ReSiLex

D5.3 – Intermediate report on sourcing end-of-life PV panels in Europe

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Executive Summary

The amount of end-of-life PV panels is expected to grow exponentially from 2025, with a tipping point of its growing speed by 2035, corresponding to PV panels installed after 2010 reaching their end. PV panel waste in Europe is forecasted to go from around 50,000 To in 2025, to more than a million tons by 2050. This very rapid growth will force European countries to invest in very efficient treatment solutions. The recycling of critical materials such as silicon, silver or copper contained in PV panels could help Europe reach better independence in those elements against countries monopolizing the mining and manufacturing of these elements.

In the Europe-27, countries from western Europe are leading the way in terms of installed capacity, with Germany dominating at 81 GW installed. Nonetheless, rapid growth is expected in eastern European countries, especially Poland and Hungary.

Main European Countries

This first part analyzes the recent evolution of photovoltaic capacity in the nine countries with the largest photovoltaic installations in the 27-members European Union in 2024.
Each country is evaluated according to seven fundamental criteria: installed capacity, electricity production, regulatory aspects, trends, strengths, and challenges (*Table 1*).

Table 1: Ranking of EU countries according to installed photovoltaic capacity (2024).

Rank	Country	Installed Capacity (GW)
1	Germany	81
2	Spain	49
3	Italy	33
4	France	28
5	Netherlands	25
6	Poland	18
7	Greece	11
8	Belgium	9
9	Austria	7

1. Germany
   - Production: ~70 TWh (2023), continued growth.
   - Regulatory aspects: reform of the "EEG" (Renewable Energy Sources Act) facilitating self-consumption and storage.
   - Trends: strong push for residential and industrial installations.
   - Strengths: historical leadership, strong industry.
   - Challenges: network congestion, administrative slowness.

2. Spain
   - Production: ~50 TWh.
   - Regulatory aspects: end of the "sun taxed", encouragement to collective self-consumption.
   - Trends: growth of large solar parks without subsidies.
   - Strengths: high sunshine, land available.
   - Challenges: network integration, political volatility.

3. Italy
- Production: ~35 TWh.
- Regulatory aspects: simplification of procedures for residential installations.
- Trends: revitalization after post-2013 stagnation.
- Strengths: good solar potential, extended network.
- Challenges: administrative barriers, local acceptability.

4. France
- Production: ~20 TWh.
- Regulatory aspects: EPP ambitious but slow implementation.
- Trends: dynamic roofs and solar agriculture.
- Strengths: large territory, innovation.
- Challenges: slow tendering, nuclear dependence.

5. Netherlands
- Production: ~22 TWh.
- Regulatory aspects: stable support, net metering.
- Trends: residential roofs and agricultural greenhouses.
- Forces: efficiency, innovation.
- Challenges: network congestion, urban density.

6. Poland
- Production: ~13 TWh.
- Regulatory aspects: «Mój Prąd» program for private individuals.
- Trends: explosion of the residential sector.
- Strengths: public support, high demand.
- Challenges: dependence on coal, limited infrastructure.

7. Greece
- Production: ~9 TWh.
- Regulatory aspects: favorable policies and simplification of authorizations.
- Trends: strong growth of ground-based photovoltaics.
- Strengths: strong sunshine.
- Challenges: limited island network, slow connections.

8. Belgium
- Production: ~8 TWh.
- Regulatory aspects: decentralized support (regions).
- Trends: residential saturation, stability.
- Forces: high yield.

- Challenges: limited space, fiscal uncertainties.

9. Austria

- Production: ~5 TWh.
- Regulatory aspects: national and local subsidies.
- Trends: recent acceleration on buildings.
- Forces: political support, public awareness.
- Challenges: variable climate, strong seasonality.

