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Circular Economy Strategies for the EU's Renewable Electricity Supply

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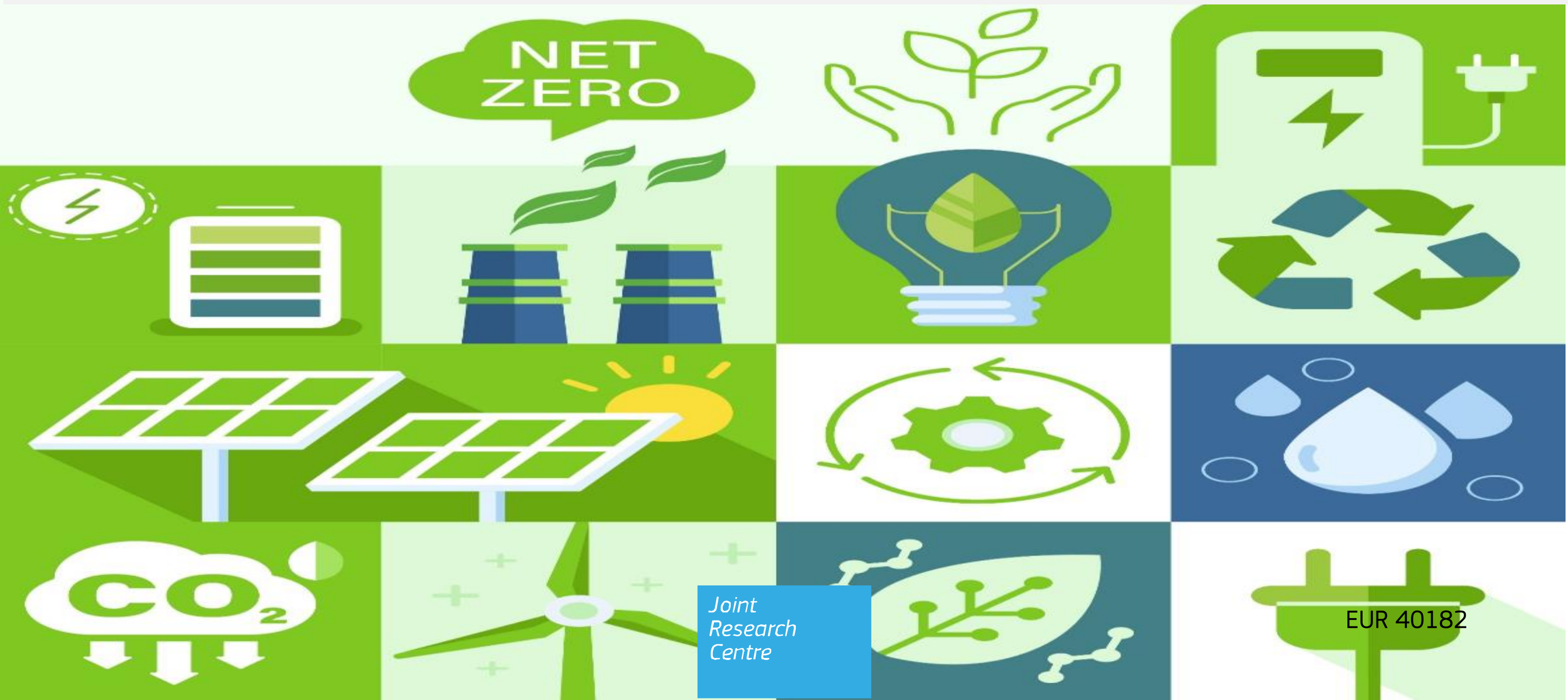

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Contents

Abstract

Circular Economy Strategies for the EU's Renewable Electricity is a Joint Research Centre (JRC) exploratory study that provides a new perspective and new evidence on waste streams emerging from the transition to renewable electricity in the EU. The analysis supports the policy-making process and the JRC's research on clean energy technologies implementing the European Green Deal, 2030 Climate and Energy Framework, Renewable Energy Directive, and the Waste Framework Directive. The report summarises the available information on the topic (technologies, waste streams, relevant literature and data, and technical, economic and information challenges). The clean energy technologies contain substances covered by the Critical Raw Materials Act; although the report does not focus on the permanent magnets and rare earth minerals associated with renewable energy, mostly wind turbines. Instead, the report highlights potential priority waste streams such as steel, cement and silicon. It provides a strategic assessment highlighting the rapid increase of wastes driven by the energy transition's demand for technologies and infrastructure to replace fossil fuel infrastructures. Policy-relevant strategies to address gaps in regulation and research are highlighted. The report demonstrates that future waste volumes from solar and wind electricity generation in the EU are complex and will be generated in far greater quantities and at different rates than previously estimated. In addition, the report quantifies the waste footprint of decommissioning fossil fuel electricity plants.

Key words: circular economy, emerging wastes, electricity supply, solar, wind, fossil fuel, decommissioning, Green Deal, Net-Zero Industry Act, Renewable Energy Directive

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The authors would like to thank Christophe Schuman for his input to the literature review, David Klenert for his review of an early draft, Nacef Tazi for his input to the workshop discussion paper, Erika Pierri for acting as Rapporteur for the CEPRES Workshop on 5, December 2023, and Nigel Taylor for his helpful review, which improved the quality of the report. The authors are grateful to the co-lead of CEPRES, Fabrice Mathieux of JRC D3, for his careful review and insightful comments.

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Executive Summary

The European Union (EU) is committed to converting its electricity supply system from fossil fuels to mostly low- and net-zero-energy sources. This shift necessitates a substantial overhaul of infrastructure. The transition also involves decommissioning materials from fossil-fuel-based electricity production. The Joint Research Centre (JRC) has carried out the Circular Economy Pathway for Renewable Electricity Supply (CEPRES) project to tackle the waste management challenges of this transition. CEPRES is a collaborative effort that aligns with the European Green Deal, the Circular Economy Action Plan, the REPowerEU Plan, the Critical Raw Materials Act, and the Net-Zero Industry Act, aiming to estimate future waste volumes and address technological, economic and regulatory barriers to circularity.

The waste streams from decommissioning obsolete technologies and obsolete fossil fuel plants represent a source of useful materials if recycled. Therefore, the "Circular Economy Strategies for Europe's Renewable Electricity Supply" (Strategies Report) takes a comprehensive view of the electricity system in transition, rather than specific products. The report sheds light on new large-volume wastes and problematic wastes.

Research Questions

The main chapters focus on waste from wind turbines, solar panels, and fossil-fuel plants, answering the same research questions and following the same structure. The research questions are as follows:

- What technologies, infrastructures, and materials are driving the waste streams that require a circular economy perspective?
- Can all renewable electricity supply waste be recycled?
- How much waste will there be in future?
- What policies are needed to increase circularity?

Each waste stream presents a different conundrum that is addressed in this report. Also, policy-relevant strategies to address gaps in regulation and research are raised.

Results and policy strategies

Waste from Wind Power

Large-volume waste from wind turbines present a particularly challenging key component, wind turbine blades. Blades are large-volume and have limited commercial-scale recycling and reuse possibilities. Therefore, the chapter discusses components of wind turbines and focuses on the issue of blade waste estimation and management.

The net capacity of wind energy installed in 2050 is predicted to be around 860 GW. If all wind turbines are assumed to be 10 MW machines, there will be 86,000 turbines.

The chapter discusses strategies for improving blade waste management. Policy strategies include:

- Improved data collection for installation and decommissioning of wind turbines to better fore see waste volumes;
- Creating common waste codes;
- Tracking the fate of materials after decommissioning to support reuse and repurposing business models; and

- Considering an extended producer responsibility scheme for turbines.

Waste from Solar Photovoltaics

The solar photovoltaic chapter offers a detailed bottom-up analysis of materials in PV panels that result in large-volume waste. Dedicated PV recycling processes are capable of recovering valuable materials like silver and silicon. However, economic barriers such as the high costs of collection and processing hinder the development of widespread commercial-scale recycling.

PV waste volumes will rise significantly as the EU has just increased its aim for renewable energy deployment to 42.5% from 32.5% by 2030. Compared to the 135 GW deployed in total by 2020, the total installed PV capacity in the EU-27 in 2022 reached 200 GW, a rise of 50% in just 2 years (IRENA 2022). The EU will amass 6-13 MT of PV waste by 2040 and 21-35 MT of PV waste by 2050.

Challenges and policy strategies discussed in the chapter include:

- The possibility of recycling targets focused on economic value of materials;
- Improving recyclability of PV modules and inverters through design regulation;
- Measures to better understand and promote PV reuse including certification requirements, safety measures, and warranty

Waste from Fossil Fuel Power Plant Decommissioning

The chapter on decommissioning estimates large-volume waste streams due to fossil fuel power plant closures. The main challenge is creating a method to estimate the composition of the waste stream. This new analysis applies material intensities at the construction phase to the decommissioning of fossil fuel power plants in the EU.

The Strategies Report estimates that significant quantities of steel at 5.6 million tonnes, concrete at 23.54 million tonnes, copper and aluminium are contained in decommissioned fossil fuel power plants, cumulatively between 2014 and 2023 (medium scenario).

The results guide policy strategies raised in the report including:

- Pre-demolition planning;
- Guidance and knowledge sharing on repurposing and reuse of materials; and
- Surveying locations and materials for better EU-wide future planning.

A Multi-sector Waste Challenge

Each of the three sectors investigated have unique technologies, value chains and waste streams. Nevertheless, there are similarities, including the limited direct observation of waste stream management in these sectors, for example on reuse. The CEPRES estimations rely on assumptions about the large volume waste materials deployed based on type of units deployed over time, lifetime of equipment, available treatment options, and recovery rates.

The Strategies Report estimated the cumulative amount of materials available for recycling in the three waste streams by 2023. This highlights how much materials would be lost without recycling. For example, 6.2 MT of steel, aluminium, and copper are estimated waste available for recycling in the three sectors as shown in Table A. The time frames are different for each sector because they were rolled out and decommissioned in different eras and available data varies. The data for decommissioned power plants is collected for 2014 to 2023. For a general comparison of scale to other significant electricity supply wastes, Eurostat's 2021 estimate of cumulative collected waste portable batteries and accumulators (all materials) between 2012 and 2021 is 0.83 MT.[1]

Up to now, only a small percentage of photovoltaic and wind turbines have retired, while the opposite is true for fossil fuels plants, particularly coal.

In the coming decades, the contribution of waste materials from PVs and wind will be far greater. The synthesis of data for solar power and wind power indicates that in 2050, wind power will generate an annual volume of bulk material waste higher than solar power.

Table A. Estimated cumulative decommissioned large volume waste materials by 2023

Estimated cumulative decommissioned large volume waste materials by 2023 in the transition from fossil fuels to renewable electricity generation (tonnes)				
Materials	Photovoltaics (regular loss conservative scenario)	Wind Turbines	Coal, Gas & Oil Plants (medium scenario)	Tonnes ±2014 – 2023
Steel	10,940	274,194	5,611,000	5,896,134
Aluminium	20,510	3,226	139,000	162,736
Copper	3,763	1,120	172,000	154,883
Total Tonnes				**6.2 MT**

The findings emphasise the need to focus attention on recyclable materials markets related to the transition from fossil fuels to renewables, in light of the Net-Zero Industry Act.

This report contributes to the groundwork for informed waste policy-making that supports a more sustainable and circular electricity supply system in the EU.

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[1] Source: Eurostat: https://doi.org/10.2908/ENV_WASPB

1 Introduction

1.1 Achieving a renewable and circular electricity supply

The EU (European Union) is accelerating the transition of the electricity supply system from fossil fuels to renewables including onshore and offshore wind, solar photovoltaics, hydropower, and others as per the 2030 Climate and Energy Framework.[2,3] The JRC exploratory activity and study "Circular Economy Pathway for Renewable Electricity Supply (CEPRES)" delves into the waste management challenges and waste streams emerging waste from this transition.

Circularity in the electricity supply is important because the transition necessitates a massive shift in infrastructure, requiring the deployment of materials for renewable electricity production and supply to homes and industry. The transition also entails the decommissioning of materials that were dedicated to fossil-fuel-based electricity production. Decommissioning fossil fuels generates wastes that are rarely highlighted in the forward looking policy debate. These materials are needed by the EU economy and future renewable electricity supply. Materials for renewable electricity supply include those contained in electricity generation equipment, buildings, transmission equipment, substations, storage units, grid expansions and connections, for example. The scope of materials employed in the renewable electricity supply is large, including concrete; asphalt; various grades of iron and steel; aluminium; copper; nickel; glass; silver and other precious metals; plastics; fibreglass; many critical raw materials such as silicon, cobalt, lithium and rare-earth elements; and carbon-blended metals (Carrara, Bobba et al. 2023).

Although critical raw materials (CRMs) such as platinum and rare earth elements receive significant policy and research attention, they represent a very small percentage (by weight) of future material flows associated with renewable electricity. The recent inclusion of aluminium on the list of CRMs extends the concept beyond the trace metals often indicative of CRMs.[4] **In the main,** raw materials for renewable electricity (by weight) are not critical, rare or particularly "high-value" per tonne. Thus, recycling these materials for secondary materials remains challenge in the EU today.

Emerging wastes - The transition to renewable electricity supply is creating new and emerging waste streams that will grow significantly in terms of volume over time**.** The first wave of decommissioning of solar panels and repowering wind farms is already happening because newer and more efficient technologies are starting to drive replacements (Majewski, Florin et al. 2022). Until today, the focus of circular economy (CE) policy and business models has been on the recovery, reuse and recycling of materials from waste, bringing these materials into secondary materials markets. As a result, gross demand for primary resource extraction is expected to be lessened. The majority of JRC research in this area has focused on material demand for low-carbon technologies, particularly for CRMs. The JRC has also studied the circularity of CRMs in selected technologies (Mathieux, Ardente et al. 2017), including in batteries (Bobba, Mathieux et al. 2019, Latini, Vaccari et al. 2022) and in PV panels (LATUNUSSA, MANCINI et al. 2016). There are many in-depth JRC projects on material demand aspects that focus so far on the recovery of trace metals and on the quality of alloys. As an example, the JRC is currently finalising the technical

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[2] https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2030-climate-energy-framework_en

[3] The current discussion paper assumes prior knowledge of the relevant policies and objectives of the Commission, including REPowerEU, the Fit for 55 Package, the Raw Materials Initiative, the "Green Deal Industrial Plan for the Net-Zero Age, the Critical Raw Materials Act, the Waste from Electrical and Electronic Equipment (WEEE) Directive, and the Waste Framework Directive.

[4] https://www.consilium.europa.eu/en/press/press-releases/2023/11/13/council-and-parliament-strike-provisional-deal-to-reinforce-the-supply-of-critical-raw-materials/

recommendations for calculating recycling efficiency and material recovery level targets in the context of Article 71 of the 2023/1542 Battery Regulation.[5] In contrast, CEPRES applies a systems perspective to the entire renewable electricity supply system and attempts to estimate the scale of recovery and recycling needed to “close the loop” for a wider range of materials (wastes) spurred by the transition. CEPRES highlights the importance of a CE perspective for large-volume wastes in addition to trace metals.

The CEPRES literature review demonstrates that waste estimates are not currently available for all components of the renewable electricity system for a variety of reasons. Therefore, CEPRES seeks to identify the gaps in our current knowledge and develop a better understanding of important emerging waste streams.

1.1.1 CEPRES project objectives

CEPRES is the result of a collaboration between three JRC units: B5 Circular Economy and Sustainable Industry; C6 Economics of Climate Change, Energy and Transport; and D5 Land Resources and Supply Chain Assessments; in addition to two external experts. The JRC’s multi-unit representation in CEPRES indicates the crosscutting nature of the CEPRES topic.

CEPRES’ goal is to further CE by exploring future waste volumes (identifying and addressing data gaps) and technological, economic and regulatory barriers to circularity including the product dimensions of the renewable electricity supply system. The main objectives are to:

- highlight the European Commission policies that influence the circular management of renewable electricity supply, with respect to waste prevention, reuse and recycling;
- develop a comprehensive circular economy concept for electricity supply;
- identify priority waste streams created by renewable electricity supply infrastructure;
- identify priority waste streams created by fossil fuel electricity supply infrastructure decommissioning; and
- provide updated estimates of the volumes and types of wastes from new and obsolete infrastructure.

This Strategies Report is the major deliverable of CEPRES. Section 2 explains the current policy domain and why research on CE for renewable electricity is timely and relevant. This section integrates the conceptualisations of sustainability agreed upon by the Commission as defined in key policy documents, including the European Green Deal, the Circular Economy Action Plan, the REPowerEU Plan, and the February 2024 Net-Zero Industry Act's (NZIA) other strategic objectives. Section 3 summarises the research questions of the Strategies Report. It also explains the scope of CEPRES as a complex system of interconnected technical and regulatory regimes. Section 3 also presents the relevant academic literature and highlights previous JRC work. Section 4 focuses on wind power waste. Section 5 focuses on solar power waste. Section 6 focuses on waste streams from fossil fuel plant decommissioning. Section 7 discusses the results and presents the conclusions of the CEPRES Strategies Report.

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[5] JRC, ‘JRC Technical guidance proposals for the methodology for calculation and verification rules of rates for recycling efficiency and recovery of materials of waste batteries’, Draft report, 2024.

2 Policy context and legal framework

The policy context and legal framework and the positive economics of alternatives to fossil fuels are driving the uptake of renewable electricity projects across the EU. The **European Green Deal (EGD)'s** main environmental goal, as incorporated in the **European Climate Law**, is to become the world's first climate-neutral continent.[6] The legally binding European Climate Law sets the "new target for 2030 of reducing net greenhouse gas emissions by at least 55% compared to levels in 1990" (European Parliament 2021).[7] In addition, the EU **Renewable Energy Directive** is set to increase the share of renewables in energy consumed to 42.5%aim of reaching 45%). **REPowerEU** is the European Commission's plan to make the EU independent from Russian fossil fuels well before 2030, considering Russia's invasion of Ukraine, while still meeting the "Fit for 55" objectives. REPowerEU's main strategies are to diversify supply, to enhance energy savings and to accelerate the transition to clean energy. The **Fit for 55 package** includes revised and new EU legislation to deliver the EU's target of reducing net greenhouse gas emissions by at least 55% by 2030. In summary, recent EU-level initiatives and legislation have raised the bar for climate change mitigation and adaptation with a wide range of targets affecting most economic sectors from aviation, buildings and transport to shipping and many more.

Furthermore, the February 2023 **Green Deal Industrial Plan for the Net-Zero Age "**complemented by the 2024 **Critical Raw Materials Act**, [aims] to ensure sufficient access to those materials, like rare earths, that are vital for manufacturing key technologies, and the reform of the electricity market design, to make consumers benefit from the lower costs of renewables" (Commission) 2023). Net-Zero is a political commitment. The scientific concept "net zero" means "anthropogenic flows to and from the atmosphere to balance on aggregate. This necessitates a radical reduction in fossil-fuel- and land-use-related carbon emissions as well as an increase in geological and biological sinks" (Fankhauser, Smith et al. 2022). A conceptual view of achieving net zero is shown in Figure 1. The Green Deal Industrial Plan links the above-mentioned initiatives. It states that "The European Green Deal sets in stone our green transition ambitions, including our climate targets towards net-zero by 2050. The Fit for 55 package provides a concrete plan to put the EU an economy firmly on track, with the REPowerEU Plan accelerating the move away from fossil fuels. Alongside the **Circular Economy Action Plan (CEAP)**, this sets the framework for the transformation of the EU's industry for the net-zero age" (Commission 2023).[8]

In summary, the use of renewable technologies to supply electricity as the main energy carrier to reach climate neutrality is endorsed by the EU. This direction is made clear with the **Net-Zero Industry Act**, which is now in force. The regulation (EU) 2024/1735 on establishing a framework of measures for strengthening Europe's net-zero technology manufacturing ecosystem was approved by the European Parliament and of the Council and published on June 28, 2024. Prior to the Net-Zero Industry Act coming into force, the revised EU Renewable Energy Directive came into force in November 2023, setting targets to increase the share of renewables in energy consumed.

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[6] The European Green Deal - European Commission (europa.eu)

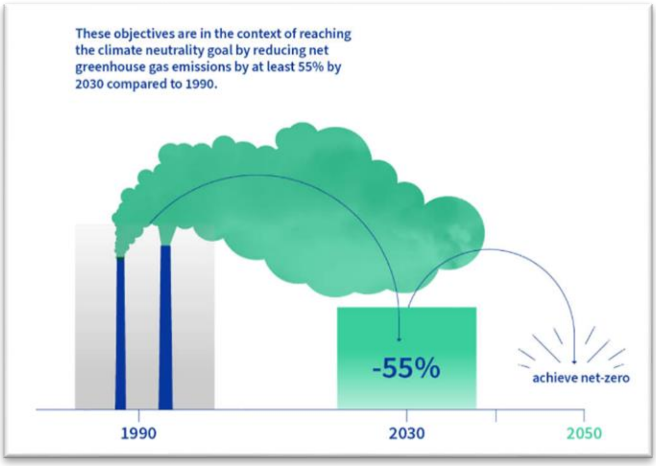
[7] https://climate.ec.europa.eu/eu-action/european-climate-law_en

[8] Green Deal Industrial Plan for the Net-Zero Age

EUR-Lex - 52023DC0062 - EN - EUR-Lex (europa.eu)

At this watershed moment, this CEPRES Strategies Report contributes to the groundwork for estimating the wastes from renewable electricity, starting from the new baseline of the Net-Zero Industry Act and the Renewable Energy Directive.

Figure 1: A conceptual view of achieving net zero.



Source: https://www.consilium.europa.eu/en/infographics/net-zero-industry-act/

With a view to gauging the consequences of the transition, the JRC takes a closer look at how the overarching objectives of the EGD (European Green Deal) intersect and diverge with the CEAP's objectives. The Commission's ambitions under the EGD are to:

- achieve climate neutrality / reduce greenhouse gases;
- realise economic growth decoupled from resource use; and
- leave no person and no place behind.

