practical terms, the lifetime of a Residential PV panel which broke 10 years after its installation and was left for another 10 years on the roof-top before being discarded is 20 years, similarly to a Commercially-used PV panel, which has a hypothetical lifetime of 30 years but was discarded, despite being fully functioning, already after 20 years due to possible repowering of the solar park.

Due to the nature of the stock-driven model, the lifetime represents a particularly sensitive parameter. On the one hand, it determines when and with which probability PV panels become obsolete. On the other hand, it also determines indirectly how many panels are being discarded since a shorter lifetime translates into a higher PV Waste Generated. Vice-versa, given that PV Stock (installed capacity) remains steady, this in turn increases the required PV POM. A more detailed description of the mathematical relations of the different indicators and variables is described in the subchapter 3.2.5 and 3.2.6.

PV panels represent a relatively new technology, and their relatively long functional lifespan means they are not yet sufficiently represented in the waste stream to allow for generic assumptions on their lifetimes with high certainty. Furthermore, the constant and rapid improvements in PV technologies, quality, and adoption across application, make general estimates prone to error.

In Task 6.1, a consultation with the project partners was conducted and it was complemented with literature review to assess average life times by application. The differentiation for different lifetimes per technology was not implemented because in a consultation with the project partners it was concluded that lifetimes do not vary substantially across technologies but rather across applications.

In the literature (Kastanaki & Giannis, 2022)(Kastanaki & Giannis, 2022)summarizes various average lifetimes that have been used in different models. They suggest average lifetimes from 20 to 35 years. Several use the "Regular Loss" and "Early Loss" scenarios developed by IRENA (IRENA, 2016). However, in the "Regular Loss" no early attrition is considered, while in the "Early Loss" failures before the 30-year lifespan is taken into account.

The experts' consultation yielded similar estimations of around 25 years in 2004 and 35 years for panels introduced in 2023. The exact numbers adopted were provided by ERION based on the PARSIVAL project, which show an estimated year-over-year growth of 1.4%-2.4%. This lifetime assumes no differences in-between different technologies and applications. In the PARSIVAL project, ERION has calculated the lifetime of the PV panels (as the difference between the year of sampling and the year of installation of the PV panels. The estimated lifetime of PV panels at the beginning of the period under study was 25 years, while it increased to an average of 30 years in 2016 and 35 from 2022 with the ongoing development of the technologies. Table 4 below summarizes the increase of average lifetime over the years. (Alves Dias et al., 2020)(Peeters et al., 2017)(IRENA, 2016)(Sultan & Abdullah, 2022)(Wiser et al., 2020)

Table 4 End-of-life of PV panels based on bibliography data

Manufacturing year	EoL (years)
2004	25
2016	30
2022	35

In order to obtain yearly data by installation year from 2000 to 2022, a quadratic estimation has been performed from the aforementioned data.

This quadratic estimation was obtained with the Equation 1.

$$T = 0.0231 \times I^2 - 92.639 \times I + 92{,}710 \qquad \text{Equation 1}$$

Where:

- T is the lifetime in years
- I is the installation year

The average lifetime provided by ERION were used as a starting point and further refined with partner's expert inputs. The consultation with project partners suggested that the average lifetime used for Utility-scale applications had to be adapted to better reflect the phenomenon of repowering that drives the substitution of functioning PVs to cope with the declining of the PV efficiency over time. This practice was particularly prevalent in the past but remains present until today, despite increasing durability, better and longer-lasting panel efficiency, and generally increased efficiency, all of which counter-act the need for repowering.

To account for this practice, it was decided to create three combinations of different life-time parameters:

1. Original lifetime parameters that take into account original lifetimes suggested by ERION
2. Medium lifetime parameters that assume 30-10% shorter lifetimes for Utility-scale applications
3. Low lifetime parameters that assume 40-25% shorter lifetimes for Utility-scale applications

Figure 7 shows the lifetimes used in the model in Task 6.1:

1. The original lifetime parameters were given by ERION and were adopted unaltered. These display the comparatively longest lifetimes.
2. The medium-lifetime parameters assume a 30% reduced lifetime for Utility panels in 2004 and a 10% reduced lifetime for Utility panels in 2023 with a linear interpolation for the years in-between. Therefore, lifetimes for Utility panels in 2004 and 2023 are 17.5 years and 31.5 years, respectively.
3. Similarly, the low-lifetime parameters reflect a 40% reduced lifetime for Utility panels in 2004 and a 25% reduced lifetime for Utility panels in 2023 with a linear interpolation for the years in-between. Therefore, lifetimes for Utility panels in 2004 and 2023 are 15.5 years and 26.3 years, respectively. The converging lifetimes of Utility panels with other panel application lifetimes are intended to account for the decreasing practice of repowering observed by experts since solar power inception.

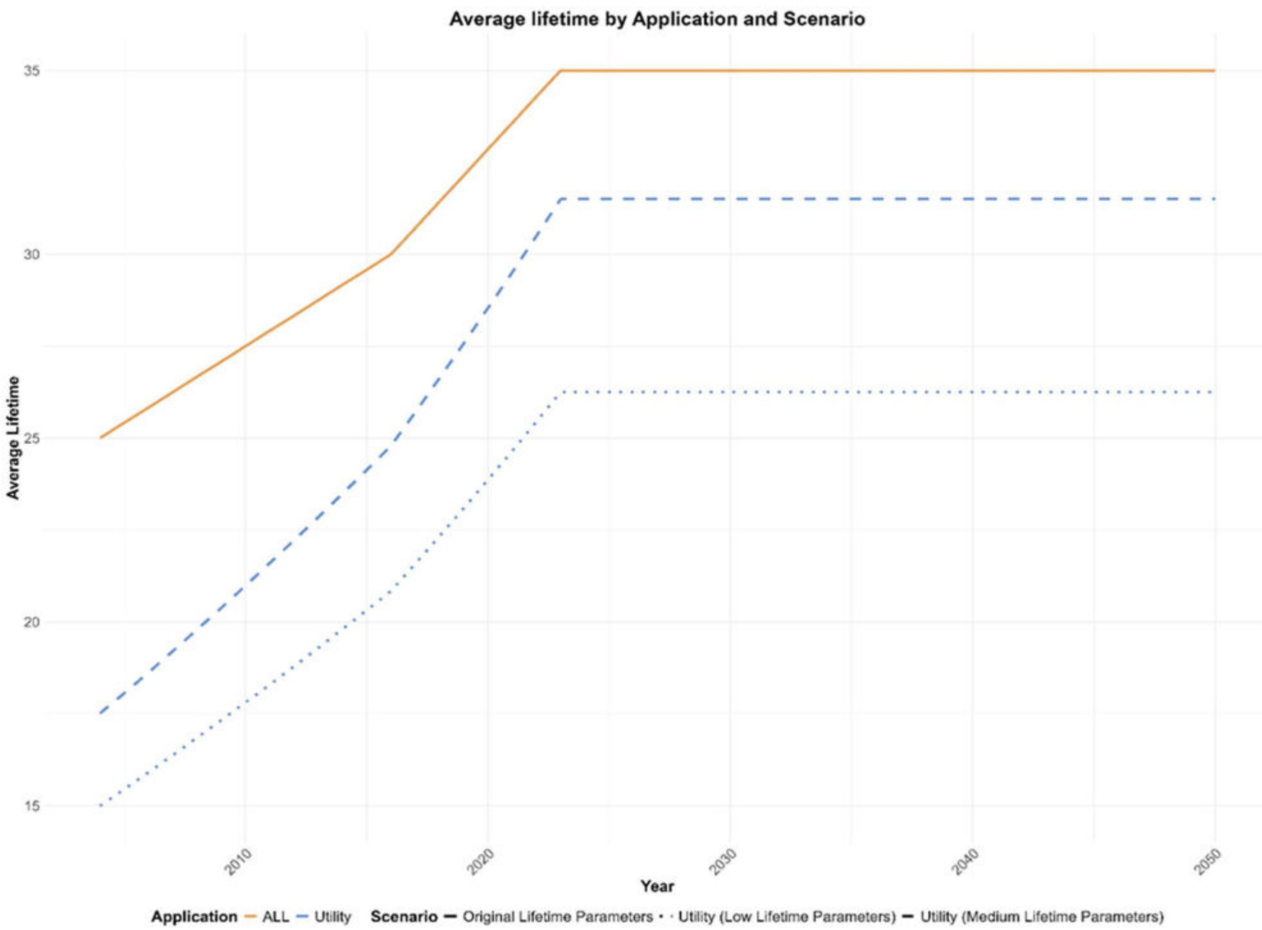

Figure 7 Evolution of the average lifetime by application and scenario

Shape and Scale parameter in the model

To convert the lifetime into applicable parameters in the model, a density probability distribution in form of a Weibull curve was chosen. To derive appropriate scale parameters from the lifetimes given and to determine the behaviour of such a curve, different shape factors in literature were studied.

The shape factor in such a function determines the spread of the curve, and thus the point in time when waste is produced. For example, a low shape value (e.g., <3) leads to a spread-out bell-curve which translates into a gradual disposal of PV panels over time. Such shapes are more typical in consumer products which lifetimes are highly dependent on use patterns and individual disposal behaviour and thus are akin to highly variable lifetimes. Contrary, a steep shape value leads to a horizontally compressed bell curve, translating into a more rapid and complete disposal pattern of PV panels. This was assumed to be more reasonable due to the nature of PV panels being usually installed and discarded in larger batches, as renewal or repowering is conducted for whole solar farms or larger areas like roof tops.

Figure 8 presents the different shapes that were chosen for the average lifetimes presented before (original, low and high).

1. The high lifetime parameters assume a shape of 5.3759 in accordance with the "Regular Loss" scenario studies by IRENA (IRENA, 2016). This translates into an aggressive disposal pattern of ad-hoc disposal.
2. The medium lifetime parameters assume a 3.40 shape factor, which accounts for earlier and later disposal of PV panels.
3. The low lifetime parameters assume a 2.4928 shape factor in accordance with the "Early Loss" scenario studied by IRENA (IRENA, 2016). This translates into a curve that can account for a high variety of disposal patterns, such as high early loss and delayed disposal of consumer panels.

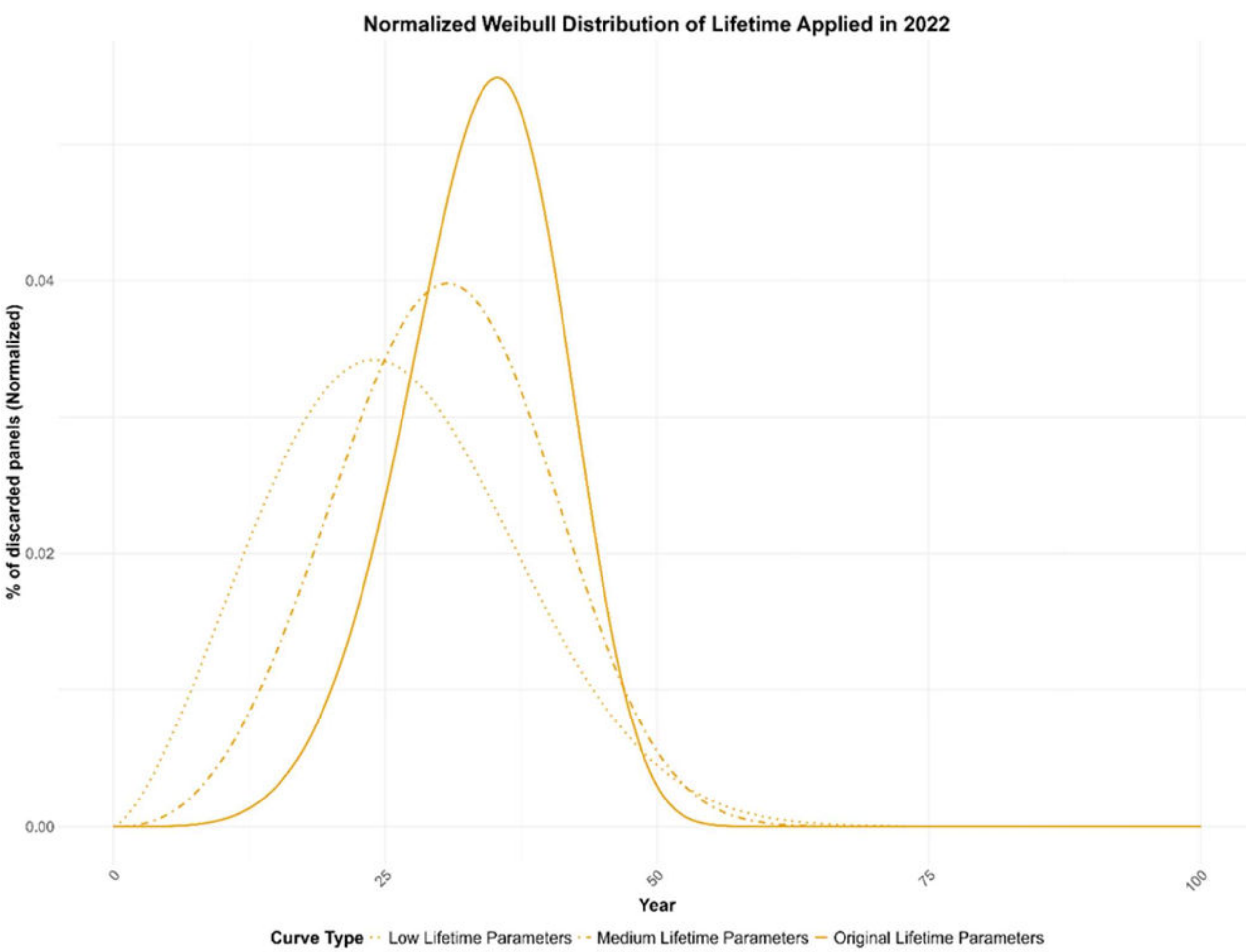

Figure 8 Weibull distributions by scenario (example for 2022)

The scale was derived from the average lifetime and the shape parameters and computed for each year-lifetime-application combination, using the equation 2

$$\beta(\mathrm{t}) = \frac{V(t)}{(\ln(2))^{\frac{1}{\propto(t)}}} \qquad \text{Equation 2}$$

where $\beta(t)$ represents the scale value in a given year, V represents the given lifetime value for each combination in a given year, and α represents the shape value determined per application in a given year. As outlined previously, the rapidly changing lifetime value requires a time-dependent shape and scale parameter, therefore changing the values of β *and* α as necessary to represent the obsolescence probability of each individual panel in relation to the respective year.