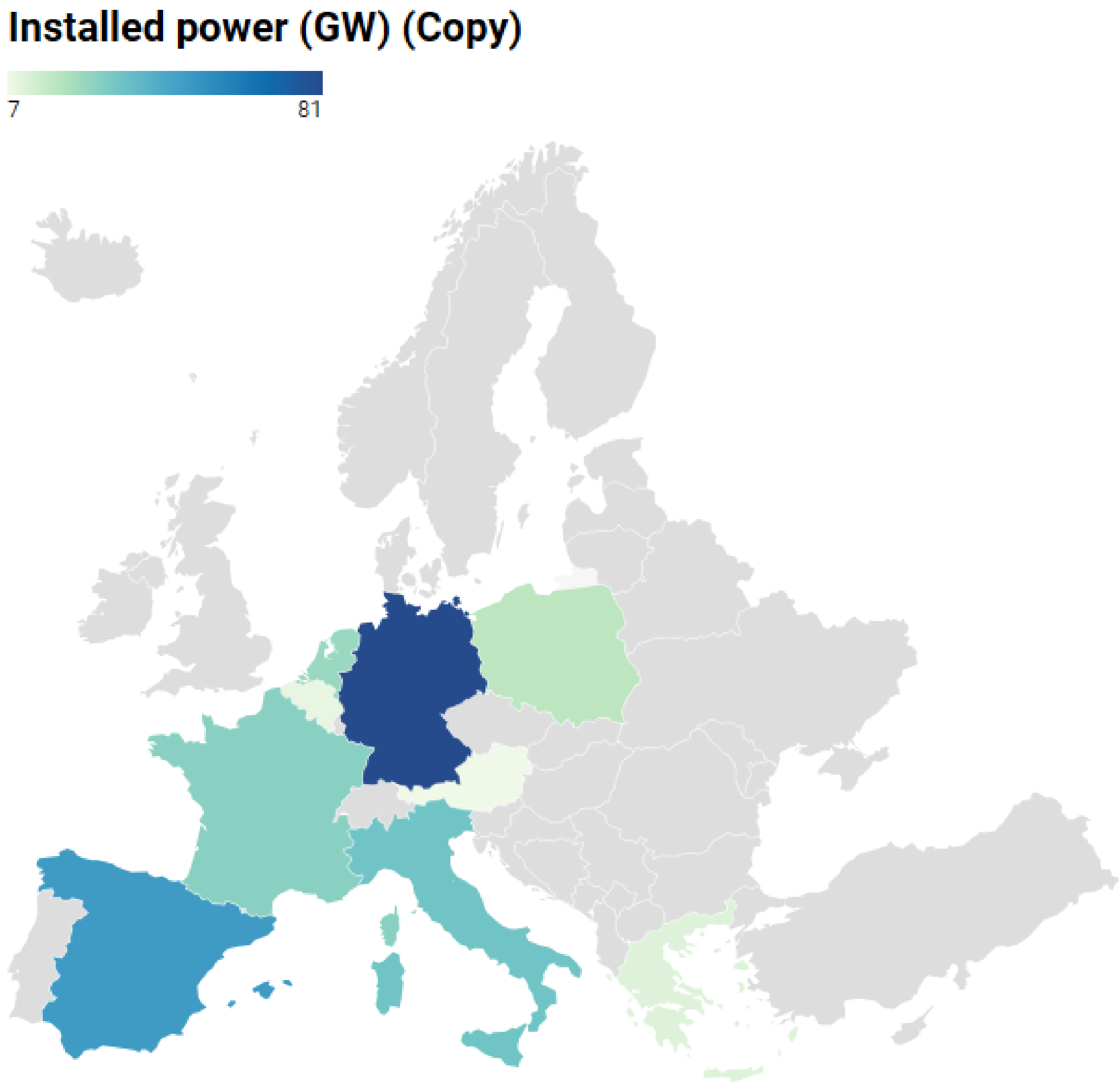


Figure 1: Power (GW) installed in Europe.

Strong acceleration of installations

- 2022: Around 41 GW of new capacity installed in the EU.
- 2023: The pace accelerated with 56 GW installed, a record.
- 2024 (estimated): Projections indicate an addition of 60 GW or more, according to SolarPower Europe.