The CEAP's ambitions under the EGD umbrella are to:

- increase the contribution of recycled materials to raw materials demand;
- make sustainable products the norm in the EU;
- focus on the sectors that use most resources and where the potential for circularity is high such as: electronics and ICT, batteries and vehicles, packaging, plastics, textiles, construction and buildings, food, water, and nutrients;
- empower consumers and public buyers;
- make circularity work for people, regions, and cities;
- ensure less waste; and
- lead global efforts on circular economy.

How are the CEAP's objectives implemented in the Net-Zero Industry Act? The Net-Zero Industry Act (NZIA) is the most recent statement of intent for the transition to a renewable electricity supply in EU countries under the EGD.[9] As such, we observe that although the NZIA does

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[9] Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on establishing a framework of measures for strengthening Europe's net-zero technology products manufacturing ecosystem (Net Zero Industry Act)- Letter to the Chair of the ITRE Committee of the European Parliament

not reference the CEAP, it does elaborate on the already established concept of a ‘circular’ energy system and the text applies CEAP principles and objectives by inference. This is an important clarification, applying circularity in the contexts of specific net-zero technologies, procurement criteria, manufacturing processes and training. These references to circularity principles in the NZIA are informative and are highlighted below.

- **Circularity for specific technologies -** “To remain competitive and circular whilst reaching their decarbonisation and zero pollution goals, these industries need access to net-zero technologies such as batteries, heat pumps, solar panels, electrolysers, fuel cells, wind turbines, and carbon capture and storage.”
- **Procurement criteria may include circularity** - “When considering the environmental sustainability of bids, either in the form of pre-qualification criteria or award criteria, public authorities designing auctions for the deployment of energy from renewable sources may consider various elements with an impact on the climate and the environment. These may include, for instance, the durability and reliability of the solution; the ease of repair and maintenance and access to such services; the ease of upgrading and refurbishment; the ease and quality of recycling; the use of substances; the consumption of energy, water and other resources in one or more life cycle stages of the product; the weight and volume of the product and its packaging; the incorporation of renewable materials, recycled or used components; the quantity, characteristics and availability of consumables needed for proper use and maintenance; the environmental footprint of the product and its life cycle environmental impacts; the carbon footprint of the product; the micro-plastic release; emissions to air, water or soil released in one or more life cycle stages of the product; the amounts of waste generated; the conditions for use.” Of course, a lot of technical work is still needed to define appropriate procurement criteria for such technologies.
- **Manufacturing processes feature circularity -** First, “‘Biotech climate and energy solutions’ means technologies anchored in the use of microorganisms, or biological molecules, such as enzymes, resins or biopolymers, able to reduce CO_2 emissions by replacing energy-intensive fossil or chemical based inputs in industrial manufacturing processes relevant for inter alia carbon capture, production of biofuels and production of bio-based materials, in line with the circular economy principles”. In a separate section, “the project contributes to reaching the Union’s climate or energy objectives by manufacturing net-zero technologies through practices that implement improved environmental sustainability and performance or circularity features.”

Despite the obvious synchronicity between the EGDs and CEAP, the future rise of wastes from renewable electricity technologies should not be obscured or remain unquantified. The CEAP’s core mantra is to use less resources and produce less waste. It is therefore important to maximise material efficiency in the deployment of low-carbon technologies. These ideals are spelt out in the Waste Framework Directive’s waste hierarchy. Decarbonisation (at least in the short term) means more infrastructure, more raw and critical raw materials, and more energy to produce this infrastructure. It also implies more obsolete infrastructure and potential waste (recyclable materials).

The transition to renewable electricity is meant to be explicitly circular. However, the role of waste prevention and treatment for these technologies needs further development

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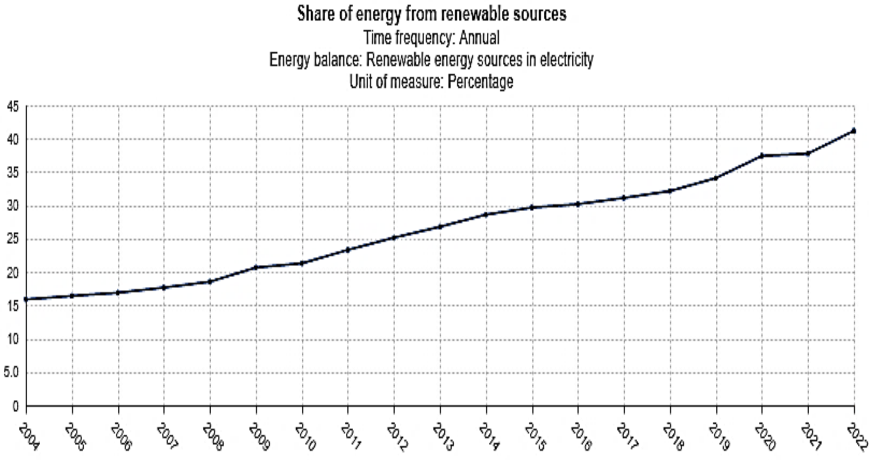
https://data.consilium.europa.eu/doc/document/ST-6269-2024-INIT/en/pdf because most of the existing research focuses on trace metals and critical raw materials rather than the significant quantities of other waste fractions such as steel and concrete for example. A more comprehensive view is needed of waste quantities, geographies, and material, economic and technical barriers, and other obstacles to the wide deployment of circular economy principles for the electricity supply system, considering the most recent policies such as the NZIA, the Waste Framework Directive, and the Waste from Electrical and Electronic Equipment (WEEE) Directive.

2.1 The electricity supply shift from fossil fuels to renewables

Today's electricity supply has radically moved towards renewables within the last 20 years. As shown in Figure 2, in 2004, the renewable electricity share in the EU-27 countries was 16%. In 2022, renewables had more than doubled since 2004, providing approximately 41% of gross electricity consumed.[10] The trend towards a greater share of renewable energy sources in electricity is clear.

Figure 2: The increasing percentage of renewable energy sources in electricity production in the EU.



Source: Eurostat

Available future projections of the energy system by 2050 and beyond are a useful tool to help understand the deep transformation that will be required (from both the supply and demand sides) to achieve the climate change mitigation objectives set. As a representative example, this section briefly presents the results of the JRC´s POTEnCIA model scenario used by the 2023 edition of the Clean Energy Technology Observatory (CETO-2023). In broad terms, this scenario achieves climate neutrality at EU level by 2050 through a mix of solutions that prominently include the combination of large-scale electrification of end-uses (direct or indirect through hydrogen and synthetic fuels) with deep decarbonisation of power production. This shift has two major implications for the electricity supply system. First, increased demand for gross electricity generation, as shown in Figure 3. Second, an overhaul of net installed capacity, as shown in Figure 4. The electricity supply system by 2050 will reflect large investment in variable renewable energy (requiring more energy storage and peaking plants to help balance electricity supply and demand) and the rapid decommissioning of solid-fuel-fired plants. While the remaining share of baseload electricity

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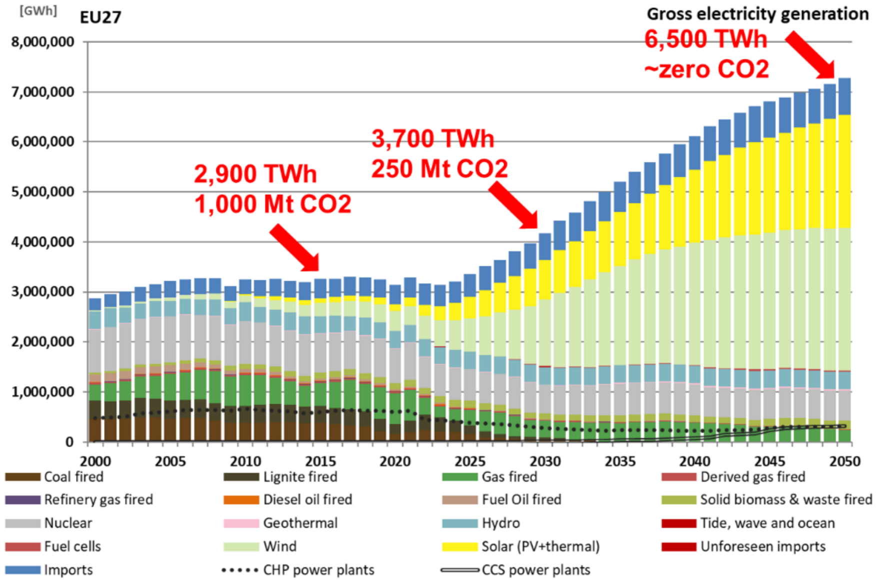
[10] Source: Eurostat - https://doi.org/10.2908/NRG_IND_REN

generation relies on nuclear (and in the longer term gas-fired plants with carbon capture and storage), gas-fired dispatchable units fulfil the crucial role of peaking plants to compensate for the intermittency of solar and wind generation. Hydropower plays a fundamental role thanks to its dispatchable nature, but further capacity expansion is highly constrained. A snapshot of the decommissioning of electricity-generating technologies based on the 2023 POTEnCIA CETO scenario expects the following:

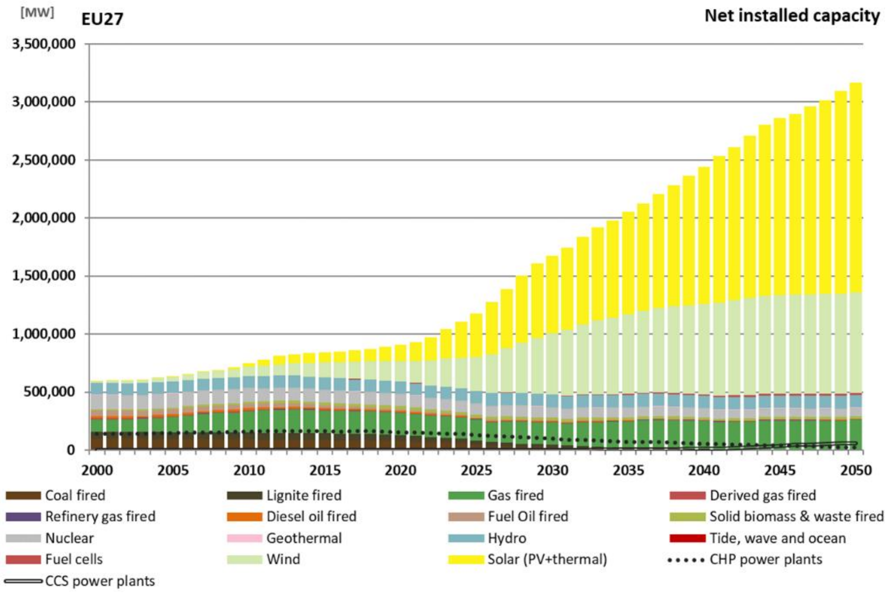
- Installed PV capacity more than triples by 2030 and increases almost tenfold by 2050. Therefore, the expected number of decommissioned units ramps up following the current rapid growth.
- Onshore wind creates a steady stream of decommissioned units, reaching approximately 200 GW (current capacity) by 2050, and a strong increase thereafter as onshore capacity more than doubles by 2030 and rises threefold by 2050.
- The offshore wind decommissioning stream reflects the later development of the offshore industry compared to the onshore counterpart; therefore, it begins around 2040.
- No new investments in coal and lignite from the present. Decommissioning times may vary, and plants may be assumed to be put in cold reserve until the end of their useful lifetime.
- Gas-fired power plant capacity remains part of the electricity supply system as they comprise: biogas, CCS (carbon capture and storage) units, and peaking plants used with very low-capacity factors. Therefore, gas is the only fossil fuel power plant type in which more new investment and less decommissioning are expected.

Figure 3: Gross electricity demand growth by 2050 – POTEnCIA CETO 2023 scenario.



Source: Own elaboration.

Figure 4: Net installed capacity shift towards renewables with enormous solar and wind growth – POTEnCIA CETO scenario.



Source: Own elaboration.

In summary, the transition towards a carbon-neutral energy system between now and 2050 in the MS (Member States) implies a massive capacity increase for solar (yellow bars in Figure 4) and wind (green bars in Figure 4).

3 CEPRES Scope, Research Questions, and Literature

The CEPRES study began at the same time as RePowerEU, slightly predating the Green Deal Industrial Plan for the Net-Zero Age. CEPRES was conceived as anticipatory, without a distinct regulatory driver. This is why it took a defining and convening approach. Its methods are literature review, horizon scanning, general estimation of wastes from the literature and dialogue.

Given that the renewable electricity supply system in the EU is complex, multi-dimensional, and multilevel, the simplified research questions that CEPRES explores are straightforward.

- What technologies, infrastructures, and materials are included?
- Can all waste can be recycled?
- How much waste is and will be generated?
- What policies are needed to increase circularity?

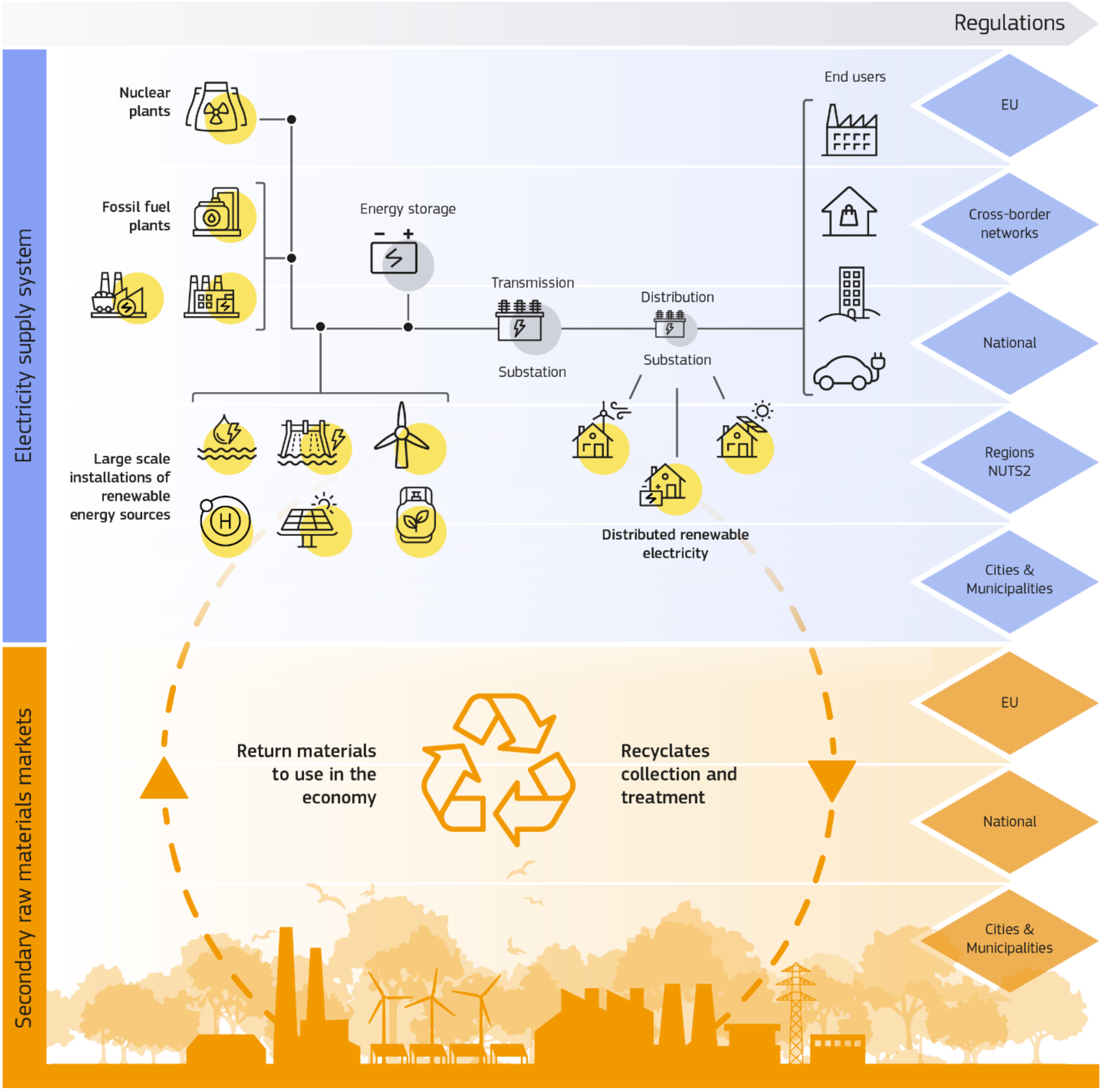
In answering these questions in this Strategies Report, CEPRES provides a solid foundation for circular economy policymaking today and in the future.

3.1 Scope of the renewable electricity supply system

The renewable electricity supply system is a multilevel, complex system of industries, stakeholders and actors, which should, in principle, move towards circular economy business models. See Figure 5. Putting in place the mosaic of programmes, regulation, and the positive and negative economic incentives that facilitate the closing of the loop for the new and increased waste streams of renewable electricity supply in the EU is a multidisciplinary challenge. This challenge requires knowledge from many angles, e.g. product policy; electricity demand; renewable electricity transition plans; supply of materials; and waste.

CEPRES is focused on the electricity supply system in transition to renewables that generates, transmits and distributes electricity to final consumers via industrial and distributed electricity producers. See Figures 3 and 4 above. For clarity, renewable electricity supply, within the scope of CEPRES, does not include the further transformation into different energy carriers such as hydrogen, e-fuels, or heat using heat pumps. Figure 5 aims to graphically represent the electricity supply system in the EU, and the secondary material markets that are key to collecting and treating wastes from the electricity supply system and returning them to productive use in the economy.

Figure 5: Illustration of the electricity supply system highlighting the circular economy for renewable electricity supply technologies and components.



Source: Own elaboration inspired by (Dai, Pan et al., 2012).

Description of the electricity supply system shown in Figure 5: The top half of the graphic, with a blue background, represents electricity generation, transmission and distribution to end users. The bottom half of the graphic, in orange, highlights how secondary materials markets should function in a circular economy. Materials that are deployed in the electricity supply system are recovered, treated and returned to productive use in the economy, when feasible for their original purposes. **The electricity supply system is comprised of the following technologies and components**:

- Fossil fuel electricity-generating plants (coal and gas, etc.) and nuclear power plants appear in the top left quadrant.

- Renewable energy sources are shown in the lower left-hand quadrant. Large-scale installations such as hydropower dams, solar power parks, wind power parks and wave and tidal power plants are grouped together. These are utility-scale electricity generators. Hydrogen infrastructure is included because it is expected to become a significant source of renewable electricity in future (see the EU's strategy for hydrogen for example), although it is not currently an important source of electricity. Distributed renewable electricity from photovoltaics and wind energy, and small biogas installations are grouped together. This includes prosumers as well as small-scale commercial operations.
- Energy / electricity storage (batteries, pumped hydro, etc.), which are particularly relevant to renewable electricity supply (red box), are shown as the first step in the electricity storage, transmission and distribution infrastructure. These are excluded from the scope of the current report, although their importance will grow in future.
- **The governance of electricity supply through policy and permitting is multilevel** as is shown by the regulatory framework in blue triangles on the right side of the graphic. The levels of regulation are not linked to specific fuels, but rather reflect system-wide governance. Likewise, the orange triangles reflect the regulation of all waste management in the EU, MS (Member States), and cities/municipalities, rather than specific wastes. Estimating waste flows from the electricity supply system is dependent on identifying priorities in EU policies, national waste management plans and municipal management of waste collection and treatment. Furthermore, companies operating in the renewable electricity sector operate within this multilevel regulatory environment.

3.2 Literature review

A literature review was performed to gain an understanding of CEPRES-related waste studies in the literature. The search was conducted for the period 2018-2023, using the Publications Office of the European Commission to identify JRC studies, Google Scholar, and the Web of Science. We found that it is important to use expert knowledge of the field, more than one search engine, and manually trace citations (particularly in literature reviews). In addition, the literature review was not intended to be exhaustive. The study identified both peer-reviewed journal articles and grey literature, the main points of which are summarised below. We highlight the articles and reports that were the most informative.

The academic literature offers insights into the material composition of renewables as well as the recycling and reuse potential of different technologies and materials. We found that most relevant literature focuses on estimating the volumes of material demand rather than material recovery and recycling. Most of the academic publications reviewed focus on one technology rather than taking a systems perspective as CEPRES does. The literature review by Xie et al. (2023) on low-carbon actions and circular practices also concludes that existing studies "serve different fields from various perspectives, but their applicability is relatively limited, and it is difficult to conclude with overall guiding significance" (Xie, Xia et al. 2023). The few exceptions that take an energy systems perspective mention data availability challenges (Le Boulzec, Delannoy et al. 2022).

Whereas waste is less researched, material demand for the energy and/or electricity transition is often researched. Nevertheless, in 2022, Liang et al.'s literature review concluded that work remains on materials demand, with the following findings, which are relevant to CEPRES: "(1) research on the demand for low-carbon technology related metals has received much attention since the 2010s; (2) around 80% of the publications focus on the global level while national level studies are underrepresented; (3) science-based future scenarios are the main means of estimating total future material requirements; (4) most studies foresee material constraints of large-scale implementation of low-carbon technologies and the secure and responsible supply of these materials is still the subject of discussion; (5) changes in metal intensity caused by technological development and material requirements for non-critical components are important though often overlooked" (Liang, Kleijn et al. 2022) The policy and research in this area is developing at a rapid pace.

We observe that the most recent and detailed estimate of material demand for global electricity generation with climate change scenarios between 2020 and 2050 is currently Wang et al. (2023). Figure 6 below reproduces Table 1 and Table 3 of Wang et al. (2023), which provides their results for material demand for electricity generation infrastructure, transmission and distribution. The authors included electricity-generating infrastructure with a focus on renewable electricity, "onshore and offshore wind, conventional solar PV, concentrating solar power (CSP), hydroelectricity, geothermal, nuclear, and coal, biomass, and fossil gas, both with and without post-combustion carbon capture," omitting oil-fired power plants as negligible (Wang, Hausfather et al. 2023). Materials recycling is incorporated into their estimation of future supply to meet demand. Notably, the study assumes that "current input recycling rates remain constant between 2020 and 2050. Input recycling of Cd, Dy, fiberglass, Ga, In, Nd, Se, solar-grade polysilicon, and Te is assumed to be zero, as current end-of-life recycling of these materials is deficient or nonexistent. For cement consumption, we also assume that no cement inputs are recycled." Mulvaney et al. (2022) conclude similarly, "Materials produced largely lack viability or end-of-life disposal strategy" (Mulvaney, Richards et al. 2021). These authors' findings on the future lack of recycling capacity are confirmation of CEPRES's expected results at the outset - identifying the gaps in current and future recycling capacity.