Equation 3 shows the derivation of the obsolescence probability parameter, $L^{(PV)}(t, n)$, which describes the discard-based lifetime profile for the batch of PV panels sold in historical year t where n is the evolution year and t0 is the initial year that the PV panel was sold.

$$L^{(p)}(t,n) = \frac{\alpha(t)}{\beta(t)^{\alpha(t)}}(n-t)^{\alpha(t)-1}e^{-[(n-t)/\beta(t)]^{\alpha(t)}} \qquad \text{Equation 3}$$

In summary, the model framework accounts for three different scenarios to estimate installed capacity until 2030 that are combined with three different lifetimes scenarios to account for most extreme evolutions of installed capacity coupled with the most impactful discarding behaviour as indicated in the infographic below (Figure 9). The combination of the different scenarios enables to provide a comprehensive overview of the uncertainty of future PV POM and PV Waste predictions that depend on the evolution of policy interventions and discarding behaviours.

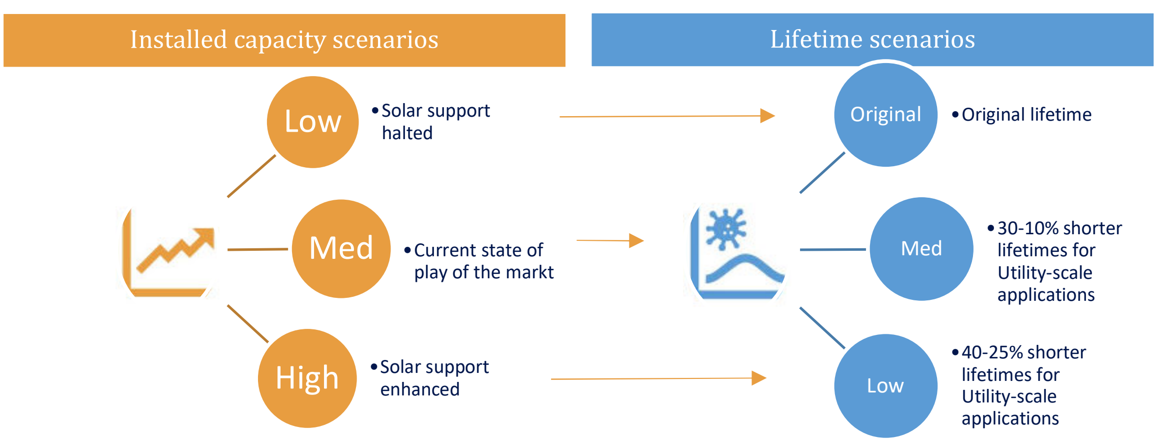

Figure 9 Summary of the features of the three scenarios used for the calculation of PV Stock, PV POM and PV waste

3.2.5 PV POM

The annual quantity of PV panels (in MW, in tons) PV_{POM} represents the basics for a stock-flow calculation. In the model it was calculated as shown in equation 4,

$$\mathrm{S(n)} = \sum_{t=t_0}^{n} \mathrm{PV\ POM(t)} - \sum_{t=t_0}^{n} \mathrm{E\ waste\ generated(n)} \qquad \text{Equation 4}$$

where the stock, *S(n)*, can be calculated as the summation of all inflow in historical years, ($\sum_{POM}$), minus the summation of all outflows, here waste generated ($\sum$PVwaste). Similarly, the annual stock-addition can be calculated as a sum of the stock-increase from each individual period.

However, as the model is stock-driven, thereby PV_{POM} being unknown but having the PV_{STOCK} as a given variable for each year, using the same equation requires the following algebraic alteration, as shown in equation 5, where it is assumed that the PV_{STOCK} in year 0 equals the PV_{POM} in the same year, as no waste generation is assumed.

$$S(t_0) = \mathrm{PV_{POM}}(t_0) \qquad \text{Equation 5}$$

From there forward, the PV_{POM} can be derived for each period from the modified equation 5, here shown as equation 6.

$$POM(t_1) = S(t_1) - S(t_0) + E\ waste\ generated\ (t_1) \qquad \text{Equation 6}$$

3.2.6 PV WASTE

To adequately calculate the market outflow or PV waste generated (PVwaste), a rate of obsolescence is determined for each annual inflow, PV_{POM}, through a normalized density probability distribution in form of a Weibull curve. The exact scale and shape parameter calculations are described in greater detail in the adequate chapter. Equation 7 describes the calculation of PVwaste,

$$\mathrm{PVwaste(n)} = \sum_{t=t_0}^{n} \mathrm{PV_{POM}\ (t)} * L^{(PV)}\ (t, n) \qquad \text{Equation 7}$$

where PVwaste (n) is the quantity of PV waste generated in evolution year n, PV_{POM} *(t)* is the PV_{POM} in any historical year t prior to year n ; t_0 is the initial year that a product was sold; $L^{(p)}(t, n)$ is the discard-based lifetime profile for the batch of products sold in historical year t.

Therefore, through the multiplication of the respective annual inflow (PV_{POMt}) with the obsolescence probability in the given year, $L^{(PV)}$(t, n), an outflow (PVwaste) for each individual inflow can be calculated.

The complete equation is shown in equation 8:

$$PV_{POM}(t_1) = (S(t_1) - S(t_0)) * \frac{\alpha(t_0)}{\beta(t_0)^{\alpha(t)}}(n-t)^{\alpha(t)-1}e^{-[(n-t_0)/\beta(t_0)]^{\alpha(t_0)}} \quad \text{Equation 8}$$

In summary, the computation of the results is achieved through the previously mentioned set of base parameters, which are applied for each year individually and are represented through the following units:

1. Lifetime (in years, translated into a Weibull function through a shape and scale parameter)
2. Conversion factors (in kg/MW or unit/MW)
3. Application/Segment share (in % of POM)
4. Technology share (in % of POM)

The calculation is a so-called stock-driven model. This means that based on the current installed capacity of PV panels (in MW), here PV_{STOCK}, an annual outflow ($WEEE_{GEN}$) is calculated, based on previously mentioned parameters. An inflow, here PV Put-On-Market (PV_{POM}), is then calculated, which aims to compensate for the outflow $WEEE_{GEN}$ and reach the predicted installed capacity for the respective year, PV_{Stock}.

3.2.7 PV WASTE FLOWS

PV waste collected

The PV waste formally collected in a country indicates the amount of PV waste which is managed according to the requirements of the WEEE national legislation. Collection mostly happens via retailers, municipal collection points, and/or pickup services. The final destination for the PV compliantly collected is a compliant treatment facility. The data on PV waste formally collected has been downloaded from Eurostat (EUROSTAT, 2024), and it includes data up to 2022. For missing data points (country, year) the data has been integrated through the WEEE Forum Key Figures from the WEEE Forum (Baldé et al., 2021), if consistent with Eurostat data from previous years available. The consistency was checked by comparing the totals of the PV collected in the WEEE Forum Key Figures and the total of PV collected from Eurostat in the last year when both data were available. WEEE Forum Key Figures Data was regarded as consistent if it deviated by less than 5% compared to Eurostat data and adjusted for the deviation prior to integration.

Going forward, two scenarios for the estimation of future collection rates are introduced. The Business-As-Usual Scenario (BAU) assumes a steady collection rate per country based on its past performance. If no positive correlation between the trajectory of past collection rates and the assumed 85% collection target was detected, a 50% collection value is assumed by 2050 over the existing collection rate.

The Recovery Scenario (REC) assumes that the collection target of 85% – 95% is achieved by each country by 2050, depending on the past performance. If the country showed increasing or high collection rates already, a higher end-point was assumed. Vice-versa, previous lacklustre performance would subsequently damper the final collection rate to the lower boundary of this scenario.

The model follows a logistic curve trajectory in a typical S-curve outline, meaning that it assumes a slower growth initially before entering a high-growth phase which tapers off toward the end of the time horizon. As the time horizon for this report is 2030, none of the countries is expected to achieve the collection target by any scenario, with the exception of countries who are already achieving these targets at the time of computation. Their performance was assumed to be constant.

Both collection scenarios were only applied to the Mid Scenario and its results. Figure 10 shows visually the features of the selected installed capacity scenario based on which the two BAU and REC scenarios were added.

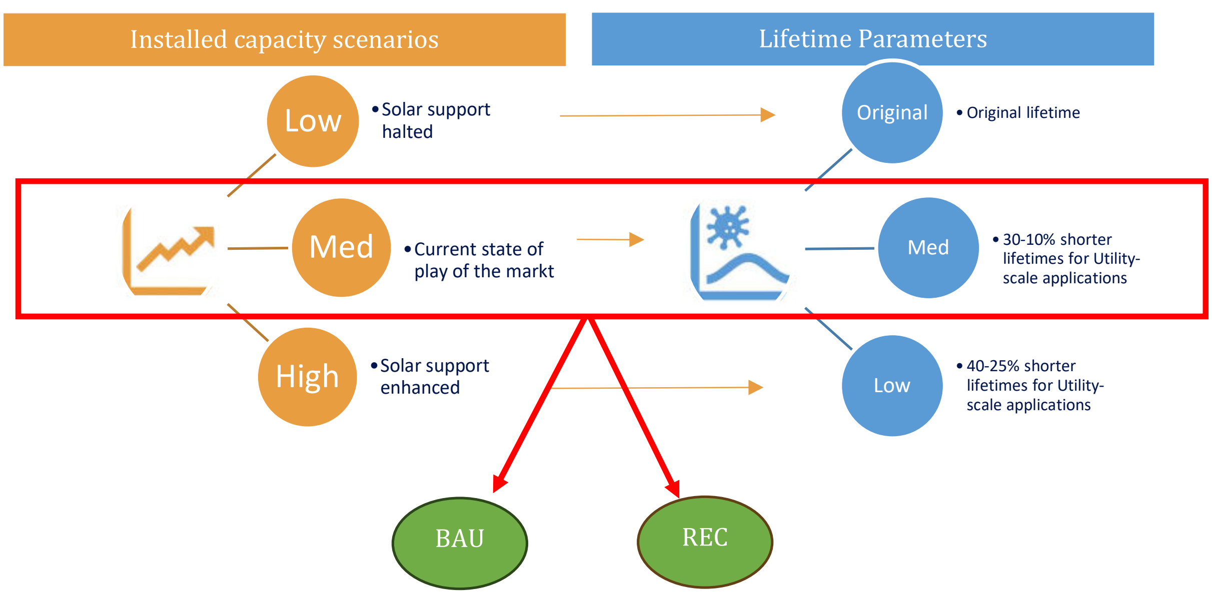

Figure 10 Summary of the features of the scenarios used in the calculation of PV waste flows

PV waste exports

The export of PV panel waste from the EU - whether intra-EU or to third countries - is driven by several factors, including the increasing volume of decommissioned solar panels, variations in recycling capacities across member states, and economic incentives for waste management companies. While some EU nations have advanced PV recycling facilities, others may lack the necessary infrastructure, leading to transboundary waste shipments. Additionally, lower treatment costs in non-EU countries create an economic incentive for exports. However, this raises concerns about the proper handling and environmental impact of hazardous materials found in PV panels, such as lead, cadmium, and silicon compounds. Weak enforcement of waste regulations and potential illegal shipments also pose risks, potentially undermining the EU's circular economy goals and environmental standards.