Most dynamic countries

- Germany: Still a leader, it exceeded 80 GWh cumulated in 2023 and continues to grow with an ambitious target for 2030 (215 GW).
- Spain: Has experienced a strong development thanks to its sunshine and lower costs of installations. It is approaching 40 GW.
- Netherlands: Very successful despite their small size, with more than 20 GW in 2023, thanks to a policy that is very favorable to self-consumption.
- France: A slower but steady progression, with about 20 GW reached at the end of 2023.
- Italy: Investments have resumed, reaching about 30 GW, including measures to simplify procedures.

Key drivers of this growth

Energy crisis
Since 2022, Europe has seen an unprecedented acceleration in the development of solar electricity, directly linked to the energy crisis. This rapid transformation is due to several key factors.
The war in Ukraine has brutally exposed Europe's energy vulnerability, particularly its dependence on Russian gas. Faced with soaring energy prices and supply uncertainty, European governments have massively reoriented their policies towards renewable energies, with solar at the front line.
Photovoltaic installations have experienced record growth: the installed solar capacity in Europe increased by more than 40% between 2022 and 2024. Germany, Spain and Italy led the transformation, but Eastern European countries also accelerated their transition.
Government grants have been significantly strengthened. The REPowerEU plan has released more than €300 billion to accelerate energy independence, including a significant share for solar. At the same time, administrative simplification for panel installation has reduced deployment times.
Technological innovation has accompanied this transition: the efficiency of panels has improved while their cost has continued to decline, making solar competitive with fossil fuels even without subsidies in some regions.

Energy decentralization has also accelerated with the proliferation of local energy communities and the increase in the number of self-consumers. More than 3 million European households installed panels between 2022 and early 2025.
This positive dynamic has, however, faced challenges: problems of network integration, storage issues and dependence on Chinese imports for equipment. Europe has nevertheless responded by strengthening its local photovoltaic value chain.
The energy crisis has thus played the role of an unexpected accelerator of the European energy transition. Solar, once considered a back-up technology, is now at the heart of national energy strategies and the European energy sovereignty plan.

The REPowerEU Plan and the Solar Boom in Europe (2022-2025)

It accelerated the solar power in Europe. Launched in May 2022 in direct response to the energy crisis triggered by the Russian invasion of Ukraine, this ambitious plan has since become the central catalyst for development, radically transforming the European energy landscape.
At the heart of REPowerEU is the European Solar Strategy, which has set a target to install more than 320 GW of photovoltaic capacity by 2025 and 600 GW by 2030, more than doubling previous ambitions. To achieve this vision, the plan has mobilized more than €300 billion in funding, a substantial portion of which is specifically dedicated to solar infrastructure.
REPowerEU has introduced the European Solar Roofs Initiative, making the installation of solar panels mandatory on all new public and commercial buildings as well as on new residential constructions. This has led to an explosion of decentralized solar power, with more than 7 million new installations in three years.
Regulatory simplification has been a major lever: REPowerEU's renewable energy acceleration zones have drastically reduced the lead time for large-scale solar projects, from several years to a few months in many member states. This administrative acceleration has been decisive in attracting investment.
The plan also significantly strengthened European industrial resilience in the solar sector. Targeted subsidies and tax incentives have allowed a European PV manufacturing industry to revive, gradually reducing dependence on Asian imports which accounted for more than 90% of the market before 2022.
REPowerEU's focus on technological innovation has stimulated the development of energy storage solutions and smart grids, which are essential to manage solar intermittence. Research funding has accelerated the commercial deployment of advanced technologies such as perovskite-silicon tandem cells.
The social component of the plan, including the Climate Social Fund, has democratized access to solar energy for low-income households and small businesses, making solar a vector of energy inclusion and no longer only a technology reserved for the wealthiest.