In summary, Wang et al. (2023) conclude that, globally, "Most material-associated emissions result from the high demand for solar-grade polysilicon, as well as bulk materials such as steel, cement, and copper that are commonly required across most generation technologies. Proactive industrial sector decarbonization efforts alongside the process of power sector decarbonization can help avoid some of these material-associated emissions." CEPRES research offers new estimates for the large volume, bulk materials, steel, cement and copper that will result as waste from the potential decommissioning of fossil fuel plants for the EU-27, which rely on inputs of these bulk materials.

Figure 6: Material demand results presented in Wang et al. (2023).

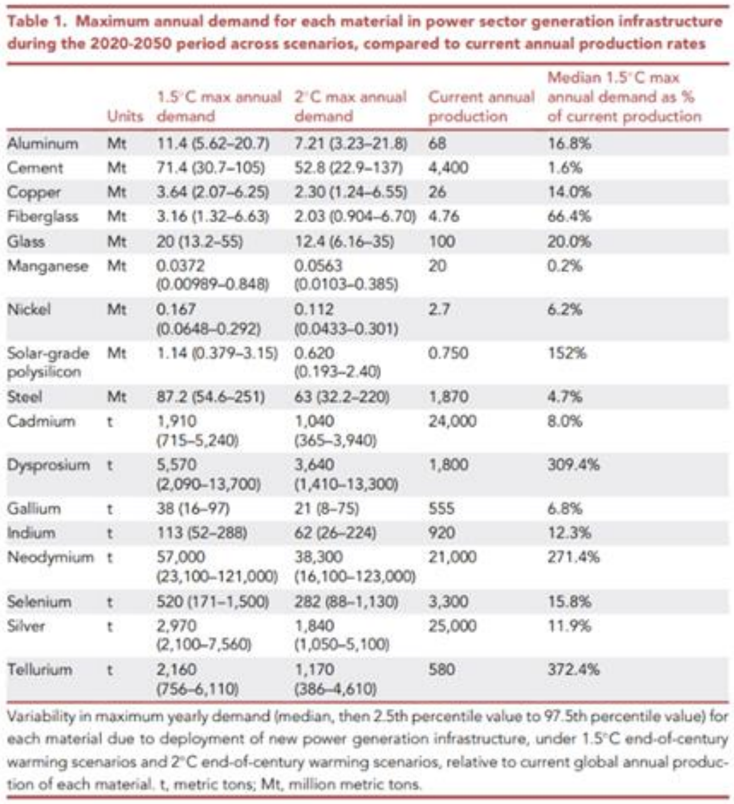


Table 1. Maximum annual demand for each material in power sector generation infrastructure during the 2020-2050 period across scenarios, compared to current annual production rates

	Units	1.5°C max annual demand	2°C max annual demand	Current annual production	Median 1.5°C max annual demand as % of current production
Aluminum	Mt	11.4 (5.62–20.7)	7.21 (3.23–21.8)	68	16.8%
Cement	Mt	71.4 (30.7–105)	52.8 (22.9–137)	4,400	1.6%
Copper	Mt	3.64 (2.07–6.25)	2.30 (1.24–6.55)	26	14.0%
Fiberglass	Mt	3.16 (1.32–6.63)	2.03 (0.904–6.70)	4.76	66.4%
Glass	Mt	20 (13.2–55)	12.4 (6.16–35)	100	20.0%
Manganese	Mt	0.0372 (0.00989–0.848)	0.0563 (0.0103–0.385)	20	0.2%
Nickel	Mt	0.167 (0.0648–0.292)	0.112 (0.0433–0.301)	2.7	6.2%
Solar-grade polysilicon	Mt	1.14 (0.379–3.15)	0.620 (0.193–2.40)	0.750	152%
Steel	Mt	87.2 (54.6–251)	63 (32.2–220)	1,870	4.7%
Cadmium	t	1,910 (715–5,240)	1,040 (365–3,940)	24,000	8.0%
Dysprosium	t	5,570 (2,090–13,700)	3,640 (1,410–13,300)	1,800	309.4%
Gallium	t	38 (16–97)	21 (8–75)	555	6.8%
Indium	t	113 (52–288)	62 (26–224)	920	12.3%
Neodymium	t	57,000 (23,100–121,000)	38,300 (16,100–123,000)	21,000	271.4%
Selenium	t	520 (171–1,500)	282 (88–1,130)	3,300	15.8%
Silver	t	2,970 (2,100–7,560)	1,840 (1,050–5,100)	25,000	11.9%
Tellurium	t	2,160 (756–6,110)	1,170 (386–4,610)	580	372.4%

Variability in maximum yearly demand (median, then 2.5th percentile value to 97.5th percentile value) for each material due to deployment of new power generation infrastructure, under 1.5°C end-of-century warming scenarios and 2°C end-of-century warming scenarios, relative to current global annual production of each material. t, metric tons; Mt, million metric tons.

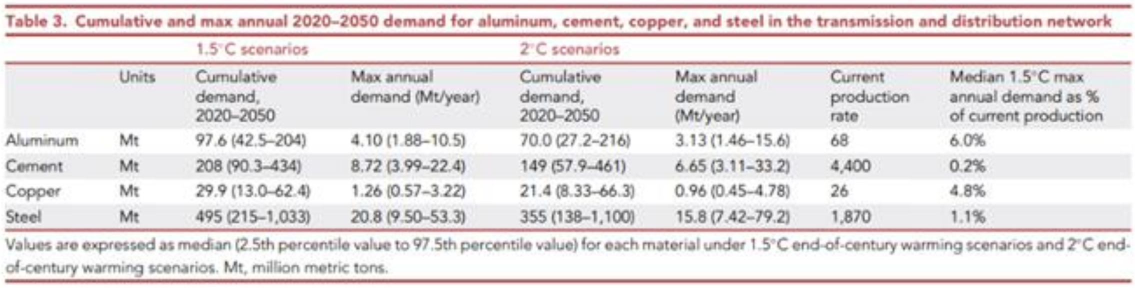


Table 3. Cumulative and max annual 2020–2050 demand for aluminum, cement, copper, and steel in the transmission and distribution network

		1.5°C scenarios		2°C scenarios			
	Units	Cumulative demand, 2020–2050	Max annual demand (Mt/year)	Cumulative demand, 2020–2050	Max annual demand (Mt/year)	Current production rate	Median 1.5°C max annual demand as % of current production
Aluminum	Mt	97.6 (42.5–204)	4.10 (1.88–10.5)	70.0 (27.2–216)	3.13 (1.46–15.6)	68	6.0%
Cement	Mt	208 (90.3–434)	8.72 (3.99–22.4)	149 (57.9–461)	6.65 (3.11–33.2)	4,400	0.2%
Copper	Mt	29.9 (13.0–62.4)	1.26 (0.57–3.22)	21.4 (8.33–66.3)	0.96 (0.45–4.78)	26	4.8%
Steel	Mt	495 (215–1,033)	20.8 (9.50–53.3)	355 (138–1,100)	15.8 (7.42–79.2)	1,870	1.1%

Values are expressed as median (2.5th percentile value to 97.5th percentile value) for each material under 1.5°C end-of-century warming scenarios and 2°C end-of-century warming scenarios. Mt, million metric tons.

Source: Reproduced with permission.

Another role played by the academic literature is to put forward the theoretical links between higher materials demand (at least in the short term) with the long-term energy transition strategies *and* the economic and resource efficiency trade-offs this entail as relevant to policymaking today (Heath, Silverman et al. 2020, Mulvaney, Richards et al. 2021, Liang, Kleijn et al. 2022, Wang, Hausfather et al. 2023, Desing, Widmer et al. 2024). The application of design for recycling principles to clean energy technologies is explored by (Norgren, Carpenter et al. 2020).

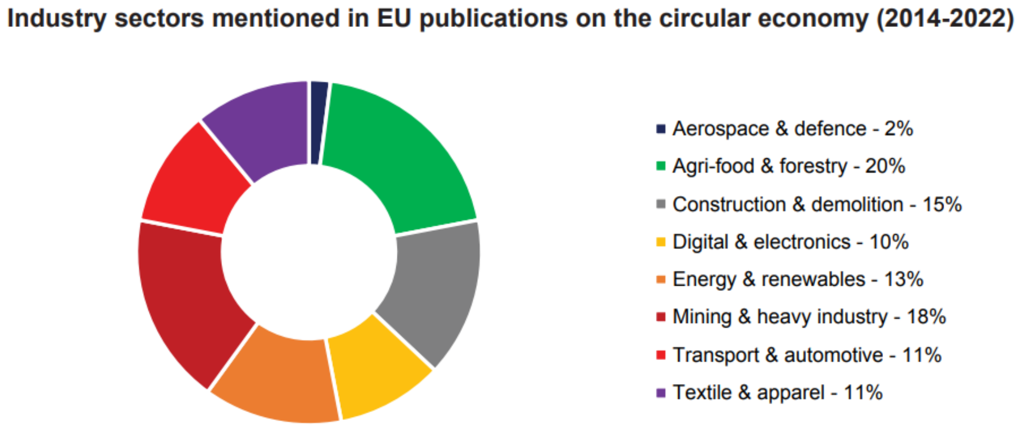
The question of environmental impacts and waste volumes due to decommissioned infrastructure from electricity production tends to be omitted, even from most of the life cycle analyses reviewed. Our current reading of the literature agrees with Invernizzi et al. (2020) that the “decommissioning of existing and future energy infrastructures is constrained by a plethora of technical, economic, social, and environmental challenges that must be understood and addressed if such infrastructures are to make a net-positive contribution over their whole life” (Invernizzi, Locatelli et al. 2020). Articles describing fossil fuel power plants in future tend to focus on their loss of value as they become stranded assets. There is a significant body of work on stranded assets due to early retirement of fossil fuel plants including Grubert (2020) for the United States, Edwards for global coal power plants, Semieniuk, et al. (2022) on investment losses, and others (Kefford, Ballinger et al. 2018, Grubert 2020, Cahen-Fourot, Campiglio et al. 2021, Semieniuk, Holden et al. 2022). Most fossil fuel power plant decommissioning studies look at the issue from the financial perspective. We find that there are few estimates of the waste volumes due to decommissioning of fossil fuels in the literature; therefore, the full life cycle is not understood and addressed.

As the climate impacts of the infrastructure are minor compared to the climate impacts from fossil fuels for electricity production, the infrastructure is often omitted. An exception is Ghisellini et al. (2023), which provides LCA including “end-of-life disposal for thermoelectric plants, hydroelectric, solar PV and wind power plants” (Ghisellini, Passaro et al. 2023). In addition to a lack of LCA, the quantification of waste from decommissioned fossil fuel infrastructure is not prevalent in the literature. Although the current CEPRES Strategies Report does not propose a LCA, it provides the basis for future research by comprehensively estimating waste streams and describing current waste management options and problems.

Grey literature, **such as reports by institutions, appear to be primarily motivated by an energy security focus framed by access to critical raw materials**. These tend to include more information on materials demand rather than waste streams but are extremely relevant to the waste streams that will result in the EU from products manufactured abroad. Grijelmo et al. (2022) point out that, for renewable energy, “To date, 60% of the global material demand is extracted in China while in Europe we remain dependent on foreign imports for more than 80% of our raw materials” (Grijelmo 2022). The JRC has provided many pertinent reports on this topic. Most focus on material demand for critical raw materials. The Carrara et al. (2020) JRC Report “Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system” is influential and frequently cited in the literature (Carrara, Alves Dias et al. 2020). Its estimates have been applied in several studies, including the 2023 JRC report "Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study” (Carrara, Bobba et al. 2023). This report is a comprehensive review of materials used in renewable energy production including renewable electricity supply technologies. Among others, it includes wind turbines, four electrolyser technologies, solar PV panels, and lithium-ion battery technology. The report establishes that “meeting the EU’s ambitious policy targets will drive an unprecedented increase in materials demand in the run up to 2030 and 2050. For example, to meet the REPowerEU targets for 2030, for the permanent magnet needs of wind turbines alone, EU demand for rare earth metals will increase almost fivefold. Lithium demand for the batteries in electric vehicles will also increase 11 times” (Carrara, Bobba et al. 2023). The report calls for “enhancing recycling and reuse for a stronger circular economy” and “avoiding exports of metal scrap to third countries to boost domestic capabilities and generate economies of scale in the development of recycling processes” (Carrara, Bobba et al. 2023)

The energy and renewables sector holds a significant proportion (13%) of mentions in the EU publications on circular economy (Baldassarre and Saveyn 2023)

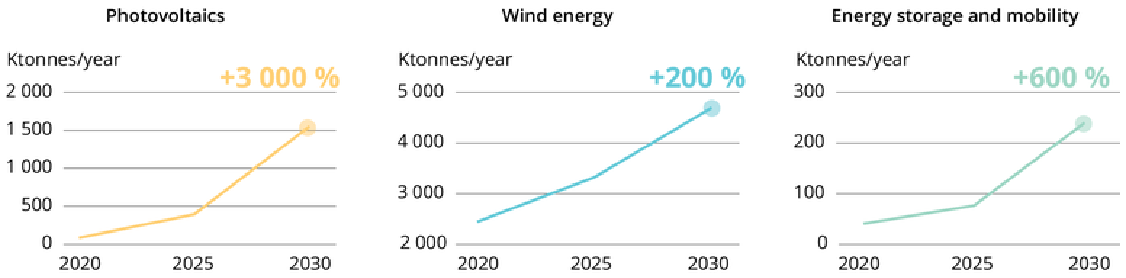
Figure 7: Industry sectors mentioned in EU publications on the circular economy.



Source: (Baldassare and Saveyn 2023)

The European Environment Agency (EEA) estimated wastes from renewables in its 2021 online briefing and 2023 update. A resource for the EEA briefing is the report of Graulich et al. (2021), which offers a detailed discussion of waste streams, materials, and secondary market challenges (Graulich K. 2021).

Figure 8: Expected growth of waste materials generated by clean-energy infrastructure.



Source: European Environment Agency (europa.eu)[11]

As shown in Figure 8, photovoltaic waste increases by 3,000%. The EEA graphic is based on the analysis by Graulich et al. (2021). The CEPRES Strategies Report updates the Graulich et al. (2021) analysis in some respects. For example, the current work, specifies the estimated number of wind turbines in 2030 and 2050 based on updated observations to estimate wastes in 2050. Furthermore, the current analysis provides new estimates for solar PV wastes that consider current market conditions and do not rely on the International Renewable Energy Agency's often cited estimates in (Weckend, Wade et al. 2016). As a result, CEPRES provides observation-based waste estimates for 2023 and projections for 2050. We believe that the current fast-paced technological and political environment requires new estimates as provided herein.

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[11] https://www.eea.europa.eu/publications/emerging-waste-streams-opportunities-and

The review of the literature concludes that volumes of PV and wind power wastes will grow exponentially over the next decade. For PV, some studies show that earlier than expected decommissioning focuses on premature equipment failures and manufacturing defects (Atasu, Duran et al. 2021). In addition, for solar PV and wind, premature decommissioning may be driven by new technologies offering higher efficiencies, intolerance to extreme weather and other features (Curtis, Buchanan et al. 2021). For wind, there are several estimates of wastes; however, the detail of these varies, and several were completed a few years ago, such as (Liu and Barlow 2017, Dragan 2019, Lichtenegger, Rentizelas et al. 2020, Sommer, Stockschläder et al. 2020, WindEurope 2020). CEPRES's review of the literature is in line with Grijelmo et al. (2022)'s top line, "**the boost in deployment of renewable energy technologies brings an unresolved problem to the table: how to manage the enormous amount of waste generated when they reach the end of their useful life**" (Grijelmo 2022). The EU's total waste from all economic activities and households was 2,233 million tonnes in 2022, meaning that the total wastes are a much larger volume than waste from renewables. However, waste from renewables are visible and in some cases lack recycling possibilities.

Overall, these complex waste streams need accurate estimations that consider new patterns of reuse and new recycling possibilities and recycling challenges, such as wind turbine blades. In contrast to much of the existing literature, CEPRES homes in on the EU case and the 2024 context of EU policy to rapidly deploy renewables; therefore, creating new and complex waste streams, for which, in some cases, tailored recovery and recycling does not yet exist for all of EU countries.

4 Waste from wind power in the EU

This section highlights the challenges of managing wind turbines and wind turbine blades when they reach their end-of-life. To this end, (i) data gaps on future waste streams are emphasised and suggestions are made to fill these gaps, (ii) policy gaps are identified that would better promote the circular economy including collection, remanufacturing, reuse, recycling, and (iii) research gaps on the advancement of wind turbine blade design that promotes recycling, recyclability, and material extraction are discussed. This section answers the CEPRES research questions with regards to electricity supply from wind power and is organised by the following research questions:

- What technologies, infrastructures, and materials are included in the composition of wind power waste that require a circular economy perspective?
- Can all wind turbine waste be recycled?
- How much waste is and will be generated in future?
- What policies are needed to increase circularity?

4.1 Which technologies, infrastructures and materials?

This section answers the second research question, “What technologies, infrastructures and materials are included in the composition of wind power waste that require a circular economy perspective?”

Wind turbines are composed of approximately 85% by weight of metals, such as steel, iron and cast iron, which have established recycling routes (Alavi et al., 2024; Mone et al., 2015). Wind estimates that a wind turbine and its foundation consist of over 90% concrete, iron and steel (WindEurope 2022). It is therefore generally assumed that **wind turbines are 85% recyclable** (Bonou et al., 2016; Korsgaard et al., 2022). **This percentage excludes the weight of the foundation, which is typically made of reinforced concrete or steel.** Iron, steel and aluminium are widely collected and recycled in the EU. However, concrete is often collected but not recycled at all—or recycled into aggregates (Damgaard, Lodato et al. 2022).

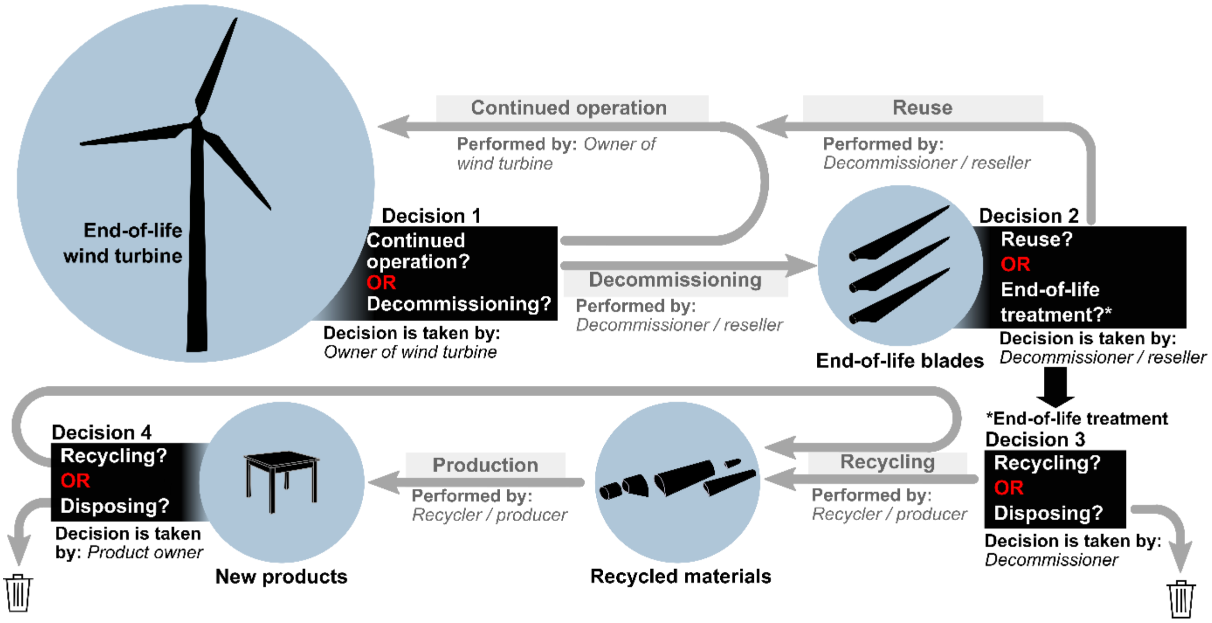
In addition, wind turbines contain valuable rare earth minerals such as neodymium in permanent magnets, which are CRMs. From a technical point of view, recycling processes exist for recovering these rare earth magnets. Because they are high value materials, recycling is economically feasible. Still, little recycling of rare earth magnets is done in the EU (Gauß, Burkhardt et al. 2021). The magnets embedded in future wind turbine waste, will be very valuable, unlike glass fibre composites in blades. Another aspect, is the need for an increased supply of rare earth magnets if planned capacity for climate neutrality is realised. Recycling magnets alone would not meet the future demand (Gauß, Burkhardt et al. 2021). Therefore, the bottleneck with rare earth is not at end-of-life, but in the supply of them.

The remaining 15% of wind turbine materials comprise polymers and glass fibre (also referred to as fibreglass) reinforced composites, mostly found in wind turbine blades, and remain challenging to recycle. Beauson et al. (2022) mention that it is unlikely that the materials in wind turbine blades could substitute primary materials for wind turbine blades (Beauson, Laurent et al. 2022). **The conundrum is that although the majority of a wind turbine is recyclable, the wind turbine blades are not recycled effectively today**. Therefore, this section is an overview of wind turbine waste management with a focus on the “problematic” waste stream of wind turbine blades.