Task 6.1 also looked at PV waste exported from EU countries as parameter of the model (see Figure 2).

Three main sources of information were used to gather data and information on PV waste exports from the EU:

1. Eurostat
2. Basel reporting
3. Literature review

The primary source of information was the Eurostat dataset on "Waste electrical and electronic equipment (WEEE) by waste management operations" (Eurostat, 2022; Eurostat 2024). As regards to Basel Convention reporting: there is no specific HS code for PV waste thus it is not possible to use UN Comtrade Database[4] which would have provided a holistic view of the exports from each EU country.

Another source of information is the Basel national reports[5] that countries are required to transmit annually to the Basel Secretariat pursuant to article 13, paragraph 3 of the Basel Convention. Through the national reports, countries are asked to provide detailed data on the export of hazardous wastes and other wastes in a table format, covering information related to classification (Basel Annex and Y Code, National code), type of waste and hazardous characteristics, amount exported, countries of transit and destination, final disposal and recovery operation.

EU countries use the EU list of Wastes as national code. Again, there is no specific code assigned to PV waste, and several codes are applicable, as exemplified in the table below:

Table 5 - Examples of waste codes relevant to PV panels from the EU List of Wastes. Source: IRENA and IEA, 2016

Table 10 Examples of waste codes relevant to PV panels from the EU List of Wastes

Type	Waste code	Remark
All types	160214	Industrial waste from electrical and electronic equipment
	160213*	Discarded equipment containing hazardous components
	200136	Municipal waste, used electrical and electronic equipment
	200135*	Discarded electrical and electronic equipment containing hazardous components
In special cases also: *e.g.* amorphous-silicon (a-Si) panels	170202	Construction and demolition waste – glass

** Classified as hazardous waste, depending on the concentration of hazardous substances. Table 10 portrays leaching test methods commonly used for hazardous waste characterisation.*
Based on European Commission, (2000)

[4] https://comtradeplus.un.org/TradeFlow

[5] https://www.basel.int/Countries/NationalReporting/NationalReports/BC2023Reports/tabid/10106/Default.aspx

In order to assess the availability of data, national reports were downloaded for five countries (Germany, Italy, Spain, France, Czech Republic) for the last 3 years available (2021-2023).

- Years were selected based on the fact that more PV waste was generated in recent years and the assumption that the higher the quantity of PV waste generated, the higher the potential of export.
- Countries were selected based on their high quantity of PV waste generated (all applications combined) over the years 2021-2023 building on the same assumption.

Then, a search by national code (as listed above) and keywords (PV; photovoltaic, module; panel – and their national translation) was conducted.

Given the lack of quantitative data from Eurostat and Basel national reports, a literature review was performed looking for both quantitative and qualitative information of PV waste export from the EU. The research team looked at studies, articles, reports or any other type of publication referring to this topic.

4 RESULTS AND DISCUSSION

This chapter illustrates the most representative results for the indicators identified in the methodological framework. The indicators are presented taking into account the 3 different scenarios (combined installed capacity scenarios and lifetime parameters) described in the methodology section Figure 9. Henceforth, the Low Scenario refers to the lowest possible installed capacity combined with the high lifetime parameters. The Mid Scenario refers to the medium-level installed capacity combined with the medium lifetime parameters. The High Scenario refers to the highest projection of installed capacity combined with the low lifetime parameters.

All results not discussed fall within the boundaries of the numbers presented here.

4.2 PV Installed capacity

The installed capacity for the Low Scenario and High Scenario, also referred to as PV Stock, shows a ±21% deviation from the Mid Scenario in 2030. As the numbers for 2024 were already based on the newest available data, the scenarios only diverge starting from the projected developments in the year 2025 with increasing severity. The proportion of applications and technologies within the installed capacity was assumed to be constant across the scenarios and therefore does not change. As shown in Figure 11, the Mid Scenario assumes the cumulative capacity of PV panels to be 816 GW in 2030 (Low Scenario: 644 GW; High Scenario: 983 GW).

Validation: Results on the total installed capacity were validated by comparing the results of Task 6.1 in the EVERPV project with scenarios for Europe and Global projections available in the literature. The EVERPV results are 2.9 times the assumed capacity in IRENA's TES and PES scenarios but critically undershoot the projection by LUT University by around 50%. This highlights the high variety in projections for solar power capacity, even for relatively short periods, as until 2030. Nonetheless, the predicted installed capacity by the EVERPV model can be interpreted as tending toward a more optimistic outlook than the majority of evaluated projections. For example, the University of Technology Sydney assumed around 600 GW for Europe in 2030. Although Stanford University does not disclose predictions for 2030, their 2050 projection for Europe, based on assumed energy-needs covered entirely by green energy, is 1950 GW and thus only double the EVERPV Mid scenario results. Nonetheless, EVERPV scenarios are strongly aligned with producer associations and practitioners and therefore, the numbers should be understood as confident. Given the wider range of results provided (±21%), the scenarios are assumed to give a high degree of accuracy if current political and socio-economic factors prevail.

Results by application:

The largest contributor to the growth is Utility-scale PV panels with a growth rate of 115% compared to 2024, reaching 330GW in the EU27 region, followed by Commercial-scale, Industrial-scale, and Residential-scale, who grow a maximum of 83% - 68% and reaching 185GW, 173GW, and 127GW, respectively. The overall growth rate of the Utility application is even steeper, when considering the historic numbers at market introduction, when this application was by far the least dominant. Despite the Residential application growth rate falling behind other applications in the projections, the long-term view from market-inception to 2030 ranks this application a close third to the Industrial-scale panels and far before Commercial-scale panels, which used to be the most prevalent category but since then lost momentum.

The installed capacity (in weight) projected translates into 96.8 kt of PV stock being in operation by 2030. While the exact proportions between applications differ slightly compared to the installed capacity in GW due to different conversion factors which account for individual weight of the PV panels by application, the overall contribution of each application remains similar. Again, Utility-scale application is contributing the most with 40% of the overall volume, followed by Commercial-scale (23%), Residential-scale (21%), and lastly Industrial-Scale (16%).

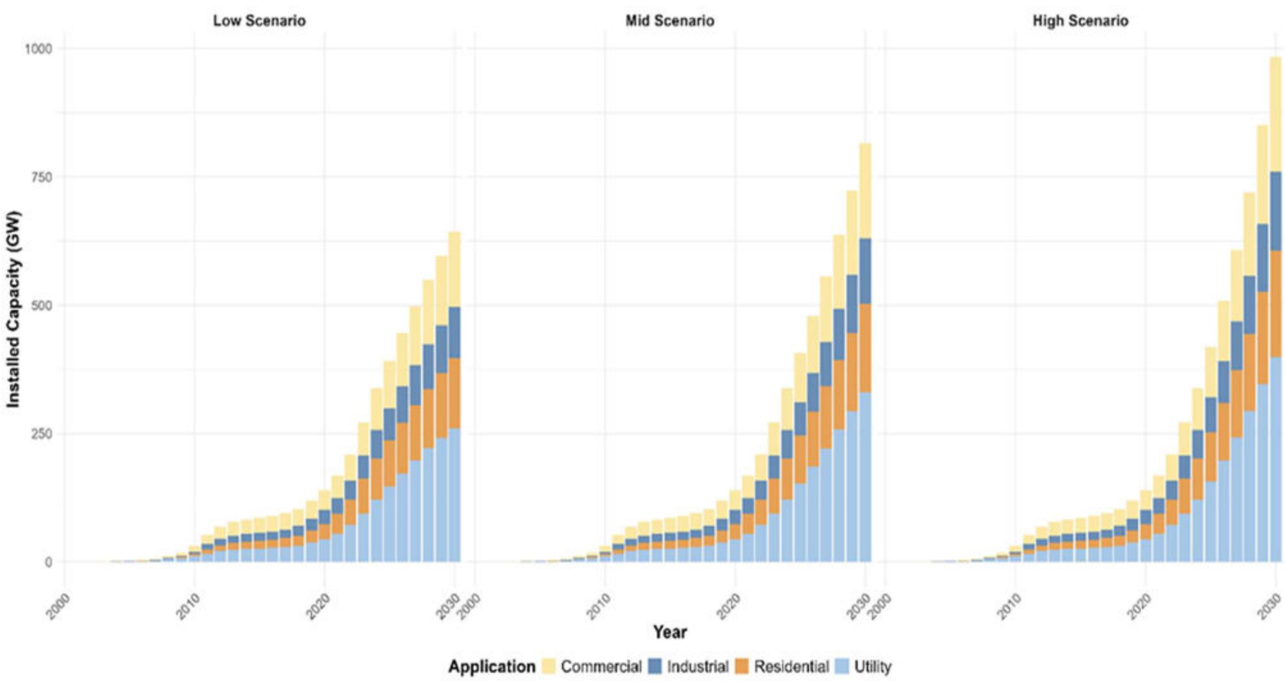

Figure 11 Evolution over time of installed capacity by application in the EU27 in GW

Annex 3 summarized the data on total installed capacity for the EU27 region in MW and kt by application.

Validation: Estimations on the segmentation were also validated by consulting scientific papers, however, many studies either do not provide such a breakdown of data or do not offer the right geographical focus or time frame. The Stanford study offers a split of 17% Residential-scale, 26% Commercial-scale, and 57% Utility-scale for Europe in 2050. This is roughly aligned with the EVERPV results, which have a 21% Residential-scale, 37% Commercial/Industrial-scale, and 41% Utility-scale split for 2030 with growth rates indicating a stark increase for Utility-scale panels and a slowing Residential-scale growth.

Results by technology:

For 2030, EVERPV estimates those shares to start shifting away from crystalline silicon technologies down to 92% (Multi-Si: 64 GW; Mono-Si: 687 GW), while also projecting a declining share in Thin-film technologies (~4%; 33 GW) as presented in Figure 12. This is due to the assumed inception of the Tandem-PK/Si technology, which was computed to achieve a 4% - 32 GW market share for the 2030

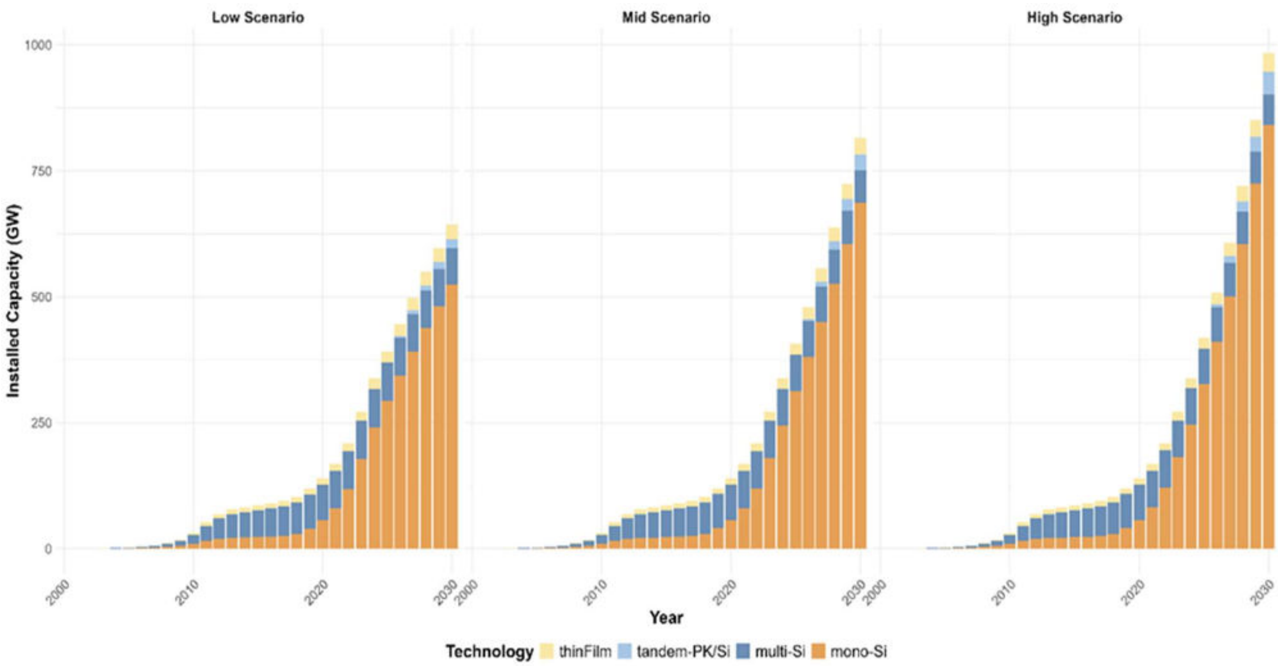

Figure 12 Installed Capacity in EU27 by Technology in GW

Annex 3 summarized the data on total installed capacity for the EU27 region in MW and kt by technology.