The first results have been spectacular: the EU's solar capacity has increased by more than 50% since the launch of the plan, with record installations in almost all member states. Spain, Germany and Italy have doubled their installed capacity, while countries like Poland and Romania have seen their solar sector increase tenfold.
Beyond the installation figures, REPowerEU has fundamentally changed the perception of solar in Europe: from a backup solution, it has become a central pillar of energy security and European sovereignty, proving that a crisis can become an opportunity for deep and lasting transformation.

Administrative Simplification and the Rise of Solar in Europe (2022-2025)

Since 2022, administrative simplification has played a key role in dramatically accelerating the deployment of solar electricity in Europe. This regulatory overhaul, initiated in the context of the energy crisis, has removed the bureaucratic obstacles that have been holding back the expansion of photovoltaics for years.
The European directive on "Go-To Areas" (priority areas for renewable energies), adopted at the end of 2022, has revolutionized authorization procedures. These designated areas now benefit from an accelerated approval process with a maximum legal deadline of 6 months, compared to 2-5 years before. This measure has unlocked more than 1,000 large-scale solar projects that were stuck in the administrative maze.
The innovative principle of "silence is worth agreement", now applied in 18 European countries for small and medium-sized residential and commercial solar installations, has radically transformed the landscape: no response from the administration after 30 days, the authorization is automatically granted. This approach has boosted the number of solar rooftop installations by 70% in 2023-2024.
The dematerialization of procedures has also been decisive. The "one-stop-shop" digital portals set up in most Member States now allow all applications for authorization to be submitted via a single interface. Spain, a pioneer with its "Tramitación Acelerada Solar" system, has reduced the average authorization time by 85%, becoming the European leader in new installed capacity per capita in 2024.
The harmonization of technical standards at a European level has eliminated regulatory fragmentation, which forced developers to adapt their projects to each national jurisdiction. The European "Solar Technical Passport", introduced in 2023, guarantees mutual recognition of certifications between member countries, significantly reducing compliance costs.
For self-consumption projects, the abolition of pre-allowable authorizations for installations below 50kW in most European countries has triggered a real democratization of solar energy. In France, the simple declaration regime introduced in 2023 has tripled the number of individuals equipped with photovoltaic panels in less than two years.

The exemption from environmental impact assessments for installations on artificial surfaces (roofs, car parks, industrial wastelands) has also considerably accelerated the pace of urban and peri-urban deployments. This measure has converted more than 15,000 hectares of unused land into productive solar power plants.
Simplified power purchase agreements (PPAs) have benefited from a standardized and streamlined legal framework, facilitating direct agreements between solar producers and industrial consumers. This development has secured more than 40 GW of new solar projects across Europe without requiring public subsidies.
The results of this administrative revolution are eloquent: the average time to develop a solar project in Europe has increased from 4-5 years in 2021 to less than 18 months in 2025. This acceleration has enabled Europe to meet its installed solar capacity targets four years ahead of schedule.
This regulatory transformation demonstrates how administrative simplification, often overlooked in discussions on the energy transition, has been the most powerful catalyst for Europe's solar boom, proving that clear political will can remove bureaucratic barriers to innovation and investment in renewable energy.

Emerging trends

- Development of large sun parks in southern Europe.
- Strong increase in residential self-consumption (notably in Germany, the Netherlands and Belgium).
- Growth of battery storage associated with solar energy.

Forecasting of Photovoltaic Waste Flows

The second part presents the future waste streams from photovoltaic panels, based on past installations and evolution projections. It is based on the current European regulatory framework (Directive 2012/19/EU) and the methodologies developed within the RESiLEX project.

European regulatory framework

Directive 2012/19/EU on Waste Electrical and Electronic Equipment (WEEE) plays a key role in managing future waste streams from photovoltaic panels.

Explicit inclusion of photovoltaic panels

Directive 2012/19/EU specifically included photovoltaic panels in its scope, classifying them in category 4 (large equipment). This inclusion makes their collection, treatment and recycling under strict environmental standards mandatory.