4.2 Can all wind turbine waste be recycled?

The end-of-life of wind turbines consists of several steps and is governed by several stakeholders and decisions; see Figure 9 (Beauson et al., 2022). Recycling of the individual wind turbine parts is only one of the steps included in a larger value chain. At end-of-life, this value chain starts with the owner of the wind turbine, who takes the decision to decommission the turbine. The next decision is taken by the decommissioning firm. A wind turbine can be carefully decommissioned using a crane or it can be tipped to the ground. Tipping a wind turbine will break blades into smaller pieces which then need to be collected. This decommissioning procedure saves the cost of using a crane. However, the composite pieces collected are contaminated with dirt and may be unsuitable for recycling technologies. The decision on the type of decommissioning depends on the damage to the blades, their potential to be reused and the owner's business case. If blades are decommissioned carefully with the purpose of being recycled, once on the ground they may be sectioned to ease their transport. Several pre-processing steps are typically performed to prepare wind turbine blades to be recycled, such as cutting and mechanical shredding (Lund and Madsen, 2024). The number of pre-processing steps depends on the following recycling process.

Figure 9: The end-of-life value chain of a wind turbine.



Source: reprinted with permission (Beauson, 2022)

This brief description of the end-of-life value chain of wind turbines shows that recycling, which takes place at the end of the value chain, is impacted by decisions taken upstream. Decisions such as the selection of a decommissioning procedure may prevent repurposing and certain recycling solutions from being performed. In the EU, Directive 2008/98/EC on waste ranks waste management solutions in five categories, which are, in order of preference:

- prevention (keeping parts for longer, design for easier dismantling and recycling, minimising the number of materials);
- preparing for re-use (repairing, cleaning, refurbishing and reuse of whole component for its original purpose);

- recycling (turning a component into new substances or product, using large sections of the component or materials extracted from it);
- other recovery (such as energy recovery aims at producing energy from the component or materials extracted from it); and
- disposal (landfill or incineration without energy recovery).

These different treatment and disposal options are presented in the next section.

4.2.1 End-of-life options

This section analyses the current and novel End-of-life options for fibre-reinforced polymer composites of blades.

Fibre-reinforced polymer composites are an attractive class of materials as they combine lightweight properties and high mechanical performance. Composites can be designed to achieve specific properties by selecting the type of polymer matrix, the type of fibre reinforcement (glass fibre or carbon fibre), the length and the orientation of the reinforcement fibres. As a result, composites are being used in diverse applications, such as wind turbine blades, boats, construction, airplanes, cars, sports equipment or suitcases (Witten and Mathes, 2023). Fibre-reinforced polymer composites are commonly divided into two categories based on the type of polymer used, either thermoplastic or thermoset polymer (Witten and Mathes, 2023). In the manufacturing of thermoplastic polymer composites, heat is applied to soften and shape the polymer (Leal et al., 2016). Thermoset polymer resins are found in a liquid state at room temperature. To achieve a solid state, the thermoset polymer resin is mixed with a curing agent and exposed to a curing cycle, where heat may be applied for a certain time duration. Unlike thermoplastics, thermoset polymers cannot be softened or melted when exposed to heat. Being able to remelt, soften or depolymerise a polymer resin at end-of-life is an advantage to recycle composite materials into new products. As a result, the development of novel recyclable thermoset polymers facilitating the separation of the fibres from the matrix have been increasingly investigated (Schenk et al., 2022). So-called vitrimer polymer resins have similar manufacturing procedures to the conventional thermoset polymers but can be softened and reshaped like thermoplastic polymers. In some cases, they can be depolymerised and separated from the reinforcement fibres under mild recycling conditions (K Dubey et al., 2020).

Currently, most wind turbine blades are made of conventional thermoset polymer composite. Wind turbine blades are large hollow structures, which can be described as two aerodynamic shells surrounding a load-carrying beam (Beauson et al., 2016; Mishnaevsky et al., 2017). These parts are made of two distinct types of composite materials: sandwich composite and unidirectional fibre composites. Sandwich composites are composed of a core material made of balsa wood, PET, or PVC foam, “sandwiched” in between two thin multidirectional glass fibre composites. Unidirectional fibre composites are made of glass fibres and/or carbon fibres with a polymer resin, which may be epoxy, polyester or vinylester (Mishnaevsky et al., 2017). Wind turbine blades also contain metals in the lightning protection system, which may be formed as an aluminium or copper mesh inserted inside the composites or a metallic thread distributed inside the blade (Kjærside Storm, 2013). Bolts, screws, and the bushing at the root section are other sources of metals in blades. Overall, the amount of metallic materials found in blades account for approximately 1% of the total weight of a blade (Liu et al., 2019). All these materials cannot be easily disassembled. The blades may be manufactured as several parts; however, the parts are glued together, and the bond cannot be easily released. As mentioned previously, conventional thermoset polymers cannot be softened, reshaped or easily separated into fibres and polymer matrix material. **At end-of-life, sorting the diverse types of materials, polymers, glass and metals therefore remains a challenge.**

According to the waste management hierarchy, the first and preferred solution is to prevent waste from being generated. Solutions implementing prevention are typically realised during the design phase of products. Prevention solutions are for example to reduce the amount of material used in a product. Or in the case of recycling to prevent waste, to enable an easy separation of diverse types of materials. New thermoset polymers that can be easily dissolved at end-of-life belong to this category of solution (Schenk et al., 2022).

Next in the waste management hierarchy is to prepare for reuse of the product for the same purpose. As mentioned earlier, wind turbine blades may be reused. As a result, wind turbine blades may be kept as spare parts or transported to a new location and installed on a turbine. In the EU, several companies decommission and sell smaller wind turbines with a size of up to 3 MW to 5 MW approximately. In 2024, a study looking at Danish and German wind turbines indicated that the percentage of wind turbines reused could be around 50% to 60% (Kramer 2024) . A non-exhaustive list of companies selling used wind turbines is presented in Table 1.

Table 1: Examples of companies selling used wind turbine blades in Europe

Name of Company	**Country**	**Description**
Windvorst	NL	“For many years WINDBROKERS has been the main business driver as independent supplier of Used and New Wind Turbines.” https://www.windvorst.com/pages/company.php
Surusin	ES	“SURUS managed the sale in secondary markets so other economies such as India or Cuba could make use of this technology at a lower price, preventing the use of natural resources for manufacturing and recapturing value for the farm.” https://www.surusin.com/en/caso/malpica-wind-farm/
P&J Windpower	DK	“Due to our long-lasting experience, we have established a wide network of international clients and cooperating partners which enables us to offer very competitive prices for used wind turbines and wind farms.” https://www.pjwindpower.com/
WindTurbines.ie	IE	“We specialise in taking end-of-life wind turbines from Europe, completely overhauling, and refurbishing them and then installing them on green field or auto-production (factory) sites throughout Ireland.” https://www.windturbines.ie/what-we-do/
Repowering Solutions	ES	“We have more than 100 units of 850kW Vestas V52 wind turbine with lattice tower, optionally we can supply tubular tower." https://repoweringsolutions.com/english/

Dutchwind	NL	"Dutchwind BV is a Dutch broker that specializes in trading used wind turbines globally. These second-hand wind turbines range from 50 kW to 5.000 kW." https://dutchwind.com/
Spares in motion	DE, NL, US, ES	"Spares in Motion is the e-business platform for the wind turbine aftermarket." https://www.sparesinmotion.com/
Business in wind	NL	"The trade in wind turbines has increased substantially over the past years. Used wind turbines, in particular, that can operate for a second term, are very popular." https://businessinwind.com/
BOYTHORPE wind energy	UK / non-EU	"We also sell remanufactured Vestas turbines ranging from 850kw up to 2 MW or more." https://www.boythorpewindenergy.co.uk/
MWPS	UK / non-EU	"[...] the aim to infiltrate the renewable energy market with the niche business model of an exclusive and worldwide trading platform for used & second-hand wind turbines." https://www.mwps.world/

Technical considerations: Recycling processes for wind turbine blades fibre-reinforced polymer composites are commonly divided into four categories: repurposing, mechanical recycling, thermal recycling and chemical recycling. The repurposing of wind turbine blades tries to reuse sections of blade or composite materials found in blades, in new structural or semi-structural applications, such as footbridges or playgrounds (Bank, 2021; Bank et al., 2018; Delaney et al., 2021; Joustra et al., 2021; Nagle et al., 2020; Ruane et al., 2022; Tasistro-Hart et al., 2019; Yazdanbakhsh et al., 2018). The challenge of this solution lies in the properties of the material which need to be characterised thoroughly and may be different from blade to blade. In addition, after being repurposed and once the repurposed blade reaches end-of-life, composite materials still need to be recycled. Table 2 presents a list of companies repurposing blades.

Table 2: Examples of companies repurposing used wind turbines in Europe

Name of Company	**Country**	**Description**
BladeBridge	IE	Design and building of blade-based structures. “BladeBridge Repurposes Decommissioned Wind Turbine Blades into Sustainable Infrastructure, Decoupling the Production of Renewable Energy from the Generation of Waste” *https://www.bladebridge.ie/*
ReBlade	UK / non-EU	“We could repurpose your blades into functional products, supply sections to academic institutions for student training or materials research or provide your GRP material to industry projects to help accelerate technical innovation.” *https://reblade.com/*
Wings for Living	PL	High-end low-volume repurposing for furniture. “Our outdoor furniture is elaborately handcrafted from recycled wind power rotor blades.” *https://wings-for-living.com/*
Anmet	PL	Repurposing. Blade Bridges. Cutting Systems. “We provide comprehensive solutions for owners and operators of wind farms in the field of cutting, transport and recycling of blades. Together with our partners, we also offer comprehensive disassembly of entire wind turbines and Repowering.” *https://www.anmet.com.pl/about-us/?lang=en*
Blade-Made	NL	“Blade-Made started in 2021 to bring the ideas of Superuse to market. New Citizen Design and Newton Brown Urban Design joined to strengthen our networks and change the way End of Life blades are treated, with a focus on Europe and North America.” *https://blade-made.com/*

Mechanical recycling is the reduction in size of composite products using shredding and grinding processes. Depending on the equipment used, different type of output materials can be achieved. With shredding equipment, the output materials will be in the form of small pieces and granulates. Several shredding steps may be applied, and the dimension of the output materials may range from a few mm to a few cm (Christeen, 2012; Jutte and Graham, 1991). With grinding equipment, the output materials will be in a powder form, with particle size ranging from a few hundred µm up to a few mm (Palmer, 2009; Palmer et al., 2009). Following these size reduction steps, sieves may be used to separate the output materials into different fractions based on size or to sort some materials out, such as metals. Shredding glass fibre-reinforced composite with high fibre content will cause wear on the metallic parts of shredding and grinding equipment and metal particles may be found in the output material. Shredded composite materials and composite powder may be used in diverse applications, such as reinforcement in new polymer profiles or sound insulation panels (Beauson et al., 2016; "Conenor," 2024, "Miljøskærm," n.d.; ten Busschen, 2017). Table 3 lists some examples of companies performing recycling of composite materials. In new polymer composite application, the reinforcing effect is limited however and is related to a stiffening effect (Beauson, 2022; Beauson et al., 2016). The strengthening effect is challenged due to the poor adhesion between shredded composite particles and new polymer matrix (Beauson et al., 2016).

Thermal recycling processes are processes that involve heat and enable the recovery of the reinforcing fibres and the polymer phase as a liquid and a gas fraction. Thermal recycling processes are, for example, pyrolysis, fluidised bed pyrolysis and microwave pyrolysis (Åkesson et al., 2012; Cunliffe et al., 2003; Pickering et al., 2000). The liquid product from pyrolysis of thermoset polymers can be used as "building bricks" for the chemical industry (Cunliffe and Williams, 2003). The gas can be reused in the process as a source of heat. Glass fibres recovered with pyrolysis processes demonstrate similar stiffness to their virgin counterparts. However, a significant loss in fibre strength is measured, above 50% (Feih et al., 2015; Fraisse et al., 2016; Thomason et al., 2013). Recovered carbon fibres shows better properties (Liu et al., 2022). Carbon and glass fibres recovered with pyrolysis are usually intended to replace virgin fibre reinforcement. The business case for recovering the fibres is different because virgin glass fibres are inexpensive, and virgin carbon fibres are costly (Liu et al., 2022). Finding applications for recycled glass fibres, which are randomly oriented, with low strength properties and limited length is more challenging than for recycled carbon fibres. Several companies sell recycled carbon fibres and in 2022 the global recycled carbon fibre market was estimated at around EUR 50 million [("Recycled Carbon Fiber Market Share, Demand & Trends by 2032," n.d.). To overcome the challenges related to recycled glass fibres properties, experimental work has demonstrated the possibility of regenerating the strength of glass fibres (Pender and Yang, 2020). This demonstration does not address the issues related to the length and the random orientation of recycled glass fibres. Another approach, based on the remelting of recycled glass fibres, resulted in the production of long continuous glass fibres using recycled glass fibre from wind turbine blades. The mechanical properties of the fibres produced were found to be similar to the reference fibres produced from virgin raw materials (MAKEEN, 2023).

Chemical recycling can be summarised as processes that involve a solvent, heat and in some cases pressure, to dissolve the polymer resin material and separate it from the reinforcement. With chemical recycling, reinforcement fibres as well as chemical products from the polymer resin can be recovered. In some cases, the chemical products may be reused to produce new polymer resin. Like thermal recycling processes, recycled glass fibres have decreased mechanical properties, mainly strength, but recycled carbon fibres are usually less impacted (Sokoli et al., 2017). The demonstration of chemical recycling was mainly performed by small-scale experiments. Chemical recycling can be costly depending on the type of solvent, temperature and pressure needed (above 200 ° Celsius and above 200 bar) (Oliveux et al., 2015). There are currently no companies performing solvolysis processes for wind turbine blade materials in a commercial set-up. In the future, most of the new recyclable resins will require a chemical recycling process at end-of-life to be recycled. The conditions for the recycling of recyclable resin are however milder than the ones for conventional thermoset. There are examples involving 90 ° Celsius and acetic acid (K Dubey et al., 2020). The recycling of recyclable composites has been demonstrated at laboratory scale.

Table 3: Examples of companies recycling composite materials

Name of company	**Country**	**Description**
Procotex	BE, UK	Formerly ELG Carbon Fibre Ltd. Carbon fibre recovery https://en.procotex.com/products/technical-fibres/recycled-carbon-fibres-carbiso
Reprocover	BE	Mechanical recycling "produces precast solutions for rail, road and building infrastructures made from Reprocessed ThermoSets." *https://reprocover.eu/*
Energyloop	ES	Integrated recycling "committed to the recycling of wind turbines within the framework of the circular economy." *https://energyloop.es/en/about-us/*
Continuum	DK	"We create compound blends based on the classified, reclaimed materials together with virgin resin(s) and/or other formaldehyde-free additives." *https://www.continuum.earth/*
Miljøskærm	DK	Mechanical recycling and reuse of shredded composite to produce sound insulation panels. Shredded composite pieces are glued together. *https://miljoskarm.dk/en/*
Roth international	DE	"As CFRP / GFRP are used in many objects, ROTH International has the know-how to recycle them." *https://www.roth-international.de/en/recycling-recovery/recycling-of-cfrp-gfrp/*

The next end-of-life option described is the cement kiln route. This solution is often categorised as an energy recovery solution rather than a recycling solution. However, in 2006, the European Composites Industry Association (EuCIA) published a position paper calling for the cement kiln route to be accepted as a 'recycling' solution in the upcoming new European legislation and waste management hierarchy ("Recycling threat to Europe's composites industry," 2006). Until 2022, in the EU, end-of-life wind turbine blades could be processed with cement kilns in northern Germany. This plant was processing 30,000 tonnes of fibre-reinforced composite waste, of which one third came from wind turbine blades (Schmid et al., 2020). This solution mixed shredded composite materials with wastepaper. The mixture was then used as a combustion material to heat the cement kiln process. In the end, the resulting ash was used as a source of silica, which is needed in the manufacture of cement. This solution was advantageous to produce cement in terms of CO_2 emission savings (Nagle et al., 2020; Schmidl and Hinrichs, 2010). However, this solution was only available in one location in Germany and required a significant investment to be implemented, EUR

5 million according to Sakellariou (2018) (Sakellariou, 2018). In 2022, the companies involved in this solution decided to put the activities on hold, as the volumes of composite waste were not significant enough to continue operating.

Economic Barriers: Disposal and landfill are not desirable solutions for the end-of-life of wind turbine blades and some countries have banned composite waste from landfill. The cost of landfilling composite waste ranges from EUR 120 per tonne in Denmark, EUR 113 per tonne in Ireland, EUR 55 per tonne in the US, EUR 130 per tonne in the UK and up to EUR 300 per tonne in Germany (Clinch, 2015; Sakellariou, 2018; Schmid et al., 2020). Alternatives to disposal were reviewed in the United States by Sproul et al. (2023) who highlight that the value of shredded composite materials is not well understood and that these materials may not be performing as well as virgin materials. Sproul et al. (2023) also report that the cement kiln route performs worse than mechanical recycling or microwave pyrolysis, although it avoids mining virgin materials for cement production.

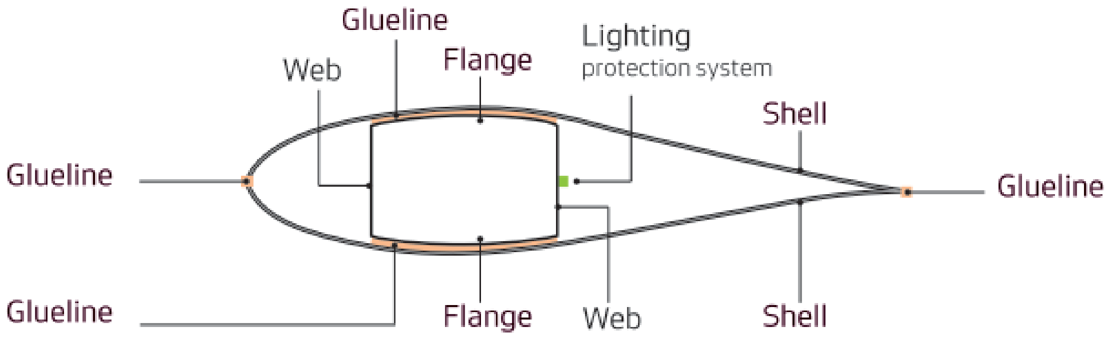
Despite the high number of research projects, only a few industries offer recycling for wind turbine blades and most of them are small to medium-size enterprises; see Table 2 and Table 3. Research on the recycling of fibre-reinforced polymer composite started in the early 1990s (Butler, 1991; Jutte and Graham, 1991; Petterson and Nilsson, 1994). Nowadays, research projects addressing most of the categories of the waste management hierarchy have been fulfilled or are ongoing. A large part of the research activities is dedicated to mechanical recycling solutions for composites and for wind turbine blades. Lund and Madsen (2024) estimate that half of the literature on composite recycling is dedicated to mechanical recycling solutions (Lund and Madsen, 2024). Ways to improve mechanical recycling processes and the quality of the recovered products have been and are still being investigated in several research projects. These include for example LIFE-GLASS FIBER 2007-2009 (EU), GenVind 2012-2016 (DK), EcoBULK 2017-2021 (EU), FiberEUse 2017-2021 (EU), DecomBlades 2021-2023 (DK), Blades2build 2023-2025 (EU). See Annex 2 for a list of all the past and ongoing projects dedicated to the recycling of fibre-reinforced composite and wind turbine blades in the EU. Nevertheless, an improved understanding of market factors and economic barriers is still needed:

- The market value of recycled materials from wind turbines and blades and whether they can compete on equal terms with virgin materials to avoid the extraction of virgin raw material need to be better understood.
- There is no research on reusing wind turbines, despite reuse being ranked as a preferable solution to recycling. This solution is proven economically and technically demonstrated by several smaller companies offering to buy and sell used wind turbines. However, it is not clear if reuse of larger wind turbines will be feasible in the future and there is a need to understand the advantages and drawbacks of that solution.

Information Barriers: Part of the technical challenges of recycling wind turbine blades is due to the structure and the type of materials used in blades. To add complexity, these structural and material aspects are evolving over time. Since the early 1990s, blades have increased in length from around 20 metres to beyond 100 metres in recent years (Singh, 2019). Materials in blades are regularly updated with for example the addition of carbon fibre-pultruded profiles or the use of new recyclable polymer resins. In addition, blade manufacturers use different polymer resins and core materials. Different types of fibres, core and polymer resins may have an impact on the processing conditions during recycling or on the business case. This type of information is therefore crucial for the recycling industry to plan activities. The challenge is that some of this information may be sensitive data in the wind industry. Wind turbine blades are highly engineered components and despite having similar structures and materials, details in geometries or fibre lay-up are competitive advantages and confidential information. In addition, different recycling solutions will need different types of information. For example, for a chemical recycling process it may be necessary to know the type of polymer resin used, while this information is not important for a mechanical recycling process. For wind turbine blade repurposing, aiming at transforming a blade into a footbridge, structural information would be essential, but may not be useful for a pyrolysis process.

In recent years, initiatives aiming at sharing information on blade structures and materials have been proposed. This is for example the blade material passport prepared in the Danish research project DecomBlades ("DecomBlades | Wind industry blade decommissioning," 2022; LM Wind Power, 2022; Siemens Gamesa Renewable Energy, 2022; Vestas, 2022). The targeted audience for this blade material passport are the companies that will take care of the blades at end-of-life. The goal for these blade material passports is to provide the necessary information for the recycling of blades. These short documents are structured in four sections and provide overall blade dimensions, blade design and blade materials. Figure 10 shows an example of the type of illustration used in such blade material passports.

Figure 10**:** Schematic representation of a wind turbine blade cross section as presented in the blade material passport for the V47 wind turbine blade from Vestas.



Source: (Vestas, 2022)

Another initiative comes from the German research project RecycleWind and is the environmental product declaration (TPI Composites, 2019). Environmental Product Declarations are standardised documents structured according to the ISO (International Standardisation Organisations) standard 14025. Their purpose is to quantify and provide environmental impact information throughout the life cycle of a product. These documents include some information about the material used in blades. The environmental product declaration prepared in the RecycleWind project looks at a wind turbine blade model from TPI Composites and intended for the recycling industry (TPI Composites, 2019). Like the blade material passport, the environmental product declaration provides information on the blade dimension, blade design and materials. Due to the nature of the document, it also includes life cycle assessment results. Finally, an upcoming EU initiative, which may address some of the needs of the recycling industry is the digital product passport (European Commission, 2024). This has not yet been implemented for wind turbines.