Validation: The technology shares of the installed capacity are broadly aligned with industry information, EVERPV pins the currently operating silicon-technology share closer to 94% with 6% being attributed to Thin-film technology. Furthermore, projections for technology shares were not given by the International Solar Alliance (ISA). For 2030, EVERPV pins the currently operating silicon-technology share closer to 94% with 6% being attributed to Thin-film technology.

Results by country:

Analysing the distribution of the installed capacity in the individually modelled countries, several trends are observed, which are highlighted in Figure 13 in a snapshot of the years 2010, 2024, and 2030 from the Mid scenario. Of the largest four EU economies, the relative share of Germany as leading country is projected to decrease to around 27% to 2030, as installation capacities from other countries are rapidly increasing. Spain, currently the second largest market for PVs in Europe, is projected to keep its relative contribution within Europe constant from 2010, which can be attributed to a high growth rate in line with the EU average. Italy, as well, retains its relative EU market share over the investigated years. Only France shows a significant increase of its share from around 3.3% in 2010 to 8.4% in 2030.

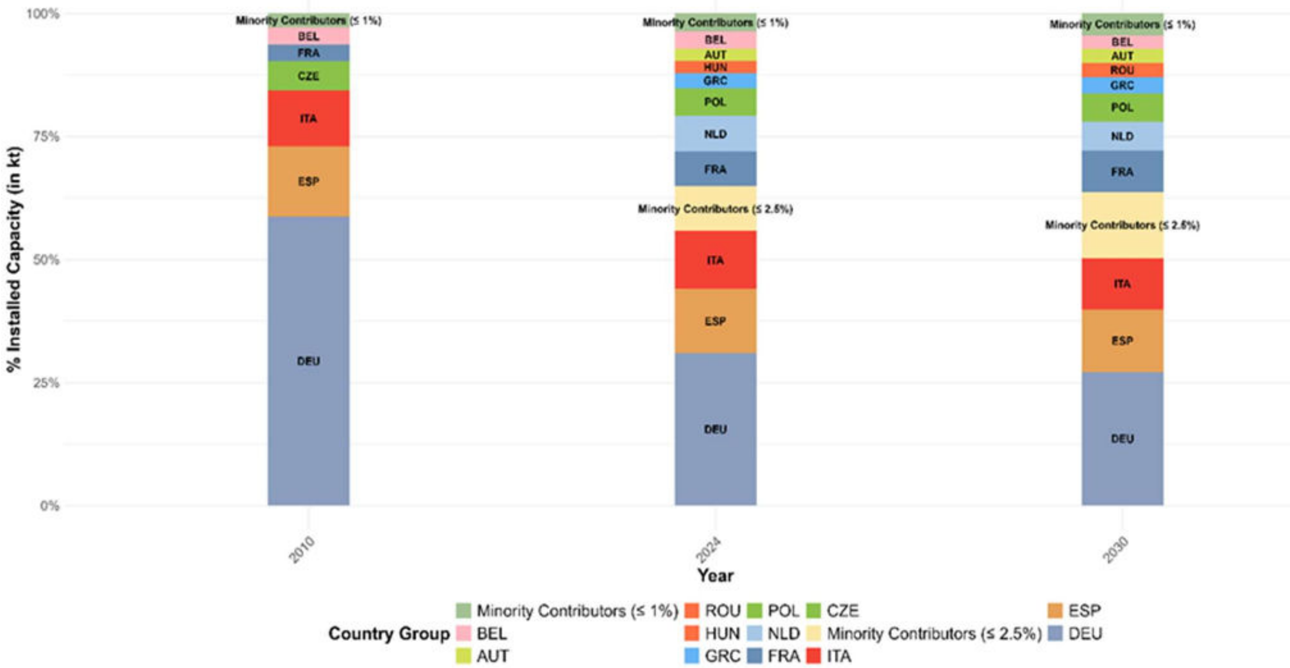

Figure 13 Country contributions to total installed capacity in the EU27 by year.

In recent years, medium-sized economies which were not highly present in the early years of the solar technology are showing high growth rates. Most notably, Poland showcased a growing installation of PV panels, which is projected to continue increasing on a steady level to around 5.8% EU total capacity. A similar pattern was already observed in the Netherlands, which grew to a notable PV market in 2024, representing around 7.3% overall EU PV capacity. This trend is also projected to continue. Similarly, Belgium as well as Romania showing high growth rates in recent years, amounting to projected ~3% each, in 2030.

Figure 13 furthermore combines small economies with limited contributions to the overall capacity of the European Union into countries with ≤ 1% installed capacity and into countries with ≤ 2.5% installed capacity. In 2010, only Belgium and Czech Republic had a market share of above 1% in addition to the large four economies. In 2024, significant changes have been observed in the European PV market and installed capacity. It is estimated that only Cyprus, Estonia, Finland, Croatia, Ireland, Lithuania, Luxembourg, Latvia, Malta, Slovakia, and Slovenia remain among the minor PV markets. Several countries are estimated to currently achieve larger shares of 2.5% or lower, i.e., Bulgaria, Czech Republic, Denmark, Portugal, Romania, and Sweden, with Austria, Greece, Hungary, the Netherlands, and Poland establishing themselves as notable markets above the defined threshold.

For 2030, the model projects only minor changes, with Finland and Ireland establishing a ≤ 2.5% share of installed capacity, and Romania achieving a share larger than that. Only Hungary is projected to grow slower than other markets to the point where it falls back into the ≤ 2.5% category.

4.3 PV POM

The PV POM strongly deviates in between the different scenarios, as shown in Figure 14. Longer lifetimes, as in the displayed Low Scenario, lead to a drop in future PV installations after the initial spike observed until 2024, as the projected installed capacity is reached earlier and less panels are required to sustain the level of installed capacity. For this scenario, a drop down to around 2,500 kt of PV panels per year (~49,600 MW) is projected for 2030. On the other hand, the High scenario, which combines shorter lifetimes with the highest installed capacity, sees a continuing trend of increasing installations per year, reaching more than 6,600 kt in 2030 (~138,000 MW). The factor combination of shorter lifetimes for Utility-scale panels, which at the same time are the main driver of the installed capacity, with the higher projected capacity levels, lead to high required annual installations. Lastly, the middle of the road Mid Scenario showcases further increasing trend, however at a staunchly diminished growth rate compared to previous years, peaking at around 4,500kt in 2030 (~96,000 MW).

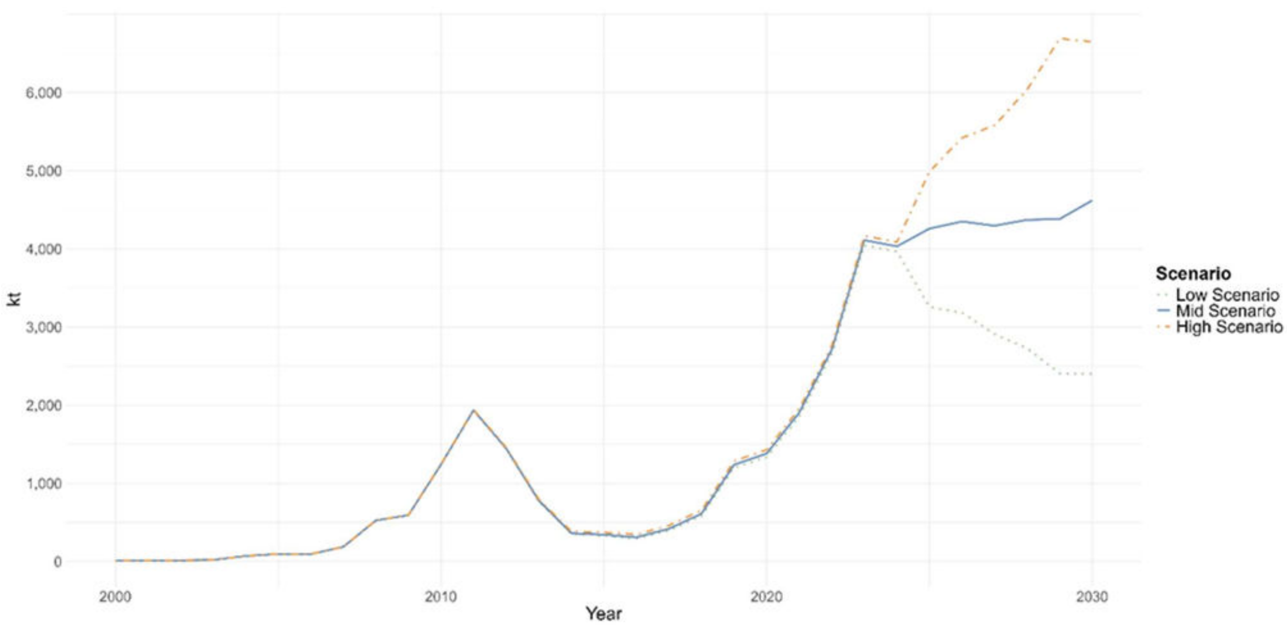

Figure 14 Evolution of PV POM over time for the EU27 in kt

Figure 15 describes the PV POM volume per country and application in the Mid Scenario.

The most prominent application by volume and capacity in 2030 is projected to be Utility. Therefore, the group of countries for which this application is the most dominant is growing from 7 countries in 2010 to 16 countries in 2030, including all four large EU economies. Only Estonia, Luxembourg, Malta, and Slovakia are projected to have the highest volumes of annually installed PV panels in the Commercial application. Projected to remain strongly driven by Residential-scale panels are Austria, Belgium, Czech Republic, Croatia, the Netherlands, Slovenia, and Sweden. This highlights the trend of increasingly economic viable large-scale electricity production from PV panels across most of the European Union.

Most interestingly, a closer look at the large four EU economies shows that only volumes in France and Spain have been consistently fuelled by the Utility sector. Italy has seen the most volumes in the Industrial application until recently, whereas volumes in Germany are driven by the Commercial sector. However, both are projected to see the most growth in the Utility application by 2030.

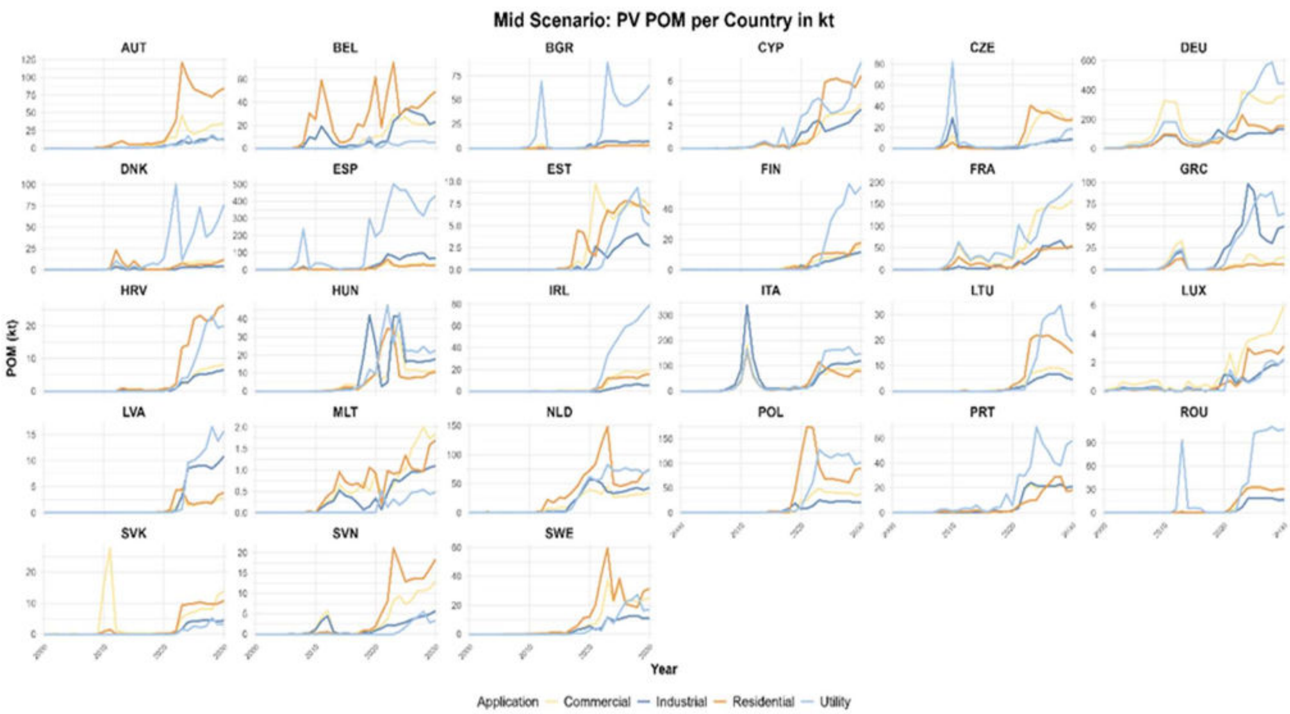

Figure 15 Evolution of PV POM over time for the EU27- Mid-scenario, by application - in kt

Validation: These harmonized data produced in the EVERPV project at country level are novel in the scientific domain and a validation was not possible due to the unavailability of such harmonized and complete datasets in the literature. Such results are useful for policy making purposes as it allows to predict trends over time and cross-country comparisons.