The directive applies the EPR (Extended Producer Responsibility) principle to manufacturers and importers of photovoltaic panels, who must:

- Fund the collection and proper processing of end-of-life modules
- Meet specific collection and recycling targets
- Design products to facilitate their dismantling and recovery

Anticipation of a growing waste stream

The first large-scale photovoltaic panels installed in the years 2000-2010 will reach their end of life in the next few years (average lifetime of 25-30 years). The Directive prepares the necessary infrastructure to deal with this growing volume of waste.
Recovery and recycling objectives
The directive imposes minimum rates of recovery (85%) and recycling/preparation for reuse (80%) specific to photovoltaic panels, promoting circular economy and recovery of valuable materials such as silicon, silver and glass.
This legislation therefore constitutes a structuring framework to accompany the transition towards sustainable management of photovoltaic waste in the European Union, anticipating the significant increase of these flows in the coming years.

Modelling methodology

Flows are modelled based on average panel life, growth scenarios, and cumulative installation data. The results allow us to anticipate the volumes to be recycled by 2050.

Modelling results

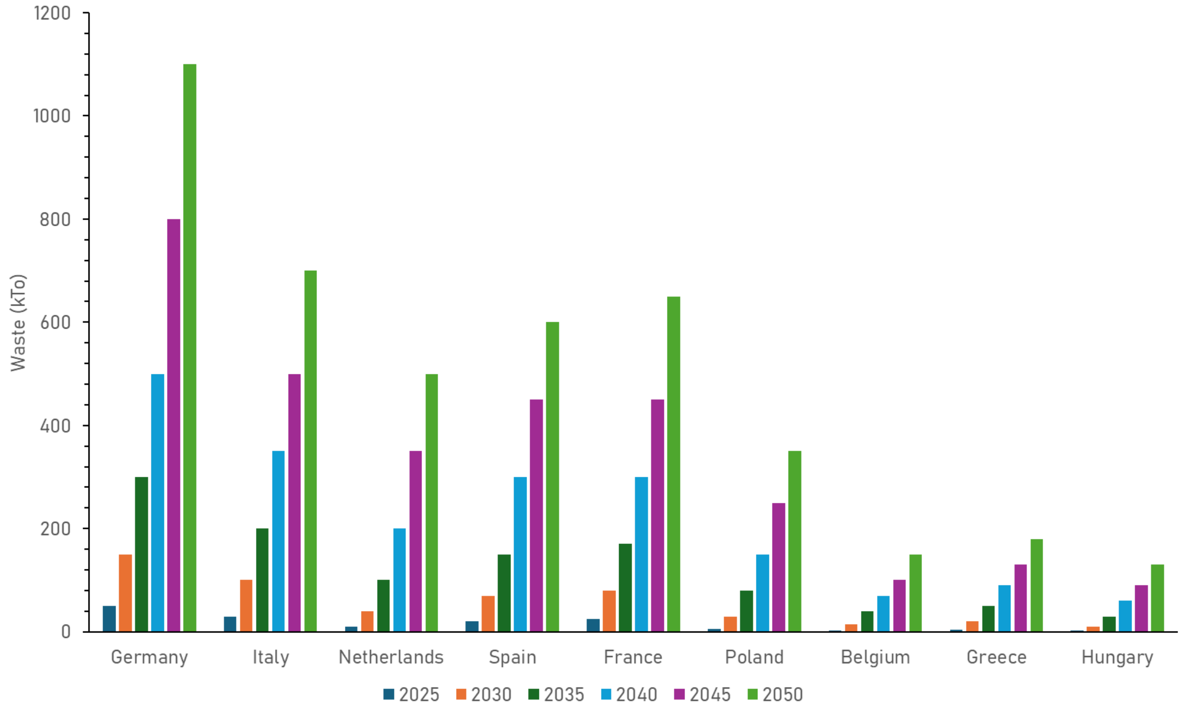
Projection of Photovoltaic Waste Flows (2025–2050)

End-of-life projections for photovoltaic panels are based on their average lifetime (25 to 30 years) and the volumes installed between 2010 and 2025. PV waste streams are expected to grow exponentially between 2035 and 2050 (*Table 2* and *Figure 2*).