To recap, these initiatives are recent and only a few wind turbine blade models have been documented. It is not clear yet whether they provide the help needed in the recycling industry and how the wind industry could upscale this type of information-sharing. The following bullet points outline the needs related to wind turbine blade information:

- Test existing blade material passports and environmental product declarations to determine if they provide the necessary information to the recycling industry. If not, adjust to address information needed by recyclers.

- Understand the optimal way of sharing information about current and future wind turbines and blades and establish a standardised way of sharing this information.

To summarise this chapter and directly answer the research question “Can all wind turbine waste be recycled?”, the recycling of fibre-reinforced thermoset composite and wind turbine blades remains a challenge in the EU. While it is technically and economically feasible to recycle carbon fibres, recycled glass fibres, which represent **up to 60% by weight of blades, do not represent a clear business case** (Liu et al., 2022, 2019; LM Wind Power, 2022). Table 3 presents a list of companies offering recycling solutions for glass fibre-reinforced composites. Only a few of them have recycling for glass fibre composites as their core business and core activity. This highlights the challenges related to the recycling of that material and of finding applications for recycled glass fibres.

4.3 How much waste will be generated?

In this section, three different topics are presented and discussed: the future amount of wind turbine waste; the future amount of wind turbine blade waste; and data related to environmental impacts.

Reliable estimates of upcoming volumes of end-of-life wind turbines and wind turbine blades are essential to upscale recycling solutions and plan circular business cases. In the last decade, an increasing number of publications have investigated and estimated the future amount of wind turbine blade waste for several regions of the world (Andersen et al., 2016; Bech Abrahamsen et al., 2024; Chen et al., 2021; Cooperman et al., 2021; Delaney et al., 2021; Heng et al., 2021; Kramer et al., n.d.; Lefeuvre et al., 2019; Lichtenegger et al., 2020; Liu and Barlow, 2017; Sommer et al., 2020; Sultan et al., 2018; Tazi et al., 2019; Tota-Maharaj and McMahon, 2020; Volk et al., 2021). Estimating upcoming amounts of wind turbine blade waste relies on three types of information:

- **The number of wind turbines** currently installed as well as future installations.
- **The type of turbines** installed to estimate the mass of wind turbine blades.
- **The time** at which wind turbines will be decommissioned, recycled or disposed of.

Estimating wind turbine installations - In 2024, not all EU countries with wind energy installations have a national register of these installations. Many, but not all, MS maintain searchable and public national wind energy records, such as the German or the Danish market data register, to inform on the number of wind turbines installed (Bundenetzagentur, 2024; Danish Energy Agency, 2022).[12] These records are regularly updated and can be downloaded by the public in Excel sheets. However, for countries without these records, the current and future installation of wind turbines needs to be estimated based on government strategies and public announcements. This future installation may be modelled using various scenarios (Liu and Barlow, 2017). The amount of wind turbine and blade waste in future is defined by the projected deployment of wind turbines in the EU today. WindEurope provides the most detailed data available. It reports that there were over 3,000 onshore and offshore turbines installed in 2023 for only 18 EU MS in 2023 (see Figure 11) (WindEurope 2024).

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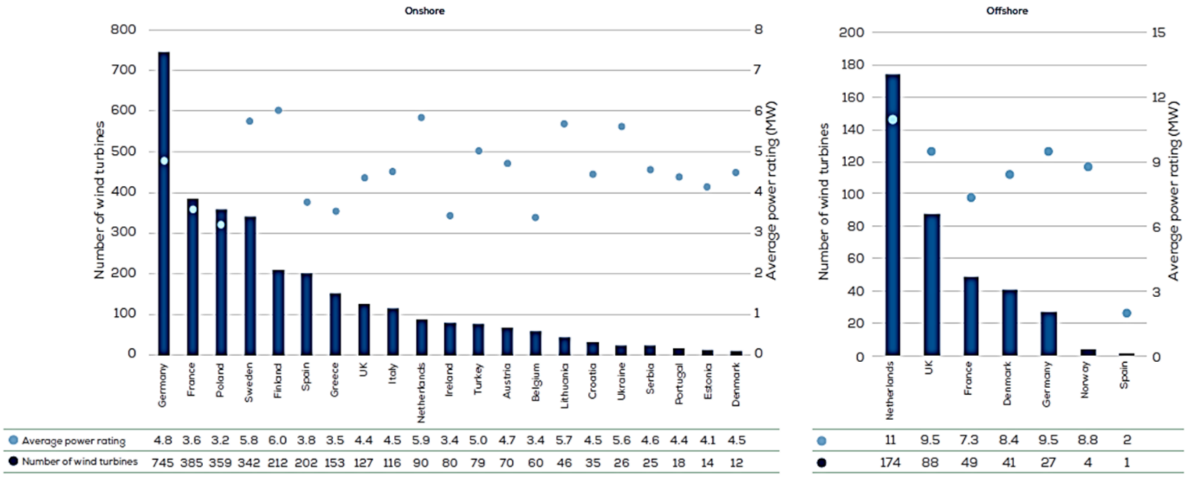
[12] Sources: Data: Oversigt over energisektoren | Energistyrelsen (ens.dk) and Erweiterte Einheitenübersicht | MaStR (marktstammdatenregister.de)

Figure 11: Number of turbines installed in 2023



	Germany	France	Poland	Sweden	Finland	Spain	Greece	UK	Italy	Netherlands	Ireland	Turkey	Austria	Belgium	Lithuania	Croatia	Ukraine	Serbia	Portugal	Estonia	Denmark
● Average power rating	4.8	3.6	3.2	5.8	6.0	3.8	3.5	4.4	4.5	5.9	3.4	5.0	4.7	3.4	5.7	4.5	5.6	4.6	4.4	4.1	4.5
● Number of wind turbines	745	385	359	342	212	202	153	127	116	90	80	79	70	60	46	35	26	25	18	14	12

	Netherlands	UK	France	Denmark	Germany	Norway	Spain
●	11	9.5	7.3	8.4	9.5	8.8	2
●	174	88	49	41	27	4	1

Source: WindEurope

Source: (WindEurope 2024)

Estimating type of turbines – The next piece of information is the mass of wind turbine blades per wind turbine. This can be estimated based on the type of wind turbine installed (Bech Abrahamsen et al., 2024; Liu and Barlow, 2017). However, information about the type of turbines installed may not always be recorded in the national wind energy records.

Estimating first end-of-life– Finally, the time at which wind turbines will be decommissioned and possibly reused or recycled is probably the most challenging parameter to model and predict. The Danish national wind energy records until 2022 and the German national wind energy records provide information on the date of decommissioning of wind turbines. In the literature, it is often assumed that the time of decommissioning corresponds to the technical design lifetime of wind turbines. Typically, the design lifetime of an onshore wind turbine is 20 years and of an offshore wind turbine 25 years (Bech Abrahamsen et al., 2024).

Common "typical case" assumptions are challenged by field observations and data collected in national wind energy records. For example, the reuse of wind turbines is estimated to be performed for 50% to 60% of Danish and German wind turbines (Kramer et al., n.d.). In addition, in 2022, in Denmark, a study concluded that 50% of wind turbines installed each year are decommissioned before being used for 29 years. This indicates that a significant number of Danish wind turbines have lifetimes significantly longer than 29 years (Bech Abrahamsen et al., 2024). Two conclusions can be drawn from these observations. First, the lifetime of wind turbines may be longer or shorter than their technical design lifetime. Second, the time of decommissioning does not correspond to the time of recycling. To model and predict the time of recycling of wind turbine blades, two questions need to be answered: When and why are wind turbines decommissioned? When and why are wind turbine blades being reused? Moreover, these questions need to be answered for specific wind power installations to have a detailed and accurate picture of wind power waste generation.

Understanding the time at which wind turbines are decommissioned includes understanding why the lifetime of turbines may be shortened or extended beyond their technical design lifetime. Incentives to decommission wind turbines may be related to technical, economic or legal aspects (Ziegler et al., 2018). For example, with high electricity prices, wind turbines may continue operation beyond the original designed lifetime as it becomes profitable to maintain their service. Another incentive may come from policy, which may encourage the replacement and repowering of existing wind turbines before the wind turbines reaches 20 or 25 years old (Bech Abrahamsen et al., 2024; Ziegler et al., 2018).

Determinative aspects such as age or repowering return on investment will be weighed differently from country to country and from owner to owner. In its 2023 Statistics Outlook for 2024-2030 report, WindEurope finds that "Many of Europe's onshore wind farms are approaching the end of their planned operational lifetime. Currently, 22 GW of Europe's existing wind farms have already been running for more than 20 years. By 2030, 52 GW of capacity will be more than 20 years old. Denmark, Portugal, and Spain have the oldest wind fleets on average. Germany has the largest installed capacity which could potentially be repowered, with almost 20 GW older than 15 years. Most wind farms reaching the end-of-life stage currently opt for some form of lifetime extension, not only because of the current economic situation, but often because legislative frameworks for repowering are not yet in place" (WindEurope 2024). Repowering or repair to extend useful life are certainly preferred circular economy strategies that are higher level options in the Waste Framework Directive's waste hierarchy than disposal. However, increasing repowering and life extension adds to the complexity of estimating when and why wind turbines are decommissioned.

The economic incentives to reuse wind turbines and wind turbine blades have not been well documented in the scientific literature yet. Reuse takes advantage of wind turbines already produced and should be the first option pursued before recycling. In 2024, several companies are selling used wind turbines; see Table 1. However, until 2024, only a single study has tried to quantify the number of wind turbines being reused (Kramer et al., n.d.). Additional studies are needed to analyse the advantages and limitations of such a solution from a technical, economic and legal perspective.

Within this context, it is difficult to predict the amount of future wind turbine or blade waste due to decommissioning and repowering. There are several credible yet wide-ranging estimates for the waste that will be generated in future from components of wind power as turbines are decommissioned. All estimates agree that a significant volume of waste will require treatment / disposal in future.

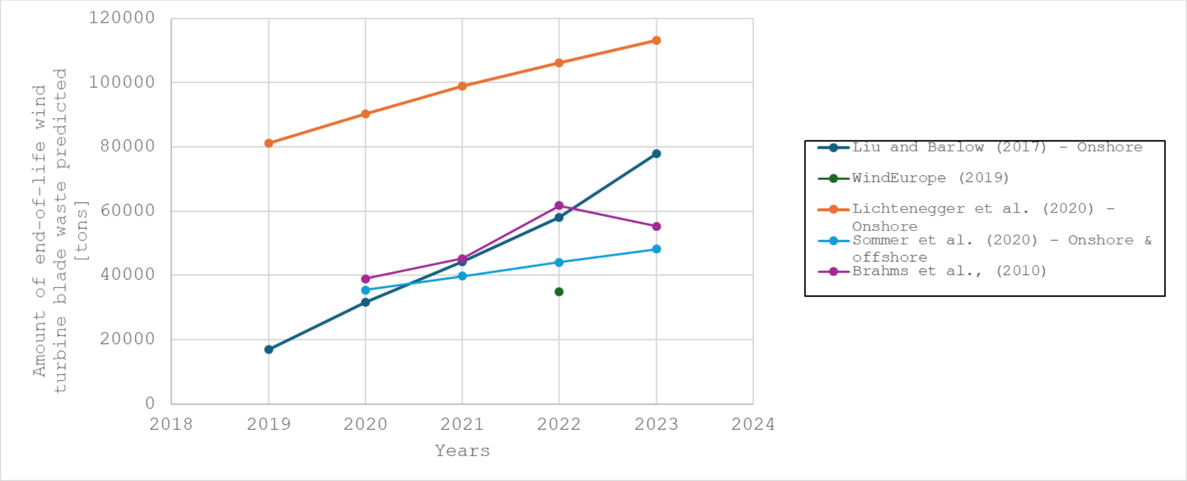
Estimates of waste going to landfill or incineration vary because of the assumed length of service (between 20 and 30 years) and the assumed treatments (refurbishment, reuse or recycling). In 2019, a projection by WindEurope, the association of wind power firms operating in Europe, forecast 35,000 tons of end-of-life wind turbine blades in 2020 in Europe (Dragan, 2019). WindEurope estimates that "about 4,700 turbines (or 14,000 blades equivalent to between 40,000 and 60,000 tons) could be decommissioned [by 2023]" (WindEurope 2020). The 4,700 refers to cumulatively decommissioned turbines. Lichtenegger et al. (2020) forecast that "the total [annual] waste blade material in 2050 will reach 325,000 t, 76% originating from onshore and 24% from offshore" (Lichtenegger, Rentizelas et al. 2020). These authors consider their results to be within the same order of magnitude as Liu et al. (2017), which estimate the global "end-of-life waste stream will annually generate more than 2 MT in 2050 and cumulative blade waste in 2050 will lie between 21.4 MT and 69.4 MT with the most probable waste level being 43.4 MT [with Europe at 25% of the global totals]" (Liu and Barlow 2017).

Figure 12 demonstrates the wide range of estimates based on the unique assumptions of each analysis for wind turbine blades. WindEurope points out that "Repowering trebles wind farm output on average while cutting the number of turbines by 25% (WindEurope 2024)". This means we are in a period of fluctuating empirical estimates.

To estimate the volume of materials in wind turbines that would become waste upon decommissioning by 2023, we apply the material intensity, defined as the volume of materials per turbine, to the estimated decommissioned turbines for 2023 (cumulatively) projected by WindEurope in 2020, which is 4,700 wind turbines and an average of 50,000 tonnes of composite material, cumulatively. (WindEurope 2020). We assume that the composite material is equivalent to fibreglass in blades. We use this estimate for two reasons. First, it reflects older turbines which would be decommissioned, and we did not identify a reported estimate of the number of turbines decommissioned in 2023 (annual). WindEurope reports that "736 MW of wind power across nine countries was decommissioned in 2023. The decommissioning took place in Germany (534 MW), France (50 MW), Denmark (49 MW), Italy (37 MW), Austria (19 MW), Belgium (17 MW), the UK (16 MW), Finland (12 MW) and Sweden (2 MW)" (WindEurope 2024). Second, the 2020 WindEurope projection of the number of turbines decommissioned in 2023 is contemporaneous with the turbine material intensity estimates of Moné et al. (2017).

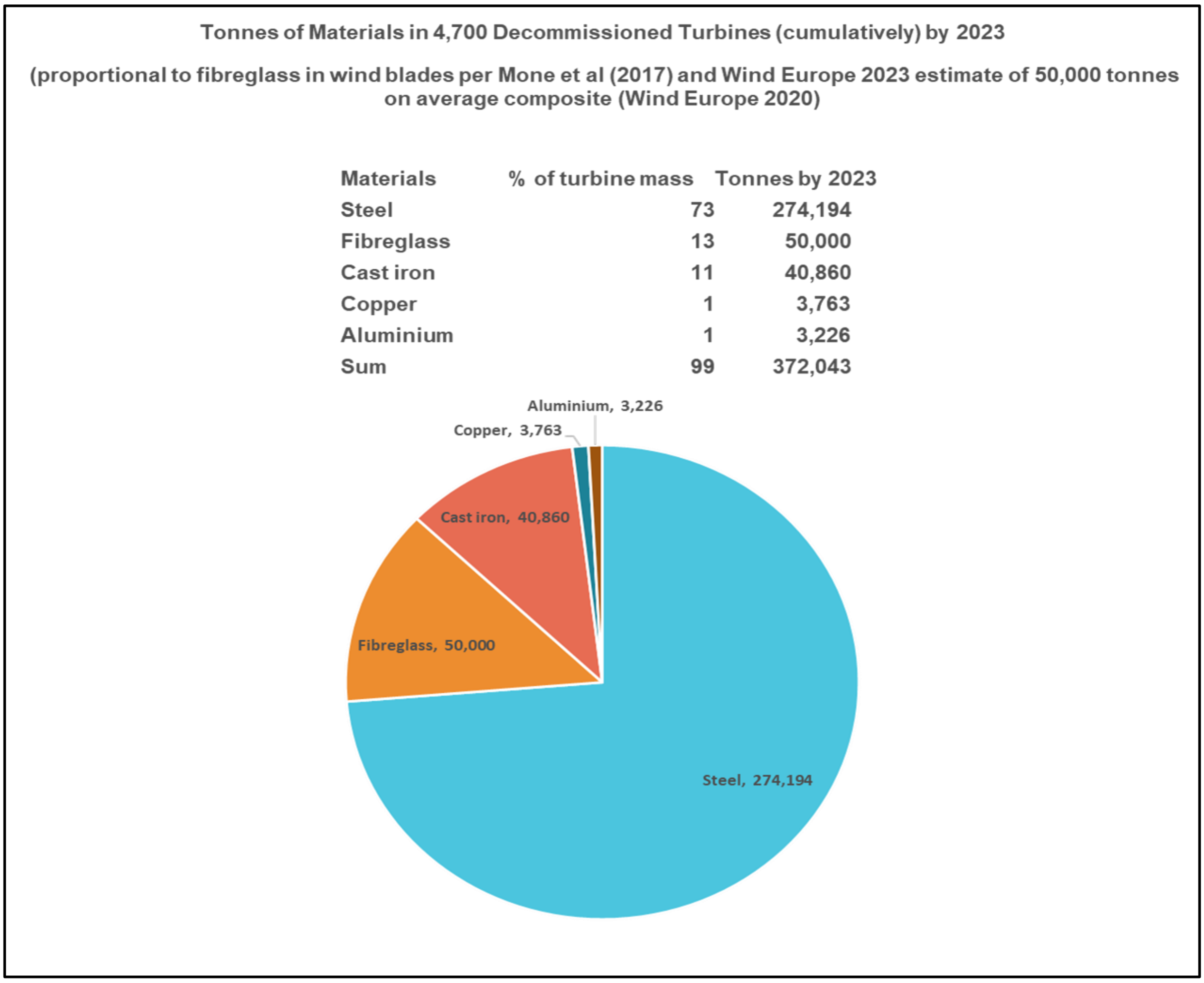
A 2017 survey of seven wind turbine models' bills of materials by Moné et al. (2017) showed that five materials, fibreglass, steel, cast iron, copper and aluminium, comprise over 98% of a turbine's mass (Moné, Hand et al. 2017). Assuming that these ratios hold, applying the average material intensity developed by Moné et al. (2017), we estimate that the material contained in the estimated turbines decommissioned by 2023 is over 3 million tonnes, as shown in Figure 13. These data take into consideration the entire wind turbine; however, it excludes the concrete foundation. While CEPRES presents first estimates of the material flows arising from wind turbines, it should be noted that the Horizon Europe FutuRaM (https://futuram.eu/) intends to release a dynamic dataset on materials arising from wind turbines in the EU, looking at base materials and trace metals, considering distributions of lifetimes and distribution in Member States in 2025. **Note that in 2024 it is not possible to verify whether this volume of waste was observed, as there are no data on the number of wind turbine parts kept as spare parts, recycled or landfilled.** There is a data collection gap which prevents detailed estimates for waste management and circular economy policy.

Figure 12: The wide range of estimates in the literature.



Source: Own elaboration.

Figure 13: Estimated materials in decommissioned turbines (cumulative) by 2023. Cumulative data highlights the waste that will be generated without establishing recycling solutions.



Tonnes of Materials in 4,700 Decommissioned Turbines (cumulatively) by 2023

(proportional to fibreglass in wind blades per Mone et al (2017) and Wind Europe 2023 estimate of 50,000 tonnes on average composite (Wind Europe 2020)

Materials	% of turbine mass	Tonnes by 2023
Steel	73	274,194
Fibreglass	13	50,000
Cast iron	11	40,860
Copper	1	3,763
Aluminium	1	3,226
Sum	99	372,043

Source: Own elaboration based on proportion of fibreglass in wind turbine blades (WindEurope 2023 and WindEurope 2020)

The collection of data on the destination of end-of-life wind turbines can support the validation of methods to predict future waste. These data would provide a better understanding of the potential for reuse and second life of wind turbines. The national wind energy records are useful tools. The following bullet points summarise recommendations to address the data gaps presented in this section:

- All EU countries with wind energy installations should have records of the installation and decommissioning of wind turbines. A common way of recording data would be optimal to perform analyses of several countries. Also, common data could include the types of turbines installed.
- National wind energy records could keep track of the fate of materials beyond decommissioning. There is a lack of data on the number of wind turbine blades kept as spare parts, recycled or landfilled.
- A comprehensive study is needed on the business of reusing wind turbines including the destinations of sold wind turbines.

Environmental impacts

Recycling is necessary to reduce the amount of waste landfilled, reduce the extraction of raw materials, and avoid environmental impacts related to these processes. However, recycling should also reduce the overall environmental impacts of the product recycled. It is therefore essential to assess the environmental impacts of recycling solutions. For this purpose, life cycle assessments (LCA) are commonly used as a method. However, LCA uses databases where recycling processes are usually not described. In general, the modelling of recycling processes with LCA is challenged by two aspects:

- **Lack of recycling at scale**: not all recycling solutions are available on a commercial scale and many processes are still being developed in research institutions. It is therefore challenging to collect representative data to perform LCA.
- **The applications of recycled materials:** when modelling recycling it is important to know what the recycled materials are used for. In LCA, recycled materials offset virgin material in new products that would otherwise need to be extracted. However, applications for recycled materials are not always known or well documented.

As a result, in existing LCA studies of wind energy, the end-of-life part is not always modelled or is modelled with generic data of common disposal processes, even though it is recognised that recycling is a potential source of significant impact reduction (Alsaleh and Sattler, 2019; Bonou et al., 2016; Martínez et al., 2009; Schreiber et al., 2019; TPI Composites, 2019; Weinzettel et al., 2009). To overcome this issue, a few studies have investigated the modelling and the comparison of end-of-life treatments for wind turbine blades using LCA (Nagle et al., 2020; Pender et al., 2023; Sproul et al., 2023). In the United States, Sproul et al. (2023) conclude that processes based on mechanical recycling and microwave pyrolysis have the lowest net greenhouse gas emissions (Sproul et al., 2023). In the UK, Pender et al. (2023) came to a different conclusion and estimated that for glass fibre-reinforced polymer composites, the cement kiln route and mechanical recycling were the only end-of-life scenarios resulting in reduced CO_2 emissions compared to landfilling.