4.4 PV Waste

Unlike the PV POM, which shows high variance across the years, the computed PV waste shows a steady increase over time across all three scenarios (Figure 15), with expected higher waste flows for the High Scenario and conversely lowest waste flows in the Low Scenario. For 2030, the EVERPV model projects an outflow of around 207 kt (~2,300 MW) for the Low Scenario, and 454 kt (~6,000 MW) for the High Scenario, a +37% - 39% deviation from the Mid Scenario, which is projected to reach 326 kt (3,900 MW). This deviation is significantly higher than for PV stock, which was at ±21%. This difference can mainly be attributed to the differing shape values in each scenario, which do not directly determine the overall cumulative waste flow but shift the timing of the annual outflows. Therefore, the contrast between the scenarios is exacerbated, given the horizon until 2030 cuts off all effects beyond the target year. Beyond 2030, the Low Scenario would yield the lowest waste generated by far, as the cumulative installed capacity difference would increase over time, influencing the total PV waste.

Results by application:

Looking at the application breakdown per scenario, the Utility application represents the largest category throughout the Mid Scenario and High Scenario, which can be attributed to increased replacement rates for this application due to repowering. In the High Scenario, the Utility-scale PV panels even represent consistently around 50% of the overall PV panel waste stream. Yet, in both scenarios, the Utility-scale PV panels are projected to decline in their relative share until 2030 compared to previous years, before potentially increasing again in future years due to expected increased installation rates of such panels. Figure 16 shows the annual PV waste for the EU27 by application.

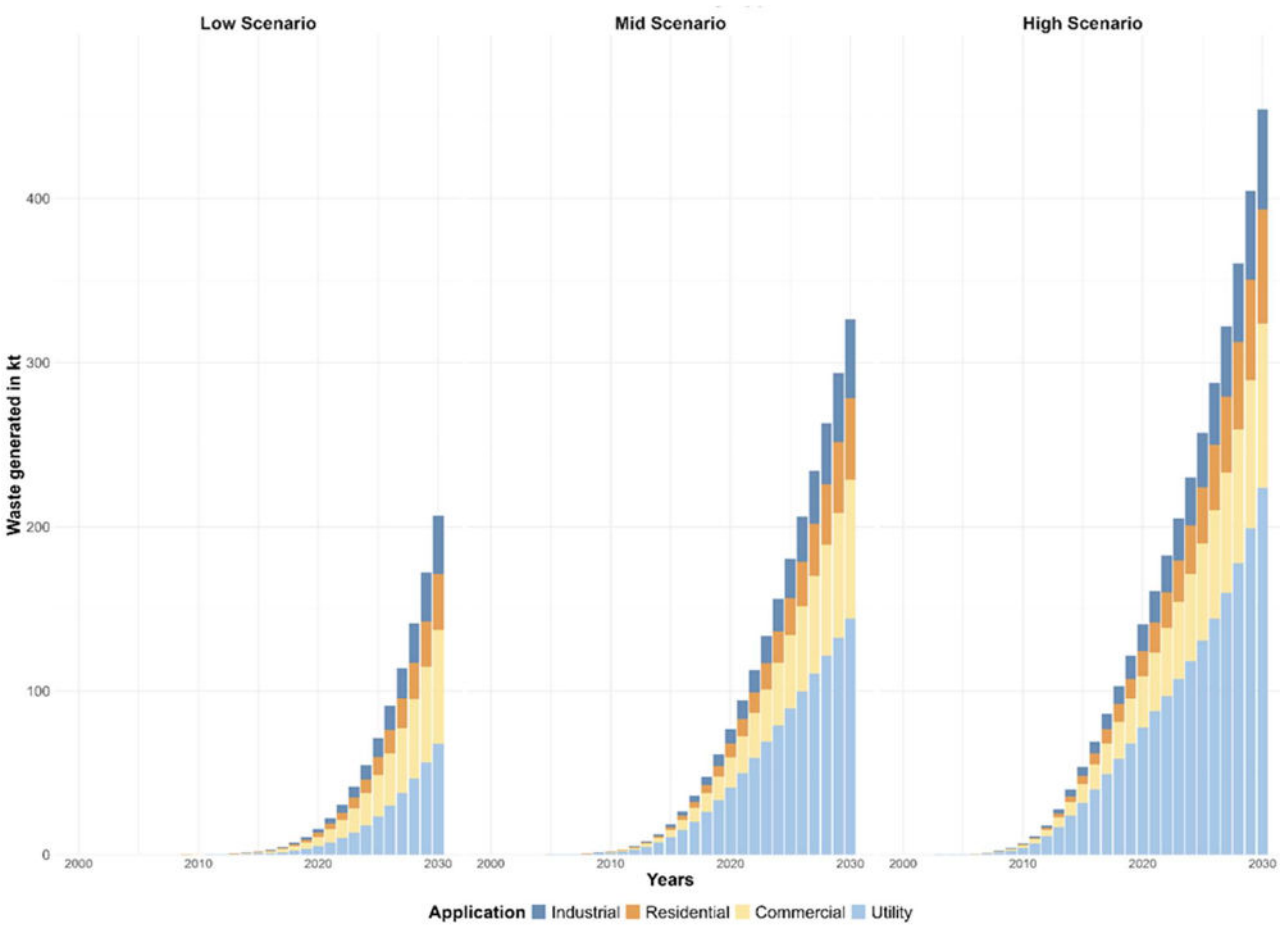

Figure 16 PV waste evolution for the EU27 by application in kt

Only the Low Scenario, which assumes similar lifespans for all applications, shows an even spread between Utility and Commercial applications as well as Industrial and Residential applications, respectively. Equally, only the Low Scenario sees the relative share of Commercial-scale PV panels decline to overall 34% in 2030, whereas the share of this application is computed at a lower level for the Mid Scenario and High Scenario but remains consistent over time with minimal fluctuations. For those scenarios, the overall shares of Industrial-scale and Residential-scale PV panels are projected to increase over time to make up around ~15% each in the Mid Scenario, and ~13% and ~15%, respectively, in the High Scenario.

Results by technology:

The waste flows by technology showcase some interesting developments and differences in-between the different scenarios. Most notably, Tandem-PK/Si panels occur only in significant quantities in the High Scenario, as shorter lifetimes and quicker disposal patterns accelerate the entry into the waste stream of this new technology. The Low Scenario projects only minuscule quantities below any threshold of significance, whereas the Mid Scenario projects around 225 t in 2030, a value more than 10-times higher in the High Scenario. Figure 17 shows the annual PV waste for the EU27 by technology.

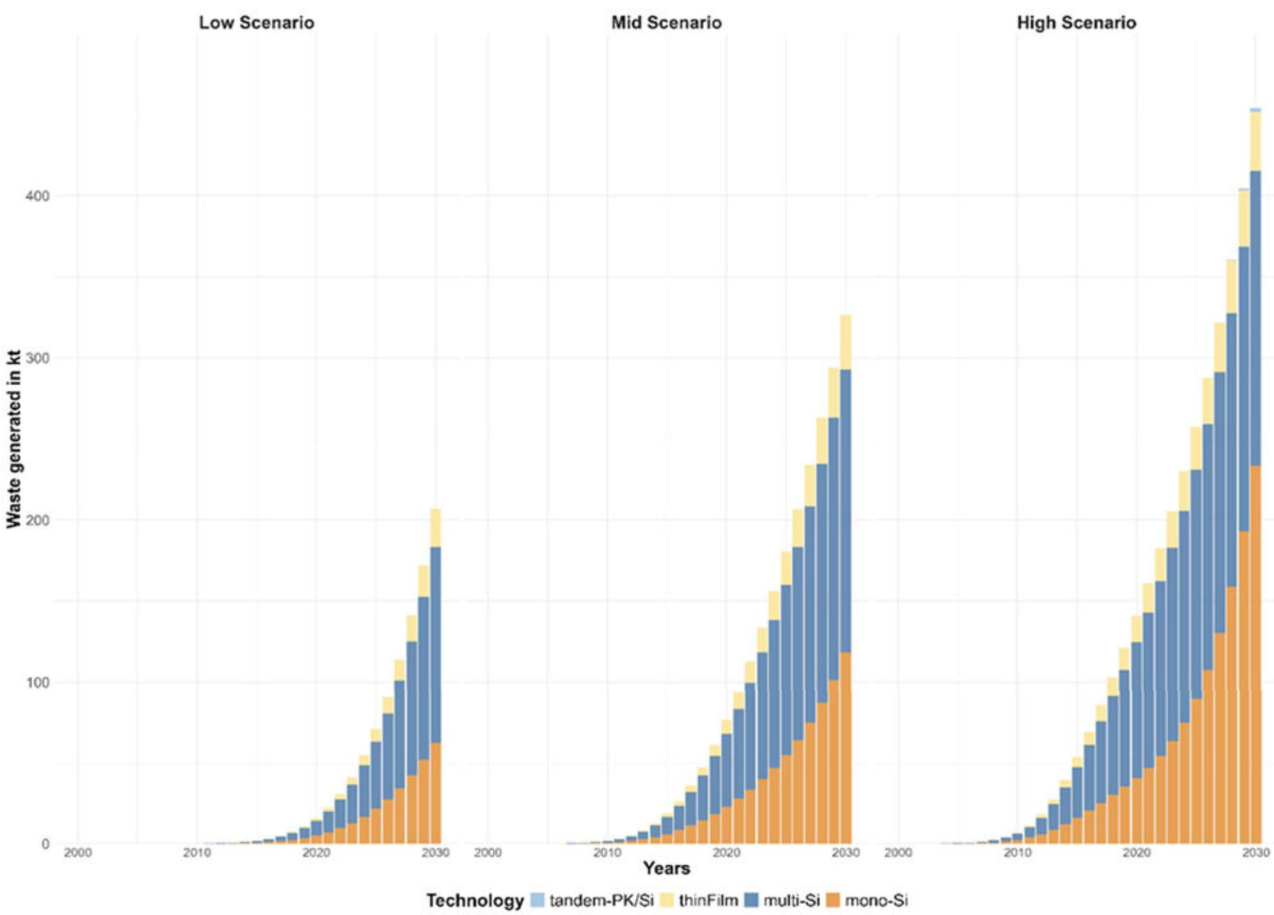

Figure 17 PV waste evolution for the EU27 by technology in kt

The largest technology waste flow found in the Low Scenario and Mid Scenario is the Multi-Si panel technology. This is due to this technology being predominant in the EU early on until 2018, when Mono-

Si technology took over the majority market share. This development is not yet reflected in those scenarios, due to the longer lifetimes and slower disposal pattern. In fact, the Low Scenario projects the zenith of the relative share of Multi-Si in the waste stream only for 2028, with it remaining the predominant technology in the waste flow well beyond 2030. Whereas the Mid Scenario computes the year 2022 as the inflection point with Mono-Si taking over the majority of the waste flow in the proximate years beyond 2030. On the other hand, the High Scenario, driven by quicker turnover rates, computes the inflection point already for 2020 and projects the Mono-Si technology to become the predominant waste flow of PVs in 2028. At this point, a large share of Multi-Si panels is already disposed. Such a trend is also visible for the Thin-film technology, which diminishes in its relative share the more rapidly the more aggressive scenario is examined.

Results by country:

Results per country show that in some cases the Low Scenario projects a similar or only slightly diminished PV waste generated than the Mid Scenario. In some other cases, the Mid Scenario projects a similar or only slightly diminished PV Waste generated than the High Scenario. Lastly, an expedited growth rate of PV Waste generated can sometimes be observed for the High Scenario (Figure 18).