Table 2: Estimated in kilotons (kTo) of accumulated waste by country 2050.

Country	2025	2030	2035	2040	2045	2050
Germany	50	150	300	500	800	1100
Italy	30	100	200	350	500	700
Netherlands	10	40	100	200	350	500
Spain	20	70	150	300	450	600
France	25	80	170	300	450	650
Poland	5	30	80	150	250	350
Belgium	3	15	40	70	100	150
Greece	4	20	50	90	130	180
Hungary	2	10	30	60	90	130

Figure 2: Estimated accumulated waste (kTo) by country between 2025 and 2050.



Key trends:

- The estimated tipping point is around 2035, with a rapid increase due to the end of life of modules installed after 2010.
- Germany leads the world in absolute volume with more than one million tons expected by 2050.
- Rapid growth is expected in Eastern Europe, particularly in Poland and Hungary, due to recent high-speed facilities.
- These flows represent both a logistical challenge and a major industrial opportunity for the creation of recycling and recovery chains of critical materials.

Economic and technical issues

The recycling of PV modules poses significant technical challenges (glass, silicon, rare metals) and requires investments in robust industrial sectors.

Economic issues

Growing volume of waste to manage

- The first large-scale installations of the 2000s gradually reaching the end of their life.
- Forecast of around 35,000 to 50,000 tons of photovoltaic waste in Europe in 2025, with a significant acceleration expected after 2030.

Opportunities for value creation

- Recovery of precious materials (silver, high purity silicon, glass, aluminum).
- Estimated value of the European PV recycling market: 80-100 million euros in 2025.
- Job creation in the dismantling and recycling sector.

Significant logistical costs

- Transport and collection of geographically dispersed panels.
- Need for an efficient network of collection points.
- Fragile economic balance between processing costs and value of recovered materials.

International competition

- Competition with Asian players on the recovery and valorization of strategic materials.
- Issue of European sovereignty over critical raw materials.

Technical issues

Complexity of processing

- Heterogeneity of technologies (crystalline silicon vs. thin films)
- Presence of polymer encapsulants that are difficult to separate from valuable components.
- Fine separation of glass, metals and semiconductors requiring specific processes.

Development of efficient industrial processes

- Optimization of material recovery rates.
- Automation of dismantling lines to reduce costs.
- Achievement of regulatory objectives (80% recycling/reuse).

Adapting to new technologies

- Arrival of new generations of panels (bifacial, heterojunction, tandem).
- Increasing presence of complex materials requiring new separation processes.

Standardization of methods

- Harmonization of treatment processes at European level.
- Implementation of common certifications and standards.
- Traceability of recycled material flows.

These challenges are part of a broader European strategy of transitioning towards a circular economy and reducing dependence on imports of critical raw materials, while respecting the ambitious objectives set by the WEEE Directive.

Industrial opportunities

The rise of PV waste flows opens major industrial prospects: creation of recycling sectors, sovereignty over critical materials, innovation in upcycling, etc.
The expected growth of photovoltaic waste streams in Europe represents a challenge but also a source of considerable industrial opportunities. This analysis explores the major prospects opening at the European level.

Creation of innovative recycling channels

Development of a specialized industrial infrastructure

- Emergence of processing units dedicated to photovoltaic panels in several European countries (France, Germany, Spain, Italy).
- Potential creation of 3,000 to 5,000 direct jobs in the sector by 2030.
- Development of technological expertise centers around existing industrial hubs.

Opportunities for specialized SMEs and startups

- Creation of innovative solutions for the dismantling and sorting of components.
- Development of exportable European proprietary technologies.
- Emergence of an ecosystem of specialized companies (reverse logistics, recovery, reconditioning).

Integration into the European circular economy

- Synergies with other already structured WEEE sectors.
- Implementation of shared platforms optimizing logistics and processing.
- Development of public-private partnerships to finance the necessary infrastructure.