Different geographical locations, different local energy mixes and different assumptions can result in different conclusions. The quality of the data also plays a vital role in the results obtained. The “RecycleWind” research project highlights the need for more data of reliable quality to obtain more reliable estimates (TPI Composites, 2019). It also highlights that, due to the lack of tight specifications around the selection of end-of-life scenarios, assumptions used in LCA modelling vary widely and that in the end it is not possible to compare results. Finally, the reuse of wind turbines is a preferred solution at end-of-life compared to recycling as it ranks higher in the waste management hierarchy, also in terms of environmental impacts avoided. However, it is rarely modelled, despite having shown great benefits in Schreiber et al. (2019) (Schreiber et al., 2019). In summary, the following is necessary:

- Collect more data on recycling processes. And there is a need for standardisation of data and information used in LCA regarding processes and material flows for all the end-of-life steps, decommissioning, pre-processing, recycling and post-processing.
- Propose a uniform approach to the modelling of end-of-life scenarios.
- There is no research on the degradation of glass fibre-reinforced composite in soils. Since landfilling of composite is still being used, there is a need to understand and characterise the environmental impacts of landfilling composites.

4.4 What policies are needed to increase circularity?

Policies and legislation play a significant role in the establishment of new sustainable behaviours such as recycling (Cherrington et al., 2012; Reynolds and Pharaoh, 2010). A policy push can be performed by using different tools and by setting different targets. Legislation could for example target the producers of wind turbines with extended producer responsibilities or the owner of the product by implementing a landfill ban. This chapter starts by presenting the importance of waste codes for wind turbine blades and clear definitions for end-of-life strategies. It concludes by presenting an overview of EU legislation, standards and procedures, highlighting the diversity of tools existing in the EU.

4.4.1 Identifying wind turbine blade materials with specific waste codes

In the EU, waste is designated with a six-digit number that describes the material content of the waste based on how it was produced (Schmid et al., 2020). As fibre-reinforced polymer composites are made of several materials, it is not always clear which code to give them. Polymers are organic material, whereas glass fibres are inorganic materials, therefore waste codes such as 17 02 03 "plastic waste from construction and demolition", 07 02 13 "waste plastic" or 10 11 03 "waste glass based fibrous materials" could be suitable to designate their content (Dragan, 2019; Schmid et al., 2020). For example, in Denmark, polymer composite wastes are treated according to the regulations of the local commune (Skaarup Justesen and Lykke Nielsen, 2013). With the challenges in designating composite waste, it has been reported that different labels are used for composites across the country (OECD, 2019). There is a need for a specific waste code for wind turbine blade materials. This would enable interested parties to keep track of amounts of wind turbine blade waste being landfilled or recycled. This would also support the development of methods to estimate more accurately future amounts of wind turbine blade waste.

4.4.2 Defining waste management solutions as chain of processes

As mentioned in the previous section, in the EU Directive 2008/98/EC on waste ranks waste management solutions in five categories (prevention, preparing for re-use, recycling, other recovery and disposal). This ranking uses broad definitions that can be challenged. An example is the case of the cement kiln route, where it is being argued that the cement kiln route is a recycling solution despite using energy recovery ("Recycling threat to Europe's composites industry," 2006). The broad definitions are also a challenge in research. In the scientific literature dedicated to the recycling of wind turbine blades, the word recycling is used to describe any processes taking place at the end-of-life of blades (Kramer and Beauson, 2023). There is a need to clarify the definitions and have a consensus on which ones to use through research-based regulation. Clear definitions also need to emphasise the value chain perspective of recycling. In research dedicated to the recycling of wind turbine blades, recycling has often been addressed as the development of one single technology. However, as explained earlier, the end-of-life of wind turbine blades is a succession of processes leading to recycling, including decommissioning, cutting, pre-processing and post-processing. Finally, to guide researchers, there is a need to clarify when a recycling value chain is successful, by defining success criteria for recycling. These success criteria could for example be based on LCA results.

4.4.3 Harmonising legislation across EU countries on wind turbine blade recycling

In the EU, despite having a common Waste Framework Directive, national legislation for composite waste may be quite different. National legislation, standards and tender requirements may have an influence on end-of-life decisions and practices, as well as waste management infrastructures available in EU Member States. Below, an overview of the European measures impacting the end-of-life of wind turbine blades is presented. As suggested by Mackie et al. (2022), this overview is divided into three categories: “hard law” measures, “soft law” measures and tender requirements; see also Table 4 (Mackie 2024). “Hard law” measures comprise laws and regulations for which legal actions could take place, if there is a lack of compliance (standards are included in this category). “Soft law” measures can be described as voluntary initiatives which are non-binding. This is typically a publicly announced strategy but could also be guidelines and recommended practices. Tender requirements are criteria used to select candidates’ bids for the construction of wind farms. In 2022, Mackie and al. (2022) concluded that there are only a few European countries that have hard law measures specifically dedicated to wind turbine blade decommissioning and recycling. As mentioned in the introduction, practices for decommissioning wind turbines can be very different, but there is currently no common legislative approach on how to plan and perform decommissioning. In some countries, a decommissioning obligation fund is set aside at the beginning of the project to cover the cost of the dismantling processes at end-of-life. In Germany, a specification for onshore decommissioning was formulated (Aschemeyer et al., 2020). This specification also includes recommendations for the recycling steps. There is a need to upscale this specification and formulate an international standard for the decommissioning of wind turbines.

Regarding recycling and landfilling, there are landfill bans for fibre-reinforced polymer composite waste in Germany and the Netherlands (Schmid et al., 2020). These landfill bans apply to end-of-life wind turbine blade materials and may apply to other composite products such as boat hulls and automobile components. However, according to WindEurope, landfilling may still be practised in the Netherlands (Schmid et al., 2020). Indeed, if the cost of recycling or other alternative treatments is higher than EUR 200 per tonne, then an exemption may be granted. In 2024, France is the only country that has a law dedicated to the recycling of wind turbine blades with a specific recycling target. In all other EU countries, the treatment of composites at end-of-life follows the general framework for waste management. Mackie and al. (2022) note that companies in the wind energy sector have committed to landfill bans, despite the lack of legislation on landfill (Mackie 2024). This observation is also reported elsewhere (Kramer and Beauson, 2023). Finally, in recent years, a range of tender requirements targeting ecology and recycling have been used in tender processes for new offshore wind farms in France, the Netherlands and Denmark. Despite addressing a similar topic, these tender requirements are quite different. Currently, initiatives at EU level in the context of the NZIA Act aim at defining non-price criteria for procurement of low carbon technologies, including wind turbines. Therefore, there is a need to understand the strengths and weaknesses and potential synergies between hard law, soft law and tender requirements. With a commitment from the wind industry on a landfill ban and tender requirements, which can be established relatively easily, the recycling of blades could be incentivised. However, given the diversity of tender requirements’ topics, one may wonder if a counterproductive effect may occur. Finally, in other regions of the world, such as the United States and China, similar challenges are experienced (Sproul et al., 2023; Yang et al., 2023). The United States and China have similar waste management hierarchies to Europe, but they have a low landfill tax, which is challenging recycling activities (Sakellariou, 2018; Yang et al., 2023). It should also be noted that companies from these countries have not yet voluntarily announced a commitment to a landfill ban.

Table 4: Overview of hard law measures, soft law measures and tender requirements (adapted from (Mackie et al., 2022))

	Country / Organization	**Year**	**Type**
Hard law measures	France	2020	Legislation specific to wind turbine blade waste with recycling targets
	Germany	2009	Landfill ban on polymer composite
		2019	Specification on decommissioning of wind turbines including recycling steps
	The Netherlands	2009	Landfill ban in principle on polymer composite
Soft law measures	Wind turbine owners (Vattenfall, Ørsted)	2021	Landfill ban commitment
	Wind turbine manufacturers (SGRE, Vestas, LM WindPower)	2021	Landfill ban commitment
	Wind industry association (WindEurope)	2021	Landfill ban commitment
Tenders	The Netherlands	2024	Requirements on ecology. Wind farm developers need to present and demonstrate their strategy addressing ecology considering a life cycle perspective.
	France	2024	Requirements on recycling, according to the French law. Since 2022, 90% of the total mass of wind turbines needs to be recycled, including 35% of the wind turbine blade mass.
	Denmark	2024	Requirements on the recyclability of wind turbine blades. The recyclability of wind turbine blade needs to be calculated and demonstrated.

Strategies to address the policy gaps mentioned in this chapter are summarised here. There is a need to:

- establish a waste code for wind turbine blades;
- clarify the definitions for wind turbine blade recycling, reuse, processing leading to recycling, etc.;
- establish international standards dedicated to the decommissioning of wind turbines;

- investigate utility of an EU-wide registry of decommissioning
- better understand the strength and weaknesses and potential synergies between hard laws, soft laws and tender requirements.

4.5 Wind Power Waste: Key learnings and policy strategies

The key learnings about wind power waste quantities and challenges are summarized below. These are followed by potential policy strategies to better manage wind power waste in the EU drawing from these insights. The strategies are noted for further exploration and potential implementation.

- In the EU by 2050, it is estimated that over 10 MT of wind turbine blade waste will be generated annually. (Based on Liu et al. (2017).)
- The target set by the European Commission on renewable energy is to increase the share of energy consumed from renewables from 23% in 2022 to 42.5% in 2030. To meet that target, 425 gigawatts of wind energy capacity must be installed by 2030. Assuming standard 10 MW turbines are installed, in 2030, there could be 42,500 wind turbines in the EU.
- The net capacity of wind energy installed in 2050 is predicted to be around 860 GW.
- If all wind turbines are assumed to be 10 MW machines, there will be 86,000 turbines in 2050.
- Approximately 85% of a wind turbine's weight is made up of metals (excluding the foundation), which have established recycling solutions. The remaining 15% includes the blades, which are mostly made of glass fibre-reinforced thermoset composite. These materials are difficult to recycle, since they cannot be softened, remelted or reshaped.
- Wind turbine foundations are mostly concrete, which has limited recyclability today. **EU-wide measures supporting increased concrete recycling will increase also impact the recycling of wind turbine installations.**
- Wind turbine blades are complex structures and blades cannot be easily disassembled and separated into parts. They are made of varied materials, including 1% by weight of metal. Wind turbine blades are not all identical and changes in materials can affect the performance of recycling processes. Therefore, **sharing information on blade structures and materials would support the recycling industry in the planning of activities and business cases.**
- The end-of-life of a wind turbine is a complex value chain, made up of many steps, with various stakeholders and decisions. **Recycling takes place after several steps and is challenged by decisions taken upstream, such as the selection of decommissioning procedure. Therefore, guidance on decommissioning strategies can improve future recycling.**
- Environmental impacts of recycling processes are challenging to estimate, because limited data are available on recycling processes. Proper modelling of environmental impacts also requires modelling the application of the recycled materials produced, which is not always clear. Some recycling solutions are not optimised yet and comparison of environmental impacts between solutions may not be relevant. **There is a need to establish a systematic collection of data to model the environmental impact of recycling value chains. An EU-wide registry of decommissioning may be a solution to be investigated.**

- **Estimating future amounts of wind turbine blade waste is essential for the recycling industry to plan activities**. However, projections are challenging because the time at which wind turbine blades need recycling is difficult to predict. Keeping track and records of wind turbine blades recycled or landfilled would support and validate estimation methods. **This requires the implementation of a waste code specific to wind turbine blade materials and the collection of data**.
- Often recycled materials compete with virgin counterparts that have more reliable and better properties for certain uses. Some countries have banned landfill or have high landfill fees, which supports the economy of recycling. However, this is very different from country to country. **There is a need to first understand and potentially harmonise waste management legislation regarding wind turbines.**
- Reuse of wind turbines is not being thoroughly investigated despite being a higher ranked end-of-life solution than recycling. Understanding the potential and the limitations of this solution could support its implementation on a wider scale. **An EU-wide policy response could be to impact assess policies to manage and track reuse of wind turbines.**

5 Waste from solar power in the EU

This section highlights the challenges in the management of PV panels when they reach their end-of-life. To this end, (i) data gaps on future waste streams are emphasised and a contribution on how to fill these gaps for the 27 EU countries is presented, (ii) policy gaps on measures for the promotion of circular economy including collection, remanufacturing, reuse and recycling are identified, and (iii) research gaps on the advancement of panel design promoting recycling, recyclability and material extraction are discussed. The section answers the research questions with regards to electricity supply from solar power and as organised by the research questions:

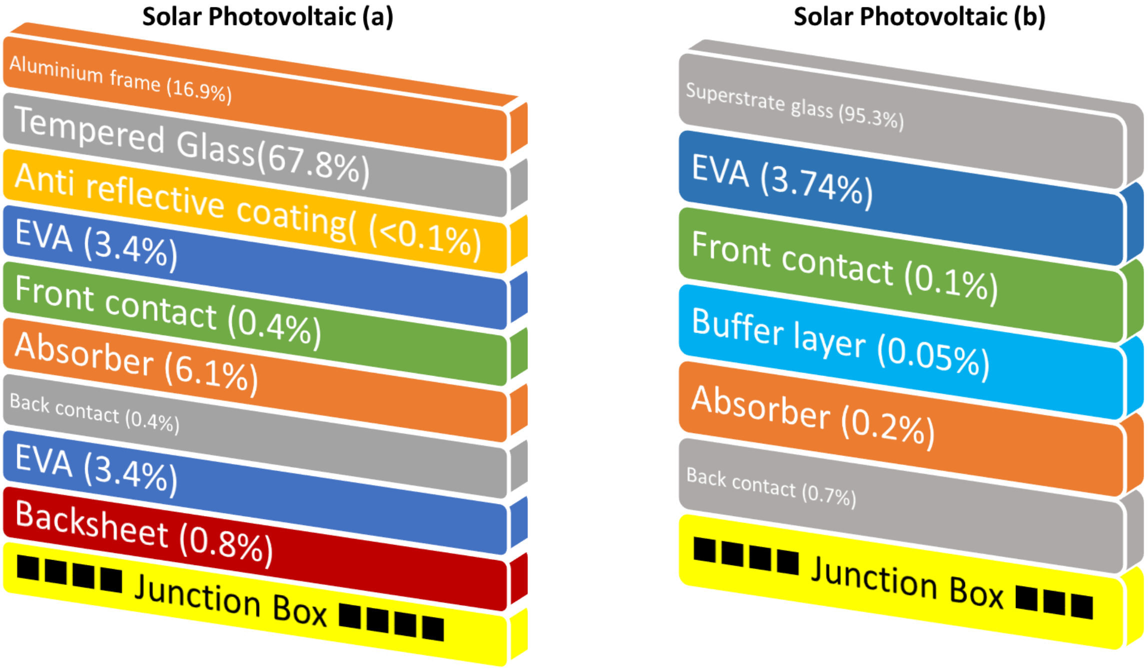
- What technologies, infrastructures, and materials are included in the composition of solar power waste that require a circular economy perspective?
- Can all solar power waste be recycled?
- How much waste in future?
- What policies are needed to increase circularity?

5.1 Which technologies, infrastructures, and materials?

This section answers the research question, "What technologies, infrastructures, and materials are included in the composition of solar power waste that require a circular economy perspective?"

Solar panels are arranged like a sandwich with a layered structure. A crystalline silicon solar cell is shown in Figure 14 (a). Tempered glass is placed on top of the photovoltaic module, while an EVA (Ethylene-vinyl acetate) film is applied between the glass and the photovoltaic cells. Again, the EVA film is deposited between the PV cells and the polyvinyl fluoride (Tedlar) backsheet. The units are framed and sealed with silicon sealant in an aluminium frame and supplied with a junction box with output contacts. Silver combined with copper forms the electrical connections. In Figure 14 (b) a CdTe panel is presented. These panels are slightly different as they do not have an aluminium frame because the solar cells are sandwiched between two pieces of glass and their structure uses more robust backsheets, yet the layered structure still applies.

Figure 14: (a) Crystalline silicon solar cell (Ag:0.07%, Cu:0.7%, Ni:0.001%,Ti:5.8E-6%) and (b) CdTe solar cell (Cd:0.1%, Cu:0.6%, Al:0.05%, Te:0.1%, Zn: 1.8E-7%). Source: Maani, T., Celik, I., Heben, M. J., Ellingson, R. J. & Apul, D. Environmental impacts of recycling crystalline silicon (c-SI) and cadmium telluride (CDTE) solar panels. Science of the Total Environment 735, 138827 (2020). (Maani, Celik et al. 2020)



Source: Own elaboration.

Despite the diversity of PV technologies, they are all based on the same layered structure. The primary technologies used in photovoltaic cell and modules are crystalline silicon (both mono and poly), thin-film (amorphous silicon, perovskite, copper indium gallium selenide, and cadmium telluride), and multi-junction modules (Chatzipanagi, A., 2023). There is continuous research and development on silicon-based new cell structures to increase cell efficiency (Yoshikawa et al., 2017; Xu et al, 2024). Research for new photovoltaic cells also includes innovative inorganic nanostructures like metal oxides and nanoparticles as well as organic-based nanomaterials like graphene and carbon nanotubes (Singh, Goyal et al. 2021, Pastuszak and Węgierek 2022).

C-Si PV cells account for 80-95% of the world's installed capacity, because of their comparatively great efficiency and reasonable cost (Pastuszak and Węgierek 2022). It is important to quantify the waste distribution of different PV technologies, as they require different recycling processes to recover the embedded materials. The CEPRES Strategies Report provides a new analysis that quantifies the waste volume and distribution of PV technologies below.

5.2 Can all PV waste be recycled?

The life cycle of a PV module starts from the production of raw material, then the manufacturing, the use of the panel and, in a closed life cycle, the waste treatment of the panel, to recover materials for new production of panels or other goods (Tao, Yu et al. 2015). To assess when PVs become waste, there are statistical and physical methods to estimate degradation rates. Many studies use different assumptions, leading to different estimated quantities of waste. Among these assumptions is the simplification of a constant degradation rate. However, it has been shown that the failure mode of a panel is not constant over time, but rather follows a probability distribution (Kastanaki and Giannis 2022).

The probability distribution scenarios commonly used are the regular loss (RL) and the early loss (EL) scenarios proposed by the International Renewable Energy Association (IRENA) (Weckend, Wade et al. 2016). The RL scenario assumes that there are no premature panel retirements or failures and that the panels operate within their manufacturers' guaranteed lifetime of approximately 30 years. Also, the lifespan distribution function proposed by the EU WEEE Directive is another scenario that assumes an average lifetime of 22.5 years, while the EL scenario assumes 26.6 years and the RL 27.7 years. The EL and the WEEE Directive predict early failures, reliably modelling panel failures under transport, installation and use conditions. However, when a failure occurs, it is not certain that the panels will enter the waste stream, as power losses may be tolerable for economic or other reasons. Thus, the EU WEEE Directive scenario can predict actual losses and RL, the amounts of waste that eventually enter the waste stream. The RL scenario predicts that 90% of installed panels will survive for about 20 years after installation, while the EL and EU WEEE Directive scenarios predict 12 and 13 years, respectively (Kastanaki and Giannis 2022).

PV waste material composition - Considering a dynamic material content (Annex 4) and 2 market share scenarios for the penetration of c-Si technology (Annex 3) the accumulated material quantities for the c-Si waste panels are computed and shown in Figure 15. "Dynamic" refers to time-dependent material content values that take into account the evolution of photovoltaic technology, which renders panels lighter and more efficient with time (Kastanaki, 2025). The methodology to calculate waste materials is illustrated in section 5.3.1 and Annex 3. For the distribution of PV technologies, two market share scenarios are employed, a Low c-Si penetration scenario (LSS) (Weckend et al., 2016; Mahmoudi et al., 2019; Kastanaki, 2025) and a High c-Si penetration scenario (HSS) (Fraunhofer ISE, 2022). The accumulated amount of waste glass will be 3.9-9.9 MT by 2040, while the amount will increase to 12-27 MT by 2050. Aluminium will total 0.86-1.8 MT by 2040 and 2.14-4.1 MT by 2050. For silver, the cumulative amount by 2040 will be 4,900-7,860 tonnes, while by 2050 it will be 9,200-13,240 tonnes. Silicon will amount to 0.2-0.45 MT by 2040 and 0.54-1.1 MT by 2050. The results here are similar to the discussion in Kastanaki (2024). The amounts are even greater when all waste technologies are considered, as shown in Table 5. In addition, graphics showing the data are provided as Annex 4 and the market share is provided in Annex 5.

The materials gathered by 2040-2050 with the highest mass shares (RL scenario, Table 5a (LSS) and Table 5b (HSS)) are glass (67-71%), Al (11.8-14.2%), steel (7.7-8.2%), EVA (5.5-6.1%), Si (2.7-3.4%), Cu (0.78-0.90%) and Mg (0.42-0.44%). However, when the revenue is calculated based on commodity prices and the recycling yield of each material, precious metals (e.g. Ag), which have a small mass proportion (0.073-0.078% by 2040), contribute significantly to the total revenue (19.2-20%). The economic share of silver will be 13.3-13.6% by 2050 because of the lower silver content (mass share of 0.046%) in modern panels. Furthermore, Si accounts for 22.9-25.6% of financial revenues by 2040-2050 despite having a mass share of only 2.7-3.4%. The 2017 metal prices in Mahmoudi et al. (2021) are employed in this work (see also section 5.2.1) and the recycling yields reported in Table 5, which are average yields reported in literature (Kastanaki, 2025).

Additionally, considering the materials collected from other photovoltaic technologies (a-Si, CdTe, and CIGS), notable quantities of Mg, Ga, In, Mn and Ti will accrue, as shown in Table 5. The EU considers these metals critical raw materials due to their significant economic value and high supply risk (Kastanaki, E. & Giannis, 2022). The a-Si technology is phased out by 2015 in this analysis, but the waste will be generated in the years after 2015.Furthermore, largely because of thin-film solar panels, the amount of harmful Cd will reach 900-1,300 and 3,400-5,500 tonnes by

2040 and 2050, respectively. However, compared to other Cd compounds, CdTe has a reduced toxicity and leachability, hence CdTe panels do not pose an environmental risk. Only non-recycled panels that may enter incineration present a risk of Cd emissions and therefore there is a strict take-back program by manufacturers to guarantee that the modules are actually recycled. In the EU there is one CdTe PV recycling plant in Germany (Raugei et al., 2012; Held et al., 2024).