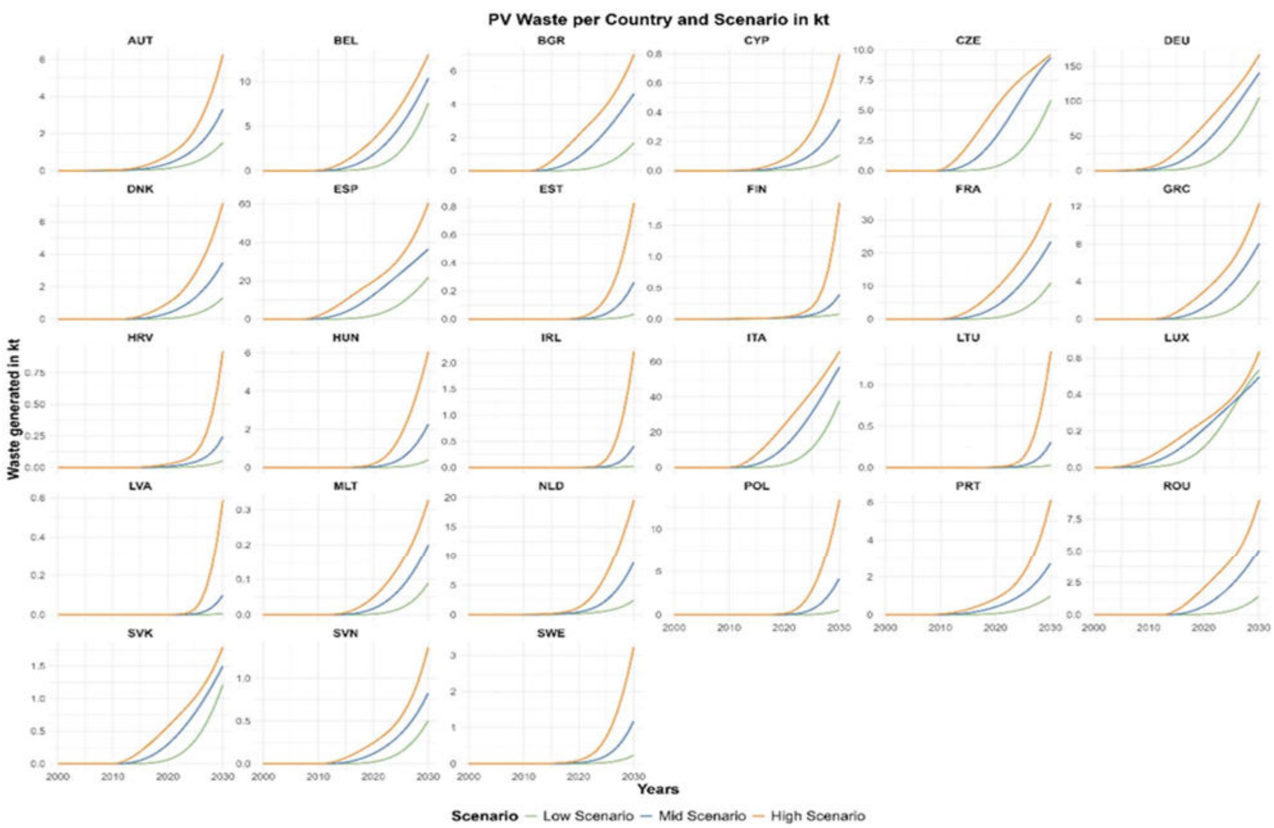

Figure 18 Evolution of PV waste over time for the EU27 by scenario - in kt

All three of these trends can be explained and are discussed subsequently through the example edge-cases of (1) Luxembourg, where the Low Scenario even projects a higher PV Waste generated than the Mid-Scenario, (2) through Czech Republic, where the Mid Scenario projects a similar PV Waste generated to the High Scenario, and through (3) Croatia, where the growth-rate for PV Waste generated of the High Scenario is clearly breaking away from the other scenarios early on.

In the first case, the Low Scenario shows a higher relative growth rate and similar absolute PV Waste generated. For Luxembourg, the PV Waste generated of the Low Scenario even overtakes the Mid Scenario by 2028. This is likely attributable to the higher shape-values used in the Mid-Scenario and High-Scenario, which ultimately concentrate the PV waste generated but delay the onset of this outflow. This coincides with particularly high installation rates for Luxembourg before 2010 and a subsequent stagnation until 2020, therefore significantly decreasing early loss outflows from the 2010s while simultaneously having larger volumes of PV panels reaching their end-of-life. Additionally, Luxembourg has a relatively low rate of Utility-scale PV panels, further contributing to decreased early PV Waste generated in the Mid Scenario and High Scenario. All these factors combined lead to a constellation of variables which cannot be compensated solely by higher installation rates and their resulting early-loss computed in the Mid Scenario, leading to temporarily higher PV Waste generated of the Low Scenario. The mid-scenario assumes a less spread-out disposal pattern of the early 2000s PVs, which peak occurs only after 2030.

In the second case, the relative growth rate of the Mid Scenario is higher than that of the High Scenario and the absolute output is somewhat similar or higher than expected. This behaviour can be explained at the example of the Czech Republic, where the Mid Scenario almost overtakes the high scenario in PV waste generated. Czech Republic was shown to have a particularly high share of Utility-scale panels in the mid-2000s. The disposal pattern due to a lower shape factor, assumed in the Mid Scenario, coincides with the end-of-life of those panels due to assumed shortened lifetimes for Utility-scale panels, leading to a spike in PV Waste generated toward 2030. The more concentrated, but delayed disposal pattern in the High Scenario assumes this spike beyond 2030. However, in this case, the increased installed capacity, as well as the converging lifetimes of Utility-scale panels over time, compensate sufficiently to project the PV waste generated for the High Scenario barely over the Mid Scenario.

The third case, which refers to a particularly high growth-rate for PV Waste Generated in the High Scenario compared to other scenarios, can be explained through rapidly growing Utility applications. Using the edge-case of Croatia as example, where Utility-scale panels gain a 30% market share in annual installations and grow to a ~16% share of PV stock within only four years. The rapid growth rate of PV waste can therefore be explained through the exceptionally high growth rate of PV waste and consequently PV stock of the application. The more aggressively shortened lifetimes of this application in combination with the higher installation rate leads to steep growth in PV waste. Contrary to the previous cases, the higher shape factor actively contributes to smoothing out this growth or rather delaying more aggressive growth beyond 2030.

Figure 19 displays the PV Waste Generated per country broken down by application for the Mid Scenario.

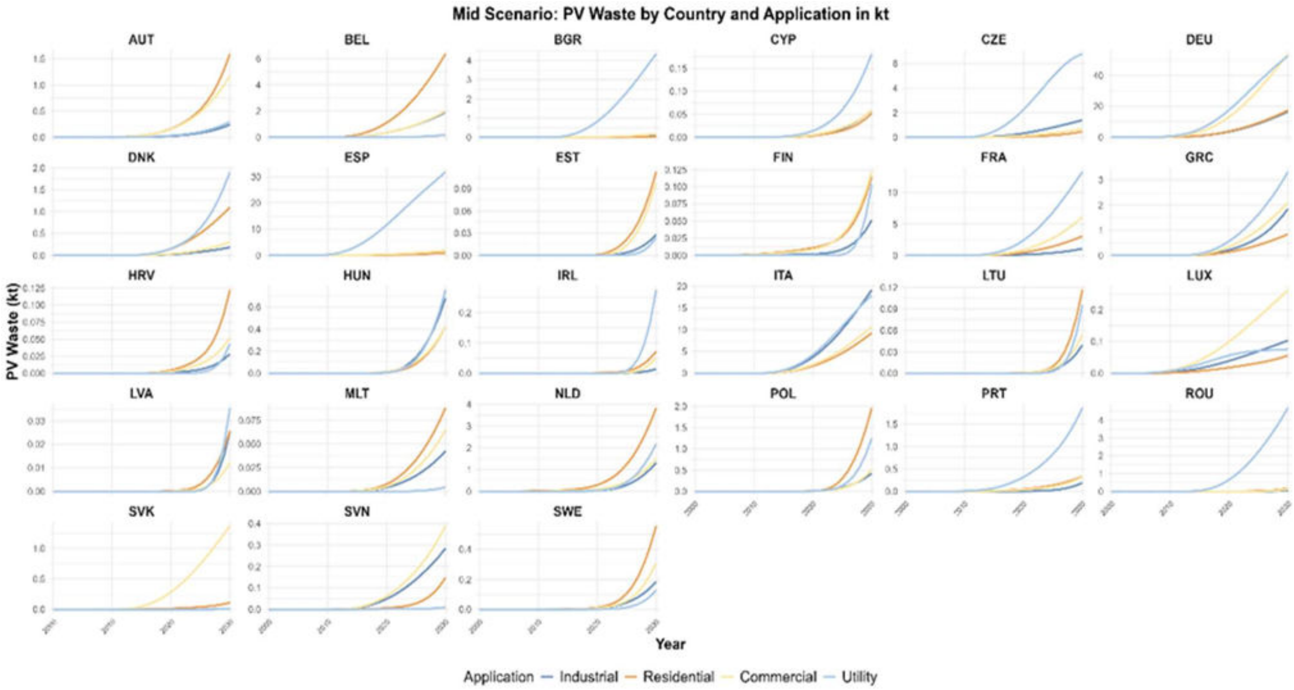

Figure 19 Evolution of PV waste over time for the EU27 by application- Mid scenario - in kt

While most PV Waste generated flows are proportional to the previous installation rates, such a relationship does not exist for the Utility application. The Mid Scenario accounts for the effect of repowering through shortened lifetimes of Utility-scale panels. Therefore, in many countries that have seen higher Utility-scale panel installation rates early on, the Utility-scale PV panel waste generated flows are strictly elevated compared to other outflows. One good example to showcase this behaviour is again the Czech Republic which, as previously explained, has seen such a development in the past. Therefore, the country breakdown shows a particularly high outflow of Utility-scale panels, as the disposal-pattern of these coincides with the end-of-life of the majority of those panels. It is important to note that, as observed in 4.2 Placed on the Market, the recent trend of highly increasing Utility-scale panel installations across the EU are not yet visible in their entire impact in the waste flows. As it is projected to be the case for most countries in 2025 or 2030, among others the largest four European economies together with other important PV markets, the bulk of these volumes will likely only enter the waste stream in the mid-2040s. Therefore, despite Utility already making up the largest application in the PV Waste Generated of the EU, further steep growth is anticipated beyond the scope of the results presented.

4.5 PV Waste Flows

4.4.1 PV WASTE COLLECTED

PV waste collected was calculated for the Mid Scenario and medium lifetime. The generation of PV waste is increasing at a faster rate than its collection. In the EU-27 region, the average collection rate of PV waste has not exhibited substantial growth over the past five years, despite an overall improvement of 3% annually from 2018 to 2022, reaching 40% in 2022. Less than half of the WEEE collection target of

85% set by the WEEE Directive since August 2018. In the current year: 2025 the BAU scenario estimates that the EU27 region will hit 47.1% collection rate, and 49.5% in the REC scenario, leading to 57.8% and 61.9% respectively in the year 2030.

Figure 20 shows the projected development of collection rates over time as an EU27 average.

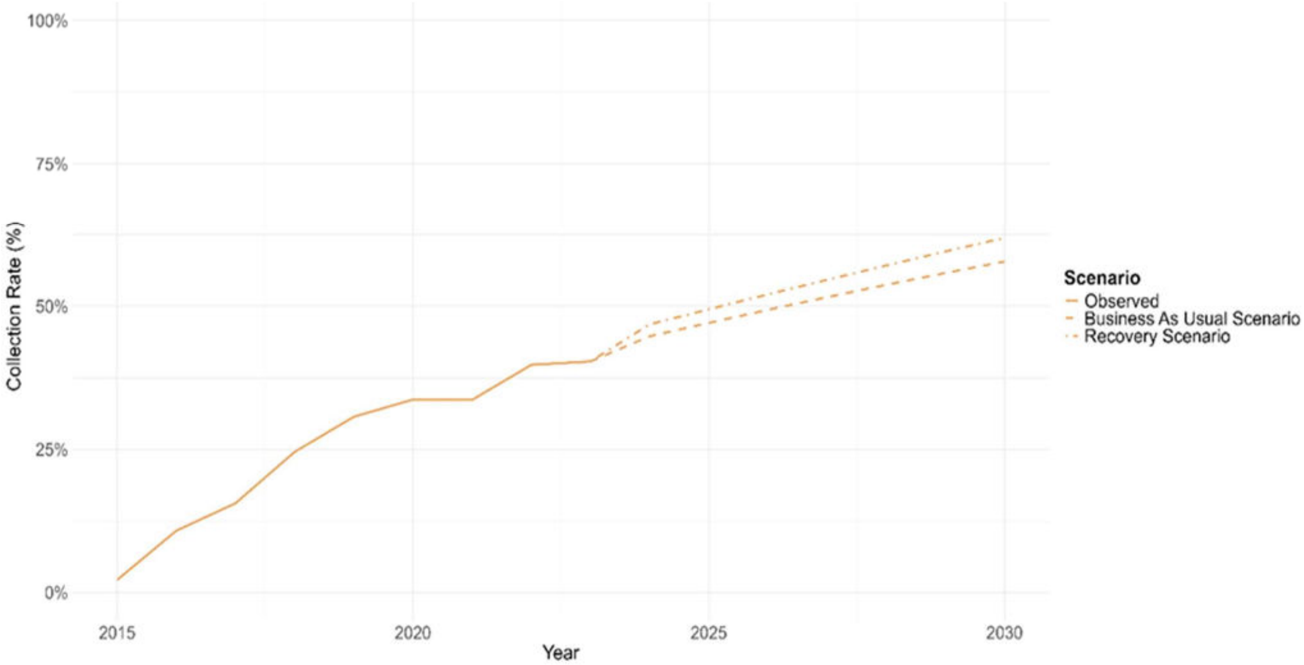

Figure 20 Evolution over time of average collection rate for the EU27 per scenario

The results are based on the overall collected quantities reported and projected across all member states versus the overall quantities of PV waste computed for previous years and projected for future years. The results between the two scenarios do not differ significantly for the 2030-time horizon, mostly driven by assumed high collection rates for some large markets, such as France, and more notably Italy. Only smaller economies, for which the overall installed capacity in the past had been lower, showcase particularly low collection rates. Calculated on the total volume of PV waste in the EU27, this has less influence. Additionally, the models assume a S-shaped improvement to target rates, therefore showing the majority of differentiation only beyond 2030. Nonetheless, a not insignificant difference in-between both scenarios can be made out, due to the assumed improvement of France and the combined effects of other mid-sized PV markets, such as Belgium, Portugal, or Austria.