Strengthening sovereignty over critical materials

Securing strategic supplies

- Recovery of high-purity silicon (up to 16,000 tons/year by 2030).
- Extraction of precious and critical metals (silver, copper, gallium, indium).
- Reducing dependence on Asian imports of raw materials.

Creation of a closed production loop

- Reintegration of recycled materials into the manufacture of new panels.
- Development of European standards for secondary materials.
- Reducing the carbon footprint of the photovoltaic industry.

European competitive advantage

- Development of high value-added processes protected by patents.
- Promoting "Made in Europe" for panels with recycled content.
- Anticipated compliance with new environmental regulations.

Innovation in upcycling and eco-design

New applications for recycled materials

- Valorization of photovoltaic glass in construction applications.
- Use of reconditioned silicon wafers in other electronic applications.
- Development of composites incorporating materials from PV recycling.

Design for dismantling

- Collaboration between recyclers and manufacturers to improve recyclability.
- Integration of end-of-life constraints from the design stage of the panels.
- Development of modular panels facilitating repair and partial replacement.

Innovative business models

- Growth of “Product as a Service” for photovoltaic installations
- End-of-life deposit and return systems
- Certification and traceability of recycled materials creating added value

Conclusion

The rise of photovoltaic waste streams represents a strategic opportunity for Europe to develop a high value recycling industry, strengthening its self-sufficiency in critical materials and stimulating innovation in the circular economy. However, this transformation requires significant investment and coordination at the European level to achieve critical mass and sustainable economic profitability.

The year 2024 confirmed the exceptional momentum of photovoltaic deployment within the EU-27, with installed capacity now exceeding 300 GW, representing an annual growth of nearly 18% compared to 2023. This acceleration, supported by the ambitious objectives of the REPowerEU plan and the Green Deal, positions Europe as a major player in the global energy transition. Germany, Spain, the Netherlands, France and Italy remain the main contributors to this expansion, although Central and Eastern European countries now show the highest growth rates, demonstrating a democratization of this technology across the continent.

This rise in photovoltaic installations is inevitably accompanied by the challenge of managing end-of-life equipment. Projections updated in 2024, based on methodologies developed within the framework of the RESiLEX project, anticipate a volume of photovoltaic waste of around 45,000 to 60,000 tons for the year 2025, with an exponential increase expected to reach 200,000 tons annually by 2030 and more than one million tons by 2040. This increase reflects not only the arrival at the end of the life of the first generations of large-scale installations, but also the early replacement of still functional panels by more efficient technologies, a phenomenon of "repowering" now significant in the estimates.

Directive 2012/19/EU on Waste Electrical and Electronic Equipment provides the essential regulatory framework for this management. Its explicit inclusion of photovoltaic panels and the application of the principle of extended producer responsibility have created the necessary conditions for the emergence of a European industrial recycling sector. The ambitious recovery (85%) and recycling/preparation for reuse (80%) targets set by this directive have stimulated technological innovation and investment in appropriate processing capacities.

The methodological advances of the RESiLEX project have also made it possible to refine the modeling of future flows and optimize collection and processing strategies on a European scale. The precise characterization of the different technological generations and the analysis of their composition have led to a better anticipation of the recovery potential of critical materials, estimated at several thousand tons of high-purity silicon, silver, and other strategic metals by 2030.

This convergence between the massive deployment of photovoltaics and the structuring of a European waste treatment sector represents a large-scale circular economy model. It illustrates Europe's ability to transform an environmental challenge into an industrial opportunity, simultaneously contributing to its energy sovereignty and strategic autonomy in raw materials. National eco-organizations, now coordinated at the European level, play a pivotal role in this organization, ensuring traceability and cost sharing.

The next decade will be crucial in consolidating this positive momentum. It will require sustained investment in collection and processing infrastructure, increased harmonization of practices between member states, and continued support for technological innovation. The gradual integration of eco-design criteria into European regulations should also facilitate the dismantling and recovery of future generations of panels, further strengthening the circularity of this strategic sector for the continent's decarbonization.

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