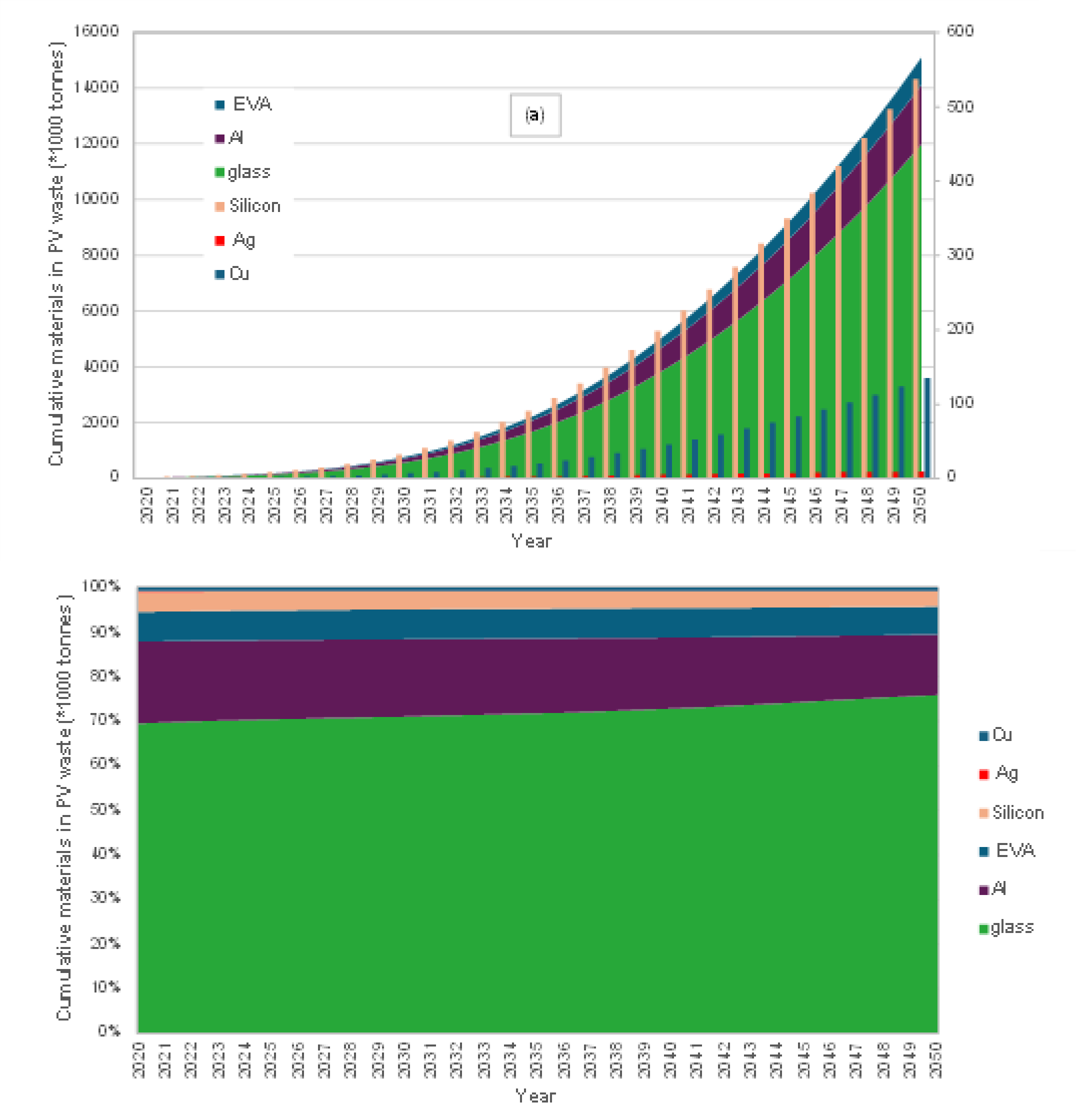
5.2.1 Economic value of recycled materials

Economic Barriers - In general, dedicated PV recycling is a complicated process and prices for alternative disposal options weigh against commercial-scale solar panel recycling. The literature points to several reasons for the slow development of recycling capacity dedicated to material recovery from the entire panel, including processing difficulties such as the delamination phase, lack of sufficient quantities of end-of-life panels, low-cost landfilling, and downcycling of several materials, including glass (Heath, Silverman et al. 2020, Tsanakas, van der Heide et al. 2020, Mahmoudi, Huda et al. 2021, Deng, Zhuo et al. 2022). Deng et al. (2022) and Grijelmo et al. (2022) note the connection between well-functioning secondary materials markets and PV recycling, which focuses on materials that are higher in volume in PVs such as aluminium and glass. “Aluminium frames and recycled silver have a large and sustainable market demand. They are openly traded in the recycled material market with different pricing matching different purity levels.” (Deng, Zhuo et al. 2022). In specialised processes, other materials in PVs with less well-functioning secondary materials markets such as glass and crystalline silicon are routinely downcycled (Farrell, Osman et al. 2020). Glass constitutes the greatest proportion by weight of all materials in PVs, which results in glass cullet. However, this crushed glass fraction contains impurities such as polymers or metals and is therefore of low economic value (Heath, Silverman et al. 2020). Recovering high-purity glass can be costly, which makes it difficult to compete with virgin raw material (quartz sand), which is abundantly available at a low price (Nyffenegger, Boukhatmi et al. 2024). Ardente et al. (2019) showed that high-efficiency and high-quality recycling of materials contained in PV panels, for example glass (Ardente et al., 2019) but also those contained in low quantities, for example silicon and silver, has the capacity to significantly increase the material efficiency and life cycle performance of PV panels. (Tao, Fthenakis et al. 2020)

The revenues are calculated considering the prices of materials and the efficiency of recycling (Gautam, Shankar et al. 2021, Gautam, Shankar et al. 2022). The gross value of materials in PV waste is projected to reach 12.2 billion euros and 32-37.6 billion euros by 2040 and 2050, respectively (RL scenario, LSS and HSS) (Kastanaki, 2025). This work references the prices in Mahmoudi et al. (2021) which are from 2017. Note that most metal prices have since risen. Therefore, recycling will be desirable in future, especially if the EU aims to develop the PV manufacturing sector and reduce material imports. However, the current relatively low levels of PV waste that are collected, and the associated high costs of collecting, transporting and processing used panels to advanced recycling are economic barriers today. There is insufficient incentive for recyclers to develop advanced recycling capacity today, given the high availability and low cost of alternative disposal methods (landfilling and recycling for base metals). However, this could change as waste volumes increase and collection efficiencies to transport the waste to advanced recycling sites improve. In 2019, Ardente et al. wrote that “More precise forecasts of the quantities of PV waste generated in future (and their geographical distribution) would help to optimise collection and recycling strategies.” (Ardente, Latunussa et al. 2019). This information is needed to gauge where and when advanced recycling plants would be viable. This question is addressed (asked and answered) in Section 5.3.

To summarise this chapter, and directly answer the research question “Can all solar PV waste be recycled?” the EU has little existing commercial-scale dedicated PV recycling capacity which can chemically recover low-concentration metals (e.g. silver). Today, recycled glass from PVs, which is the largest component by weight, is not suitable for reuse in many applications including PVs. The current recycling processes generally downcycle PV glass due to the impurities. It is possible, yet expensive, to remove impurities to make the glass suitable for new applications.

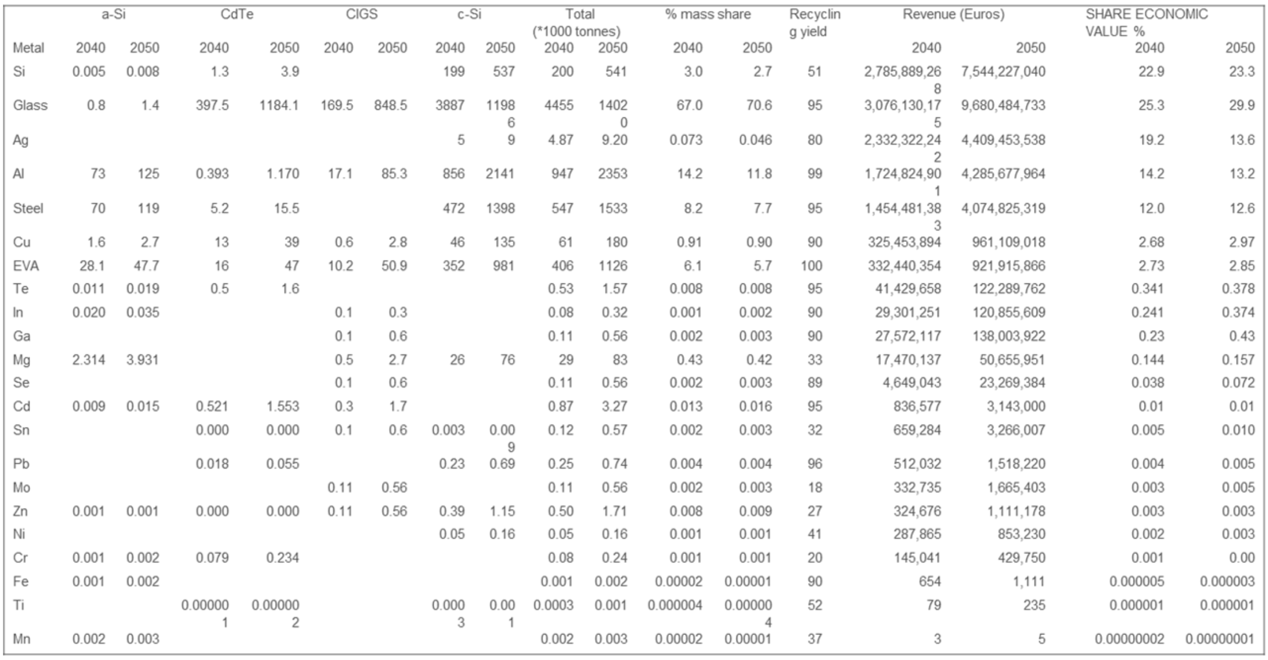
Figure 15: Amounts of silver, silicon, glass, encapsulant, aluminium and copper (fixed) accumulated from c-Si waste panels in the EU under the RL, LS scenario. In Figure 15 (a), Si, Ag and Cu (bars) correspond to the secondary axis.



Source: Own elaboration.

Table 5: Materials accumulated from PV technologies and their financial value in 2040 and 2050 (a: RL scenario), LSS; b: RL scenario HSS)

(a)



	a-Si		CdTe		CIGS		c-Si		Total (*1000 tonnes)		% mass share		Recycling yield	Revenue (Euros)		SHARE ECONOMIC VALUE %	
Metal	2040	2050	2040	2050	2040	2050	2040	2050	2040	2050	2040	2050		2040	2050	2040	2050
Si	0.005	0.008	1.3	3.9			199	537	200	541	3.0	2.7	51	2,785,889,268	7,544,227,040	22.9	23.3
Glass	0.8	1.4	397.5	1184.1	169.5	848.5	3887	11986	4455	14020	67.0	70.6	95	3,076,130,175	9,680,484,733	25.3	29.9
Ag							5	9	4.87	9.20	0.073	0.046	80	2,332,322,242	4,409,453,538	19.2	13.6
Al	73	125	0.393	1.170	17.1	85.3	856	2141	947	2353	14.2	11.8	99	1,724,824,901	4,285,677,964	14.2	13.2
Steel	70	119	5.2	15.5			472	1398	547	1533	8.2	7.7	95	1,454,481,383	4,074,825,319	12.0	12.6
Cu	1.6	2.7	13	39	0.6	2.8	46	135	61	180	0.91	0.90	90	325,453,894	961,109,018	2.68	2.97
EVA	28.1	47.7	16	47	10.2	50.9	352	981	406	1126	6.1	5.7	100	332,440,354	921,915,866	2.73	2.85
Te	0.011	0.019	0.5	1.6					0.53	1.57	0.008	0.008	95	41,429,658	122,289,762	0.341	0.378
In	0.020	0.035			0.1	0.3			0.08	0.32	0.001	0.002	90	29,301,251	120,855,609	0.241	0.374
Ga					0.1	0.6			0.11	0.56	0.002	0.003	90	27,572,117	138,003,922	0.23	0.43
Mg	2.314	3.931			0.5	2.7	26	76	29	83	0.43	0.42	33	17,470,137	50,655,951	0.144	0.157
Se					0.1	0.6			0.11	0.56	0.002	0.003	89	4,649,043	23,269,384	0.038	0.072
Cd	0.009	0.015	0.521	1.553	0.3	1.7			0.87	3.27	0.013	0.016	95	836,577	3,143,000	0.01	0.01
Sn			0.000	0.000	0.1	0.6	0.003	0.009	0.12	0.57	0.002	0.003	32	659,284	3,266,007	0.005	0.010
Pb			0.018	0.055			0.23	0.69	0.25	0.74	0.004	0.004	96	512,032	1,518,220	0.004	0.005
Mo					0.11	0.56			0.11	0.56	0.002	0.003	18	332,735	1,665,403	0.003	0.005
Zn	0.001	0.001	0.000	0.000	0.11	0.56	0.39	1.15	0.50	1.71	0.008	0.009	27	324,676	1,111,178	0.003	0.003
Ni							0.05	0.16	0.05	0.16	0.001	0.001	41	287,865	853,230	0.002	0.003
Cr	0.001	0.002	0.079	0.234					0.08	0.24	0.001	0.001	20	145,041	429,750	0.001	0.00
Fe	0.001	0.002							0.001	0.002	0.00002	0.00001	90	654	1,111	0.000005	0.000003
Ti			0.000001	0.000002			0.0003	0.001	0.0003	0.001	0.000004	0.000004	52	79	235	0.000001	0.000001
Mn	0.002	0.003							0.002	0.003	0.00002	0.00001	37	3	5	0.00000002	0.00000001

(b)

	c-Si								
	(*1000 tonnes)		% Mass share		Recycling yield (%)	Revenue (Euros)		Share Economic Value %	
Metal	2040	2050	2040	2050		2040	2050	2040	2050
Si	216	690	3.4	3.0	51	3,009,792,134	9,611,473,297	25.0	25.6
Glass	4308	16045	67.0	70.3	95	2,974,570,821	11,078,399,442	24.7	29.5
Ag	5.03	10.43	0.078	0.046	80	2,409,918,017	4,999,579,343	20.0	13.3
Al	917.11	2682.41	14.3	11.8	99	1,670,598,827	4,886,284,916	13.9	13.0
Steel	518	1849	8.1	8.1	95	1,378,100,305	4,915,675,498	11.4	13.1
Cu	50.14	178.86	0.78	0.78	90	268,213,326	956,715,320	2.23	2.55
EVA	384	1266	5.98	5.55	100	314,797,169	1,036,944,095	2.61	2.76
Mg	28.34	101.10	0.441	0.443	33	17,295,409	61,692,620	0.144	0.164
Sn	0.00	0.01	0.000	0.000	32	18,185	64,867	0.000	0.000
Pb	0.25	0.91	0.004	0.004	96	521,547	1,860,356	0.004	0.005
Zn	0.43	1.52	0.007	0.007	27	275,977	984,408	0.002	0.003
Ni	0.06	0.21	0.001	0.001	41	316,427	1,128,694	0.003	0.003
Ti	0.0003	0.001	0.000004	0.000004	52	87	310	0.000001	0.000001

Note: “Recycling yield” is the average current yield of existing recycling technologies. For a sensitivity analysis on advancements in recycling yields, see Kastanaki (2025). LSS: Low c-Silicon penetration Scenario, HSS: High c-Si penetration Scenario.

5.3 How much waste will be generated?

This section discusses the volume and composition of PV waste in future and concludes that many material demands for manufacturing in the EU can be met through recycling. The first step in establishing effective management of PV waste is to estimate future waste volumes, the distribution of different technologies and their composition. Different studies use different input assumptions, thus leading to different results. Factors affecting the results include different projections of future deployment capacity, different countries/regions considered, PV lifetime assumed to be fixed or following a probability distribution, distribution of various PV technologies considered or not considered at all, conversion from installed PV capacity to mass taken as fixed or dynamic, and material composition (and projections) considered or neglected (Kastanaki and Giannis 2022). Each of these input parameters has an impact on the estimates and raises the degree of uncertainty in the outcomes.

The updated 2023 draft National Energy and Climate Plans (NECPs) guide the current PV waste assessment for the EU-27 countries, by adopting the targets set by each of the EU-27 countries to implement solar photovoltaic modules (PVs) to cover their energy needs (Kastanaki, 2025). The updated NECPs' targets are moving towards covering 42.5% of the EU's total energy demands with renewable energy (Commission 2023).

Data on PV installations are first gathered for the years 1993 to 2022, and projections are subsequently made for the years 2023 to 2040 using the goals established in the NECPs of the 27 EU Member States. While converting panel power to mass, a dynamic conversion factor is included. Two technology scenarios are considered (Annex 3), the first considers only c-Si and thin film technology (HSS) and the second (LSS) considers eight photovoltaic technologies—a-Si, c-Si, CdTe, CIGS, CPV, OPV, advanced c-Si and 'Other'—as well as their respective dynamic conversion factors are considered. The LSS has been used in the literature to describe the distribution of PV technologies in various EU countries including Italy (Paiano, 2015), the European OECD countries (Germany, France, Spain, Italy, etc.) (Mahmoudi et al., 2021), as well as non-EU countries, i.e. Australia (Mahmoudi et al., 2019) and the HSS has been used for the USA (Ovaitt et al., 2022) and globally (Xu et al., 2024). The Fraunhofer Institute for Solar Energy Systems in the 2024 Report refers to global production of c-Si and thin-film PVs according to the HSS, which could be considered more plausible for the EU according to current trends (Fraunhofer ISE, 2024). Along with the present technologies, such as c-Si and thin-film, the market share of new PV modules, such as organic and CPV modules, is included in the calculation of PV waste flows (Mahmoudi et al., 2019). Afterwards, waste panels are predicted using dynamic material flow analysis employing three dynamic Weibull panel lifespan distribution scenarios (EL, RL and the EU WEEE Directive). Particularly for crystalline silicon panels—which comprise the vast majority of waste panels—a dynamic material composition that takes technological advancement into account is used as opposed to a fixed composition. Finally, considering the material composition of the panel technology and the efficiency of metal recycling, the potential for recovering precious materials and their economic value is computed (Kastanaki, 2025).

The NECPs predict that, by 2030, the cumulative capacity deployed in the EU-27 will be 624 GW, more than twice as much as the previous objective of 339 GW (set in 2019) and 4.6 times more than that of 135 GW in 2020 (capacities refer to DC values). Germany (34.5% or 215 GW), Italy (12.8% or 78 GW), France (9.6%, 60 GW), Spain (12.2%, 76.4 GW), the Netherlands (4.1%, 25.7 GW), Austria (3.4%, 21 GW), Portugal (3.3%, 20.4 GW) and Belgium (2.5%, 15.9 GW) are the countries with the biggest shares in 2030**. Also, the cumulative PV installations by 2040 in the EU, according to NECPs, will be 1,116 GW.**

According to the results, the EU-27 will cumulatively amass 6-13 MT and 21-35 MT of PV waste by 2040 and 2050, respectively. The annual PV waste is expected to reach 0.9-1.5 MT by 2040 and 2.1-2.5 MT by 2050. By 2040, the total PV waste under the revised

targets will be 10-42% greater compared to the old target of 32.5% renewable energy across the EU-27.