Figure 21 showcases the estimated collection rate, computed from the officially reported volumes by countries on Eurostat for 2022 and the estimated PV Waste generated in the Mid Scenario. The results of the two scenarios to estimate the collection rate for 2030, Business-as-Usual Scenario and Recovery Scenario presented in the section 3.2.7, are presented below.

The Business-as-Usual Scenario leads to significant improvements for Germany, Spain, Romania, Slovakia, and Denmark, all of which are not expected to improve their collection rates even further under the Recovery scenario. On the other hand, France and Belgium are expected to improve only under the

Recovery scenario. Most other countries show, in line with expectations, a mixed improvement under each scenario. For the countries at the bottom of the graph, it was not possible to calculate collection rate because data on PV collected for the years of reference are absent.

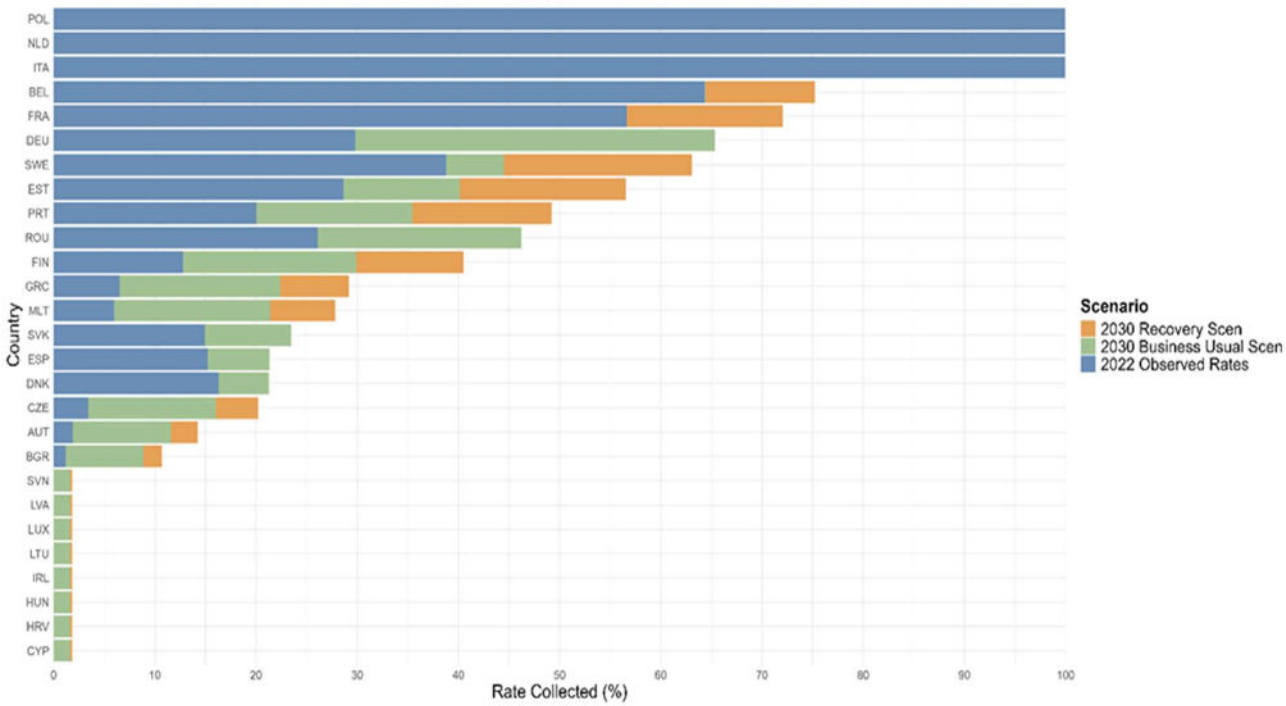

Figure 21 Collection rated per country by scenario and year – in %

Inconsistencies and data gaps have been highlighted by project partners during the execution of Task 6.1 related to the data officially reported by the Members States to Eurostat. Possible outliers may be present in the databases or the reporting on the collection of commercial PV waste may not be fully reflected in the official data.

4.4.2 PV WASTE EXPORTS

Overall, limited data is available in the Eurostat database. Data is available only for the years 2015-2022[6]. Not all country reported and among reporting countries, quantities are rather small. In addition, the Eurostat dataset does not provide information on the country of destination.

Eurostat - Waste treated in another EU Member State

Nine EU countries reported export of PV waste for treatment in another EU Member State. France is the main exporter with a total of 11,033 tonnes exported between 2015 and 2022, accounting for nearly 60% of total intra-EU exports. It is followed by Italy (4,229 tonnes), the Netherlands (1,992 tonnes), Belgium (1,053 tonnes). The other five countries reported limited amounts, as displayed in below table.

[6] Due to national discrepancy, year 2015 is not presented in the below table.

Table 6 – Quantity of Waste treated in another Member State of the EU over 2015-2022 (tonnes)

Year	2016	2017	2018	2019	2020	2021	2022	TOTAL
EU-27	377	1906	1603	2571	1453	2164	8246	18673
Belgium	0	94	72	114	44	68	661	1,053
Czech Republic	0	0	0	0	31	0	89	120
Denmark	0	0	0	0	16	4	0	20
Germany	60	26	0	-	-	-	-	86
Greece	59	0	0	-	0	0	0	59
France	223	1,786	1,449	2,380	790	1,654	2,398	11,033
Italy	-	-	1	0	68	50	4,110	4,229
Hungary	-	-	81	-	-	0	0	81
Netherlands	35	0	0	77	504	388	988	1,992

Eurostat - Waste treated outside the EU

Only Germany reported small export outside the EU in 2016 (2 tonnes) and 2017 (1 tonne).

Basel Convention

No data was available from the national reports. This could be interpreted in 2 ways:

The five countries did not export PV waste on the years checked; or

The five countries did export PV waste, but specific data is not reflected due to imprecise reporting, where PV waste is not linked to a specific HS or national code, and the country did not specified under the type of waste.

An additional check was conducted for Germany by reviewing the national reports for the years 2016 and 2017 since the country reported small amounts in Eurostat. However, the Basel national reports did not mention PV waste, nor did they include any quantity that corresponded to the figures reported in Eurostat. This underlines a certain inconsistency in the reporting between Eurostat and Basel national report.

Literature review

While there is a certain amount of literature on the export (and import) of PV panels as products globally, research on the export of PV waste remains limited.

According to the International Energy Agency (IEA), the officially reported volume of collected PV waste in the EU is lower than expected. However, it remains unclear whether this discrepancy is due to PV panels lasting longer than anticipated or if used or waste PV panels are bypassing the collection system, e.g. going through alternative storage of disposal routes, being resold on second-hand markets (including in third countries), or illegally exported (IEA, 2024). The primary incentives for such exports could stem from two key factors: the potential for reuse and the prospect of lower recycling costs (Kastanaki, 2025; Nyffenegger et. al., 2024).

Building on stakeholder consultation, Nyffenegger - repeated by several other sources - reports that a considerable amount of PV modules is exported to non-European countries for further use and therefore never reaches reuse or recycling facilities in Europe and that a large proportion of PV modules destined for reuse and recycling disappear after dismantling (Nyffenegger et. al., 2024). A few articles suggest that between 30% and 90% of PV waste is exported outside the EU (Radavičius; Nyffenegger et. al., 2024).

As of 2020, INTERPOL warned about the risk of illegal export due to the lack of appropriate recycling solution in certain countries and/or the high processing costs. INTEPROL reported that in 2019, a transnational organized criminal group was detected trafficking large quantities of photovoltaic panels through triangular transactions from Europe to Africa and pointed out that this case indicates the potential risk of organized criminal groups infiltrating the solar panel recycling industry (INTERPOL, 2020). In 2022, Europol confirmed this assumption as several investigations revealed complex criminal schemes organised by European networks to collect WEEE from multiple countries and illegally ship them to Africa and Asia. Europol reiterated that as PV waste generation increases, the illegal trafficking of outdated solar panels is highly likely to rise in the near future (Europol, 2022). According to a white paper by Deutsche Umwelthilfe (German Environmental Aid), based on stakeholder consultations, a significant number of PV modules are illegally exported. However, reliable statistics on the scale of these exports are lacking. The paper also identifies key destinations for illegal exports, including Syria, Lebanon, North Africa, and Afghanistan—countries with relatively underdeveloped waste management systems (Deutsche Umwelthilfe, 2021).

The uncontrolled export of PV panel waste from the EU to third countries poses significant environmental and economic challenges. Many of these destination countries lack the infrastructure and capacity to process PV waste in an environmentally sound manner, leading to improper disposal, pollution, and potential health hazards. Additionally, these exports represent a lost opportunity for the EU to maximize reuse and recover valuable materials like silicon, silver, and aluminium, supporting the circular economy and reducing dependency on raw material imports.

5 CONCLUSIONS AND RECOMMENDATIONS

The results showed conclusively the rapid increase in PV waste to be expected within the next years independent on installation assumptions for future years. The Mid Scenario developed in Task 6.1. predicts PV waste of ~326 kt (~3,860 MW) for the year 2030, a 178-time increase (209-time increase in MW) compared to 2010. It furthermore hinted on strongly growing amounts of PV waste beyond the 2030 horizon of this project. Already the Low Scenario predicts annual PV waste of more than 200 kt with the High Scenario more than doubling this expectation. Furthermore, while these PV waste volumes will require special attention in any case, the trajectory and expected waste volumes beyond 2030, as showcased by various shape factors in the model, will rapidly increase, posing an even greater potential for resource recovery but also a potential strain on limited recovery infrastructure.

Most notably, the PV panels entering the waste stream in 2025 and in the following years originate from the 2000s and largely predate even the installation-peak observed in the EU from 2009 to 2012. This results in a more mixed waste stream of PV panels of all sizes and different technologies, as neither a clear leading segment nor a leading technology had been established. The Mid Scenario predicts that in 2025 the Multi-Si panels slightly dominate the PV waste stream with a weight share of ~54% (~51% MW-share). Nonetheless, a more varied assortment of panel-technologies can be found, with weight shares of mono-Si being 36% (39% MW-share), and Thin-film making up 10% (10% MW-share). A similar trend is observed when analysing the market segments (applications), which are currently skewed toward Utility-scale panels with a weight share of 49% of the total PV waste generated in 2025 in the reference region. This share is projected to decrease in the subsequent years (44% weight-share in 2030) while other segments are poised to increase their 2025 weight-shares of 25% (Commercial), 13% (Industrial), and (13% Residential) further by 2030. Therefore, as of now, no size is clearly and lastingly dominant within the within the EU27. However, as segments differ strongly in-between countries, resulting waste streams highly vary depending on the individual country which is assessed.

For developments beyond 2030, only reasonable assumptions can be made as of now and based on current model inputs. It is likely that the application- and technology-composition of more recently installed PV Panels will find their way into the waste stream only toward the end of 2030 or the beginning of the 2040, thus the impacts of the recent shift toward larger Utility-scale panels (44% weight-share of POM in 2025 within EU27) and the mono-Si technology (96% weight share of POM in 2025 within EU27) will not immediately be recognizable but display themselves gradually down the road. However, once these volumes enter the waste stream, they will dominate the waste stream for years to come. Nonetheless, with the introduction of new and promising technologies, the waste stream will diversify beyond these developments. As projected by the High Scenario, which assumes a shorter turn-over rate for Utility-scale panels and an optimistic installation rate, the novel tandem-PK/Si technology may be found in small quantities of around 2 kt already in the PV waste stream by 2030.

Going forward, future research shall focus on evaluating potential waste flows beyond 2030 and possibly to 2050 to enable long-term planning. Long lifetimes and high installation rates enable such usually more complex long-term predictions by building onto the model introduced in this report.

Furthermore, while currently an ability to recycle different technologies and PV panel sizes is required, the future might see a stronger focus on only few technologies and sizes. For 2030 and the proximate years after, the Mono-Si technology on Utility-scale panels will make up the bulk of the PV waste.

A detailed assessment of lifetime parameters across different technologies and applications is recommended because the lifetime variable has a strong impact on the stock driven model developed in the EVERPV project. The lifetime is influenced by multiple variables: policy incentives and interventions, financing schemes for large-scale installations, technological advancements, repowering needs, and the effects of climate change. More extreme weather conditions, for instance, can impact the durability of PV panels. Such variations should be incorporated into modeling frameworks like the one developed in the EVERPV project.

The generation of PV waste is increasing at a faster rate than its collection. In the EU-27 region, the average collection rate of PV waste has not exhibited substantial growth over the past five years, despite an estimated overall improvement of 3% annually in the period 2020-2025. Enhancing national collection rates is crucial to maximizing material recovery, facilitating the reuse of recovered materials as secondary raw materials, and reducing the EU's dependence on external sources for critical materials. Furthermore, inconsistencies and data gaps have been highlighted by project partners during the execution of Task 6.1 related to the data officially reported by the Members States to Eurostat. Data reporting should be enhanced and improved to enable the tracking of both commercial and residential PV waste collected.

Despite the increasing volume of PV installations and their eventual decommissioning, there is a significant lack of both quantitative and qualitative data on the export of waste PV panels from the EU to non-EU countries. While general statistics on waste exports exist, they rarely distinguish between different types of WEEE, making it difficult to assess the scale of PV waste exports specifically. Moreover, qualitative insights—such as the destination countries' handling practices, compliance with environmental regulations, and the potential for illegal shipments—remain largely unexamined. This data gap poses challenges for policymakers, industry stakeholders, and environmental regulators in ensuring that waste PV panels are properly recycled or disposed of rather than contributing to environmental harm in recipient countries.

The EU should mandate detailed reporting on PV waste collected and exports within existing WEEE tracking frameworks, requiring Member States and businesses to specify quantities, destinations, and treatment methods. Ideally, a publicly accessible database should be established at EU level to track PV waste flows, including data on exports, treatment facilities, and final disposal methods.

6 LITERATURE

Alves Dias, p., Plazzotta, B., Pavel, C. (2020). Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system. https://eitrawmaterials.eu/wp-content/uploads/2020/04/rms_for_wind_and_solar_published_v2.pdf.

Baldé, C. P., D'Angelo, E., Luda, V., Deubzer, O., & Kuehr, R. (2022). Global Transboundary E-waste Flows Monitor 2022. https://ewastemonitor.info/gtf-2022/

Baldé, C. P., Iattoni, G., Xu, C., & Yamamoto, T. (2022). Update of WEEE Collection Rates, Targets, Flows, and Hoarding-2021. https://www.scycle.info/new-study-update-of-weee-collection-rates-targets-flows-and-hoarding/

Baldé, C. P., Iattoni, G., Xu, C., & Yamamoto, T. (2021). Update of WEEE Collection Rates, Targets, Flows, and Hoarding. https://www.scycle.info/wp-content/uploads/2022/12/Update-of-WEEE-Collection_web_final_nov_29.pdf

Baldé, C. P., Wagner, M., Iattoni, G., & Kuehr, R. (2020). In-depth review of the WEEE Collection Rates and Targets in the EU-28, Norway, Switzerland, and Iceland. https://www.scycle.info/wp-content/uploads/2020/11/In-depth-review_WEEE-Collection-Targets-and-Rates_UNITAR_2020_Final.pdf

Deutsche Umwelthilfe e.V. and partners (2021). Strengthening circularity in photovoltaics Challenges and opportunities along the lifecycle - A white paper on strengthening the circularity of photovoltaics. https://www.duh.de/fileadmin/user_upload/download/Pressemitteilungen/Kreislaufwirtschaft/210310_White_Paper_Strengthening_Circularity_in_Photovoltaics_ENG_FINAL.pdf

Europol (2022). Environmental Crime in the Age of Climate Change - Threat assessment 2022. Publications Office of the European Union, Luxembourg. https://www.europol.europa.eu/publications-events/publications/environmental-crime-in-age-of-climate-change-2022-threat-assessment

Eurostat (2024). Waste electrical and electronic equipment (WEEE) by waste management operations - open scope, 6 product categories (from 2018 onwards). https://ec.europa.eu/eurostat/databrowser/view/env_waseleeos__custom_15922175/default/table?lang=en

Eurostat (2022). Waste electrical and electronic equipment (WEEE) by waste management operations. https://ec.europa.eu/eurostat/databrowser/view/env_waselee__custom_15356995/default/table

Forti V., Baldé C.P., Kuehr R. (2018). E-waste Statistics: Guidelines on Classifications, Reporting and Indicators, second edition. United Nations University, ViE – SCYCLE, Bonn, Germany.

Fraunhofer ISE (2024). Fraunhofer Photovoltaics Report. https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html

International Energy Agency (IEA) (2024). Status of PV Module Take-Back and Recycling in Germany 2024. https://iea-pvps.org/wp-content/uploads/2024/03/IEA-PVPS-T12-27-Report-PV-Recycling-in-Germany.pdf

INTERPOL (2020). INTERPOL STRATEGIC ANALYSIS REPORT: Emerging criminal trends in the global plastic waste market since January 2018. https://www.interpol.int/content/download/15587/file/INTERPOL%20Report%20_criminal%20trends-plastic%20waste.pdf

IRENA and IEA (2016). END-OF-LIFE MANAGEMENT: Solar Photovoltaic Panels. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf

Kastanaki, E. (2025). Dynamic assessment of photovoltaic waste streams in the EU-27 countries under the circular economy principles of 'Reduce, Reuse and Recycle'. https://www.sciencedirect.com/science/article/abs/pii/S0921344924006244

Kastanaki, E., Giannis, A. (2022). Energy decarbonisation in the European Union: Assessment of photovoltaic waste recycling potential. Renewable Energy, 192, 1 – 13. https://doi.org/10.1016/j.renene.2022.04.098

Magalini, F., Wang, F., Huisman J., Kuehr, R., Baldé K., v. Straalen, V., Hestin, M., Lecerf L., Sayman, U. and Akpulat, O. (2014). Possible measures to be initiated by the commission as required by article 7(4), 7(5), 7(6) and 7(7) of directive 2012/19/eu on waste electrical and electronic equipment (weee).

Nyffenegger, R., Boukhatmi, Ä., Radavičius, T., Tvaronavičienė, M. (2024). How circular is the European photovoltaic industry? Practical insights on current circular economy barriers, enablers, and goals. https://www.sciencedirect.com/science/article/pii/S0959652624008230

Peeters, J.R., Altamirano, D., Dewulf, W., Duflou, J.R. (2017). Forecasting the composition of emerging waste streams with sensitivity analysis: A case study for photovoltaic (PV) panels in Flanders. https://www.sciencedirect.com/science/article/pii/S0921344917300010.

Radavičius, T., Groesser, S. N., Tvaronavičienė, M. (2025). Assessment of constraints in the European Union photovoltaics circular supply chain for enhanced circularity. https://www.sciencedirect.com/science/article/pii/S0959652625000320

SolarPower Europe (2023): EU Solar Jobs Report 2023 – Bridging the solar skills gap through quality and quantity. https://www.solarpowereurope.org/insights/outlooks/eu-solar-jobs-report-2023#download

SolarPower Europe (2024). Mission Solar 2040: Europe's flexibility revolution. https://www.solarpowereurope.org/insights/thematic-reports/mission-solar-2040-1

Sultan, S.M., Abdullah, M.Z. (2022). A new method for assessing photovoltaic module cooler based on lifespan effectiveness factor. *Case Studies in Thermal Engineering, 35*, 102126.

Wiser, R., H Bolinger, M., Seel, J. (2020). Benchmarking Utility-Scale PV Operational Expenses and Project Lifetimes: Results from a Survey of U.S. Solar Industry Professionals. https://escholarship.org/uc/item/2pd8608q

Wolk-Lewanowicz, A., James, K., Huisman, J., Habib, H., Brechu, M., Herreras, L., & Chancerel, P. (2016). Assessment of Complementary Waste Flows - Deliverable 3.2

7 ANNEXES

7.1 Annex 1: Technology shares

Year	Mono-Si	Multi-Si	Thin-Film	Tandem-PK/Si
2000	0.43	0.47	0.10	-
2001	0.39	0.52	0.09	-
2002	0.42	0.51	0.07	-
2003	0.36	0.59	0.05	-
2004	0.31	0.63	0.05	-
2005	0.31	0.63	0.06	-
2006	0.35	0.57	0.08	-
2007	0.33	0.56	0.11	-
2008	0.35	0.51	0.14	-
2009	0.35	0.47	0.18	-
2010	0.28	0.62	0.09	-
2011	0.24	0.62	0.14	-
2012	0.25	0.65	0.10	-
2013	0.23	0.68	0.09	-
2014	0.25	0.67	0.08	-
2015	0.23	0.70	0.07	-
2016	0.24	0.69	0.06	-
2017	0.34	0.62	0.04	-
2018	0.44	0.52	0.04	-
2019	0.62	0.32	0.06	-
2020	0.80	0.15	0.05	-
2021	0.82	0.13	0.05	-
2022	0.94	0.03	0.04	-
2023	0.95	0.01	0.04	-
2024	0.95	0.01	0.04	-
2025	0.96	-	0.03	0.01
2026	0.92	-	0.03	0.05
2027	0.90	-	0.03	0.07
2028	0.90	-	0.03	0.07
2029	0.90	-	0.03	0.07
2030	0.87	-	0.03	0.10

7.2 Annex 2: Conversion factors

Year	Commercial	Industrial	Residential	Utility	Unit
2000	108,000	108,000	108,000	108,000	kg per MW
2001	106,000	106,000	106,000	106,000	kg per MW
2002	104,000	104,000	104,000	104,000	kg per MW
2003	102,000	102,000	102,000	102,000	kg per MW
2004	100,000	100,000	100,000	100,000	kg per MW
2005	98,000	98,000	98,000	98,000	kg per MW
2006	96,000	96,000	96,000	96,000	kg per MW
2007	94,000	94,000	94,000	94,000	kg per MW
2008	92,000	92,000	92,000	92,000	kg per MW
2009	90,000	90,000	90,000	90,000	kg per MW
2010	94,000	94,000	94,000	94,000	kg per MW
2011	91,000	91,000	91,000	91,000	kg per MW
2012	88,000	88,000	88,000	88,000	kg per MW
2013	86,000	86,000	86,000	86,000	kg per MW
2014	82,000	82,000	82,000	82,000	kg per MW
2015	80,000	80,000	80,000	80,000	kg per MW
2016	76,000	76,000	76,000	76,000	kg per MW
2017	76,000	76,000	76,000	76,000	kg per MW
2018	71,000	71,000	71,000	71,000	kg per MW
2019	70,000	70,000	70,000	70,000	kg per MW
2020	66,000	66,000	66,000	66,000	kg per MW
2021	65,000	65,000	65,000	65,000	kg per MW
2022	64,000	64,000	64,000	64,000	kg per MW
2023	64,000	64,000	64,000	64,000	kg per MW
2024	60,000	60,000	60,816	59,505	kg per MW
2025	59,194	59,194	59,739	58,779	kg per MW
2026	58,415	58,415	58,707	58,075	kg per MW
2027	54,461	54,461	53,552	54,472	kg per MW
2028	50,631	50,631	48,607	53,850	kg per MW
2029	46,919	46,919	43,861	53,246	kg per MW
2030	46,375	46,375	43,221	52,659	kg per MW

7.3 Annex 3: Installed capacity in 2030 – EU27

Installed Capacity	Low Scenario (MW)	in kt	Mid Scenario (MW)	in kt	High Scenario (MW)	in kt
Total	643,6	39,9	815,9	48,4	983,4	56,8
Applications						
Utility-scale	260,9	16	330,7	19,6	398,6	23,1
Residential-scale	136,1	8,3	172,5	10	208	11,8
Industrial-scale	100,3	6,3	127,2	7,6	153,3	8,9
Commercial-scale	146,3	9,2	185,5	11,2	223,53	13,0
Technology						
Mono-Si	524,3	31	686,7	39,4	841,2	47,3
Multi-Si	71,4	5,9	64,5	5,3	60,5	4,9
Tandem PK/Si	19,1	995	31,7	1,6	44,2	2,3
Thin-Film	28,8	1	32	2,1	37,4	2,3

Funded by
the European Union

Funded by the European Union under Grant Agreement No 101122208. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.