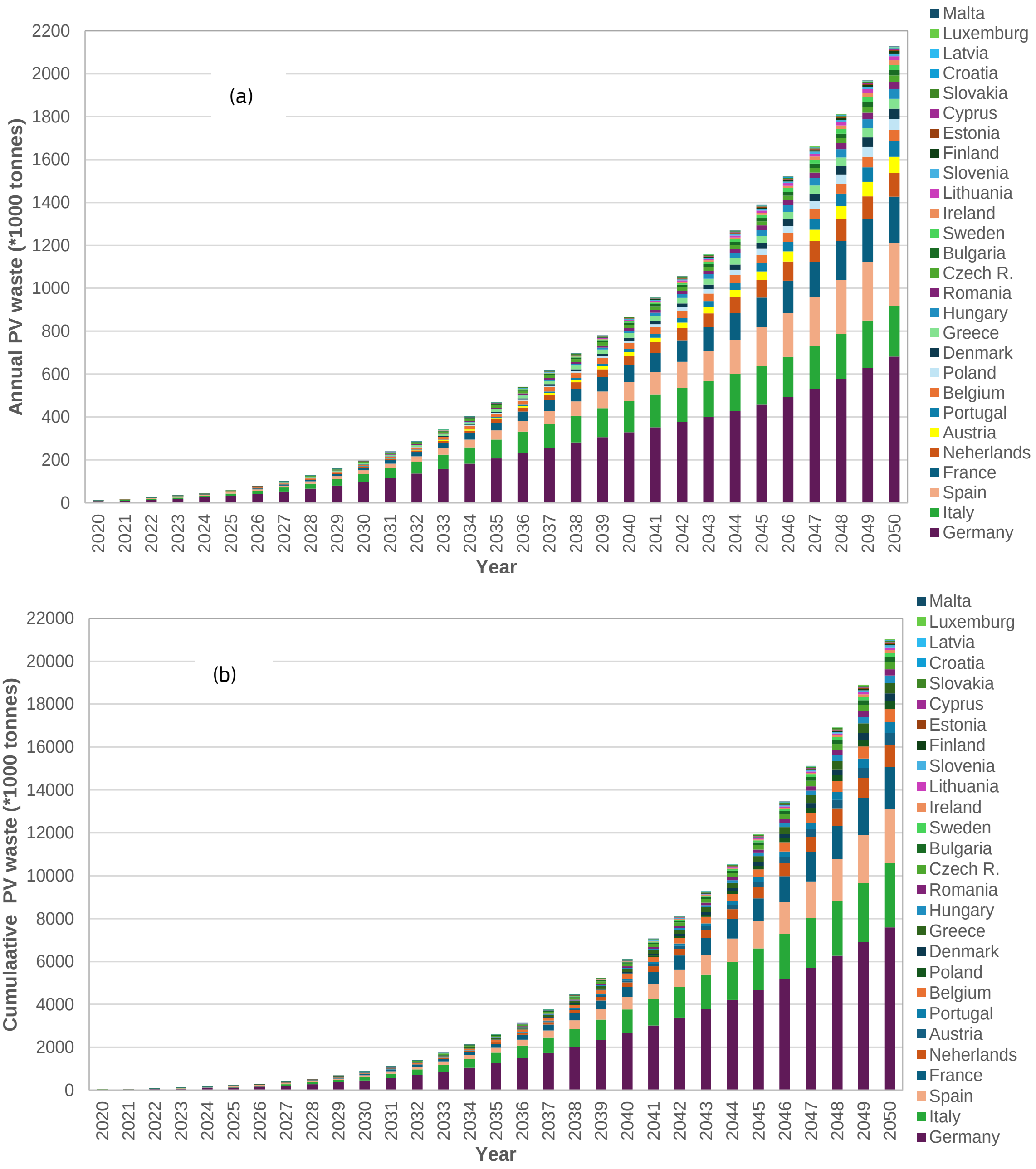
Germany has the largest amount of cumulative PV waste by 2040, ranging from 2.66 MT to 5.02 MT (compared to 2.50-3.96 MT under previous targets), as shown in Figures 16 and 17. Italy is the next country with the highest amount of cumulative PV waste, with 1.11-2.04 MT (up from 1.05-1.70 MT under previous targets); followed by France with 0.48-1.18 MT (up from 0.47-1.02 MT) and Spain with 0.58-1.5 MT (up from 0.43-0.84 MT). The estimated PV waste is considerably higher by 2050, as shown in Table 6. **Compared to the IRENA report, by 2050, Germany's waste will be 76-133% higher than previously estimated. Italy's waste increases by 43-71% and France's by 30-52%. Therefore, the EU must prepare for much larger quantities of PV waste in the future than previously predicted.**

Table 6: Cumulative PV waste by 2040 and 2050 for the RL, EL and EU WEEE Directive scenarios

Country/ Cum. MT	**2040**			**2050**		
	RL	**EL**	**EU WEEE**	**RL**	**EL**	**EU WEEE**
Germany	2.66	4.35	5.02	7.59	10.0	12.2
Italy	1.11	1.71	2.04	2.99	3.75	4.56
France	0.48	1.05	1.17	1.95	2.73	3.37
Spain	0.58	1.35	1.50	2.53	3.25	4.14
Netherlands	0.21	0.53	0.61	1.04	1.23	1.57
Belgium	0.21	0.34	0.41	0.61	0.76	0.94
Austria	0.09	0.29	0.30	0.55	0.86	1.07
Portugal	0.07	0.26	0.26	0.50	0.85	1.05
Denmark	0.07	0.19	0.20	0.37	0.56	0.70
Greece	0.14	0.27	0.31	0.49	0.64	0.78
Poland	0.05	0.18	0.19	0.36	0.54	0.68
Hungary	0.05	0.18	0.19	0.35	0.46	0.60
Romania	0.07	0.16	0.17	0.29	0.44	0.53
Czech R.	0.13	0.20	0.24	0.34	0.44	0.54

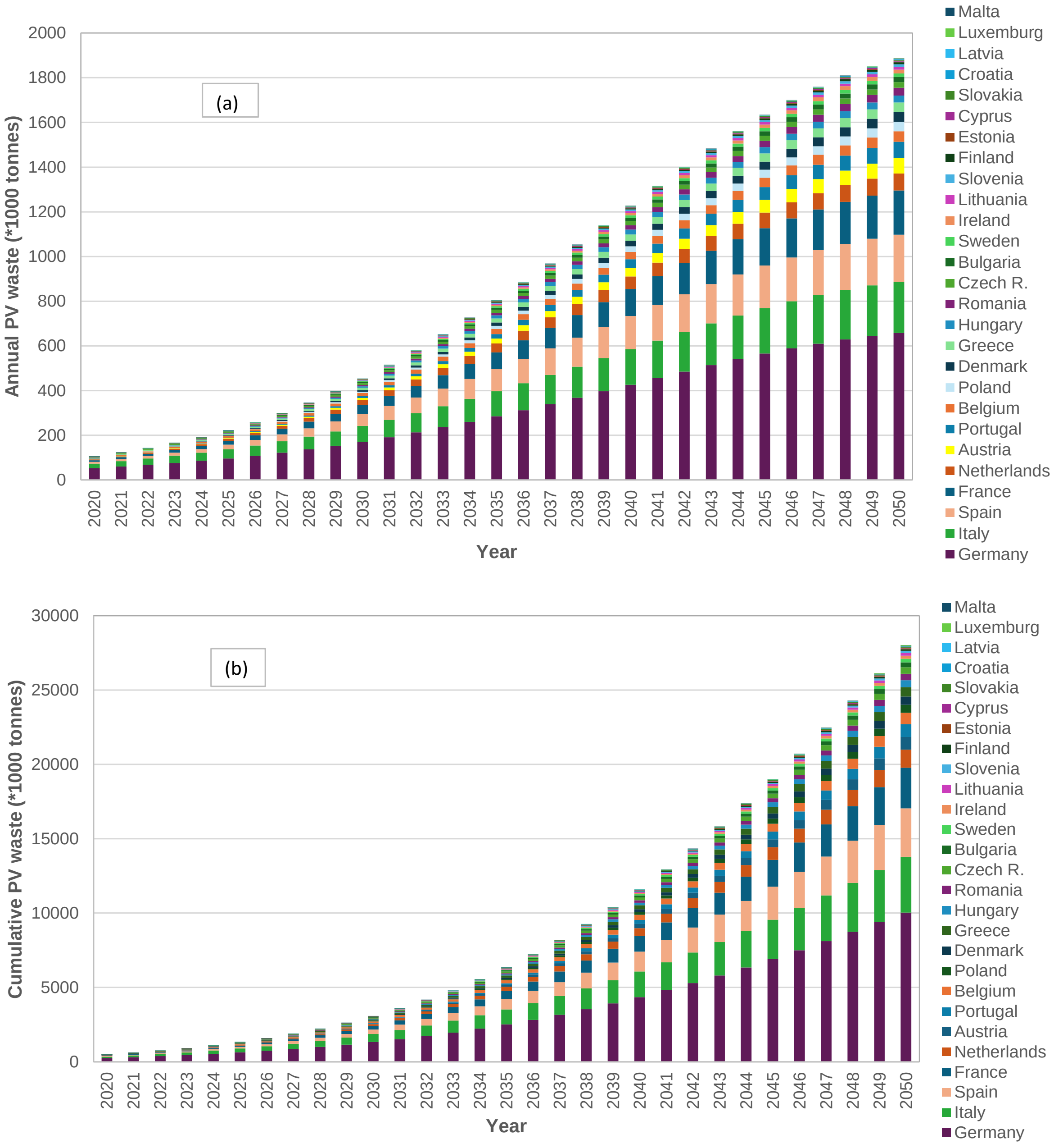
Bulgaria	0.06	0.13	0.14	0.23	0.33	0.40
Sweden	0.029	0.096	0.105	0.190	0.24	0.32
Slovenia	0.018	0.051	0.053	0.096	0.147	0.183
Slovakia	0.031	0.042	0.052	0.072	0.079	0.095
Finland	0.009	0.037	0.038	0.073	0.115	0.144
Luxembourg	0.009	0.017	0.019	0.03	0.038	0.048
Lithuania	0.014	0.065	0.066	0.126	0.17	0.23
Cyprus	0.007	0.017	0.019	0.034	0.053	0.063
Croatia	0.004	0.013	0.014	0.026	0.037	0.048
Ireland	0.009	0.068	0.061	0.127	0.220	0.286
Estonia	0.006	0.020	0.023	0.041	0.049	0.065
Malta	0.004	0.008	0.010	0.016	0.019	0.024
Latvia	0.0005	0.0024	0.0024	0.005	0.007	0.009

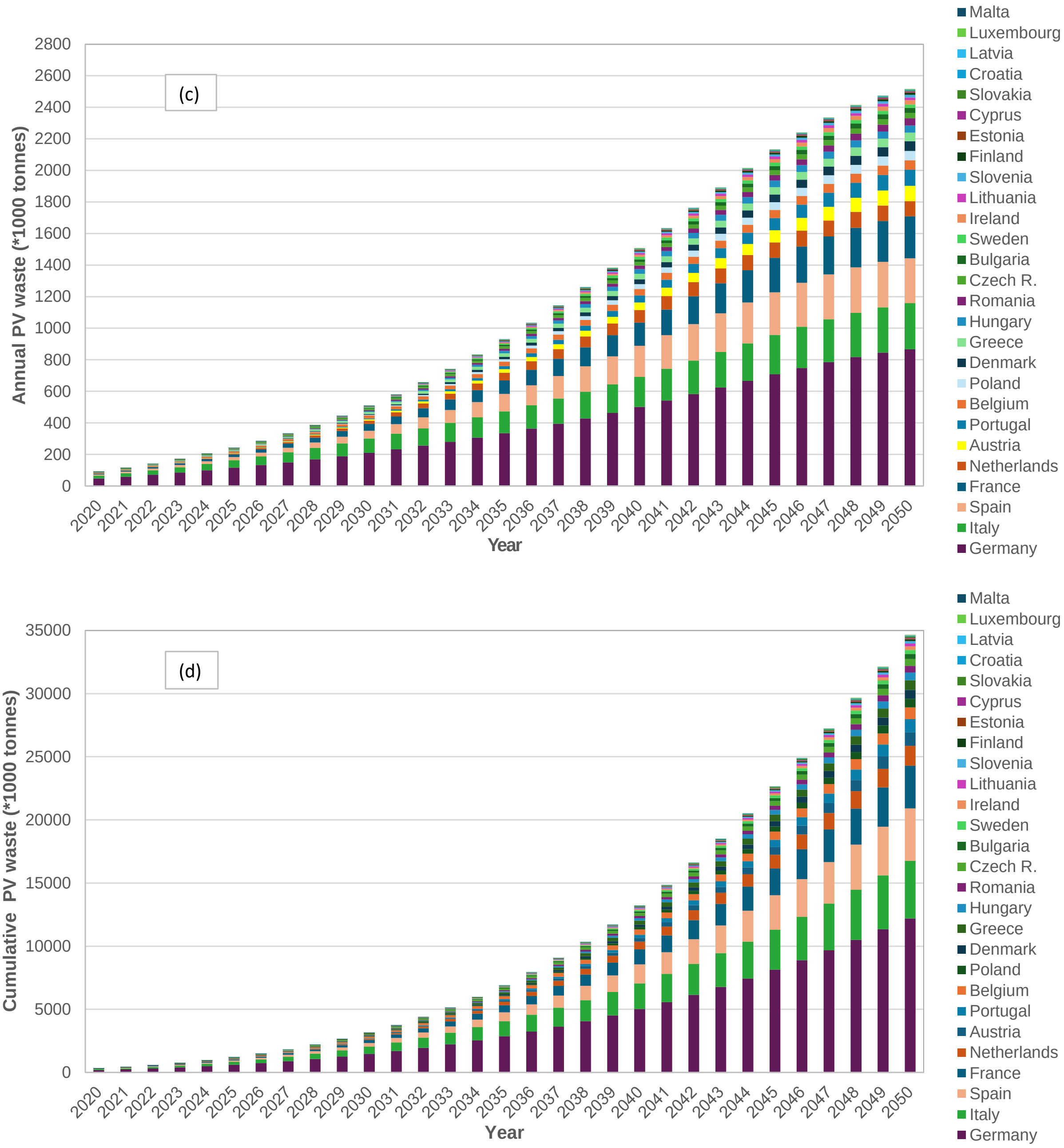
Figure 16: (a) Annual and (b) cumulative PV waste in the EU-27 countries (RL scenario).



Source: Own elaboration.

Figure 17: (a) Yearly and (b) cumulative PV waste in the EU-27 countries according to the EL scenario and (c) annual and (d) cumulative PV waste in the EU-27 according to the EU WEEE Directive scenario.





Source: Own elaboration.

The volume of cumulative PV waste as developed in the current study and presented in the above figures is not the full story. For PV waste, the type of waste panels and its material composition are also essential information needed to develop policies that improve circularity. Therefore, an additional step was taken to assess the types of panels present in the forecasted waste streams.

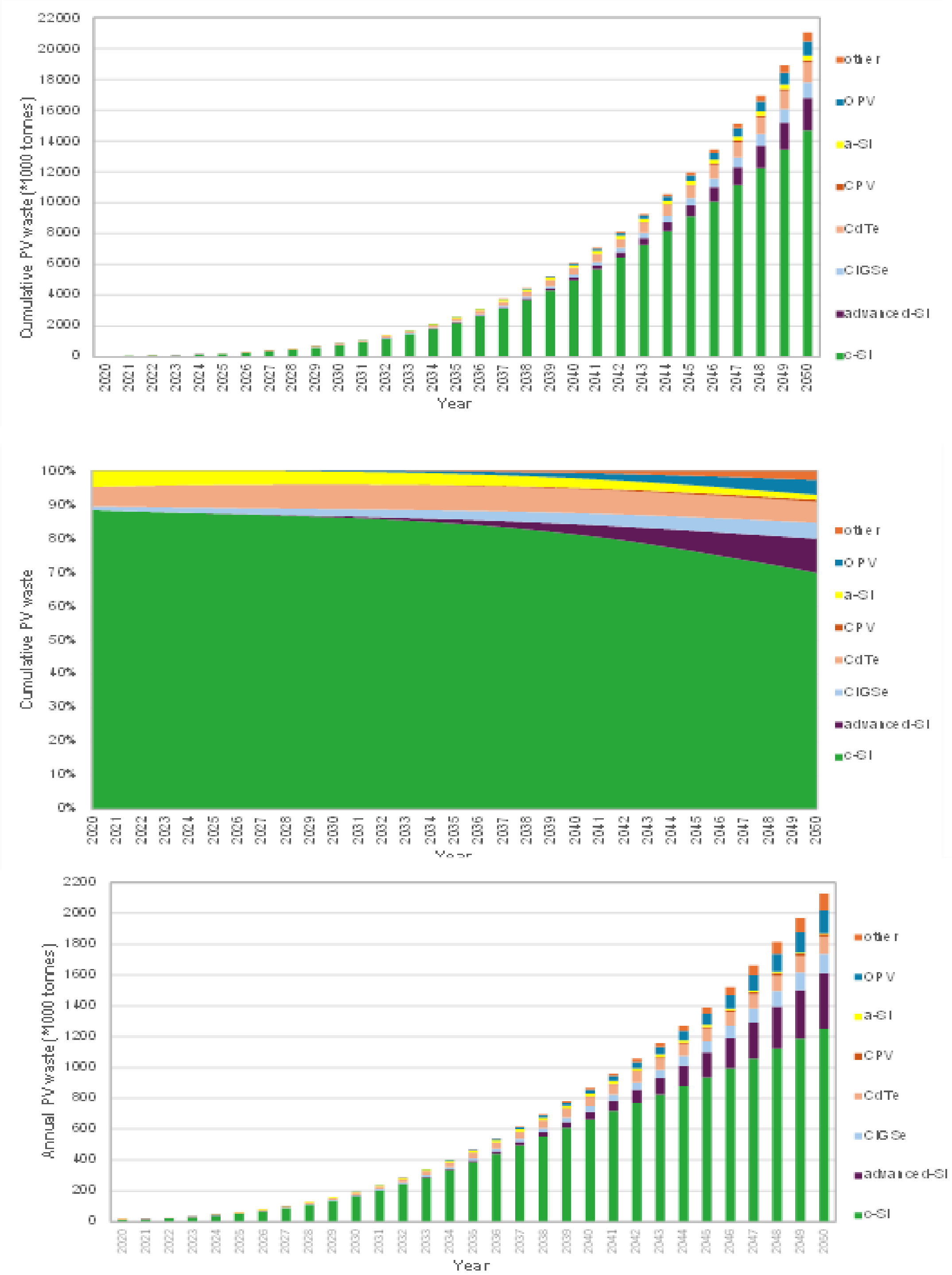
Furthermore, the RL scenario is the most conservative option. The conservative projections under the RL scenario reflect a realistic snapshot of current waste collection at the EoL (end-of-life) stage. The other two scenarios predict larger quantities of waste because they reflect the wastes that occur at all stages of transport, installation and use in addition to EoL treatment streams. The EL and EU-WEEE Directive scenarios reflect waste amounts that would be captured by better collection systems.

5.3.1 Assessment of waste streams of various PV technologies

The categorisation of waste panels is significant because different recycling processes and regulations are used for different types of photovoltaic waste, thus it is important to consider the distribution of PV technologies among the waste. Figure 18 (RL scenario, LSS) displays the yearly and cumulative PV waste in the EU-27 for the various PV technologies (c-Si, a-Si, CdTe, CIGS, advanced c-Si, OPV, CPV, and ‘Other’). Although some technologies are not currently used, i.e. a-Si is phased out by 2015 in this analysis, their panel waste will be generated in the years after 2015. CPV installations have a very low share, 1% in 2015 which decreases thereafter, and OPV also has a small share. In this analysis, there was an attempt to be as detailed as possible, as due to the long lifetime of PVs their waste will occur in the future, even if some technologies are not currently implemented.

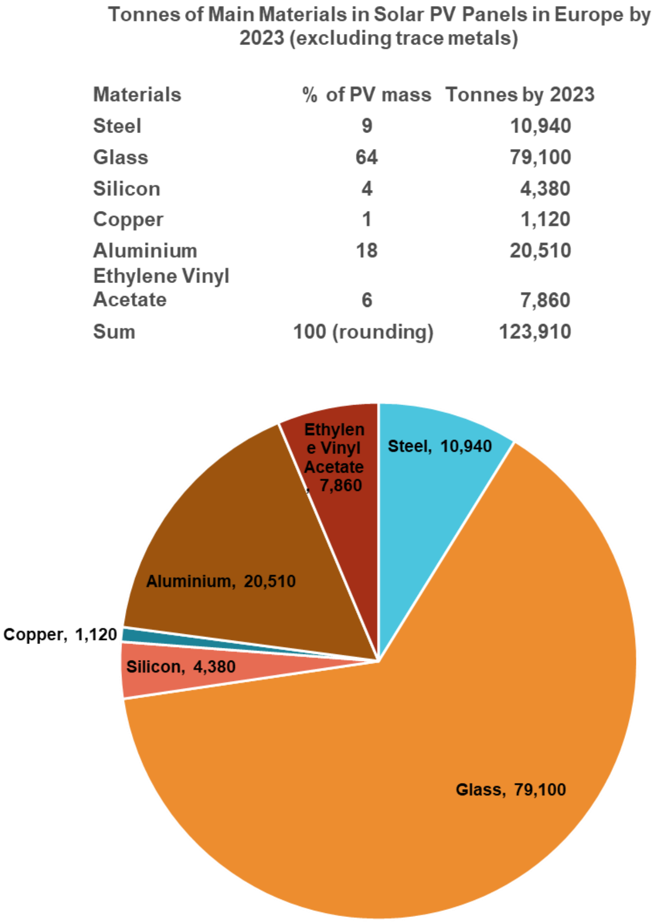
With the knowledge of the past PV technologies deployed, we can estimate the material composition and value of cumulative PV materials deployed by 2023. This is an estimated snapshot considering the technology shares of panels in use and decommissioned, as reported in Kastanaki (2025). Figure 19 shows that steel, glass and aluminium are the most prevalent materials by weight in PVs accumulated in the EU by 2023. Table 7 shows that silicon glass, aluminium, steel and silver are the most valuable materials in 2023. Most panel waste belongs to crystalline-Si technology, as shown in Figure 20 (Kastanaki, 2025). *For 2023, the results of LS and HS scenario coincide when the RL scenario is used for PV lifetime), as HS scenario differs from LSS starting from 2014 and this does not affect the calculated waste quantities until 2024.*

Figure 18: Annual and cumulative PV waste in the EU-27 for the different PV technologies (RL, LS scenario).



Source: Own elaboration.

Figure 19: Tonnes of materials in waste solar PVs in the EU by 2023.



Tonnes of Main Materials in Solar PV Panels in Europe by 2023 (excluding trace metals)

Materials	% of PV mass	Tonnes by 2023
Steel	9	10,940
Glass	64	79,100
Silicon	4	4,380
Copper	1	1,120
Aluminium	18	20,510
Ethylene Vinyl Acetate	6	7,860
Sum	100 (rounding)	123,910

Source: Own elaboration.

Table 7: Materials accumulated from waste PV technologies by 2023 and their financial value (RL, LS scenario).

2023

Metal	a-Si	CdTe	CIGS	c-Si	total (*1000 tonnes)	% mass share	Recycling yield	Revenue (Euros)	Share economic value%
Si	0.0001	0.02		4.4	4.38	3.5	51	61,055,660	23.2
Glass	0.022	6.3	1.4	71.4	79.10	63.5	95	54,612,961	20.7
Ag				0.14	0.14	0.1	80	67,079,040	25.5
Al	1.95	0.006	0.14	18.4	20.51	16.5	99	37,352,983	14.2
Steel	1.87	0.1		9.0	10.94	8.8	95	29,089,128	11.0
Cu	0.04	0.21	0.005	0.9	1.12	0.9	90	6,010,616	2.3
EVA	0.75	0.25	0.08	6.8	7.86	6.3	100	6,433,971	2.4
Te	0.0003	0.01			0.01	0.0	95	665,045	0.3
In	0.0005		0.0005		0.001	0.0	90	383,148	0.1
Ga			0.001		0.001	0.0	90	225,374	0.1
Mg	0.062		0.004	0.5	0.56	0.4	33	339,194	0.1
Se			0.001		0.001	0.0	89	38,001	0.014
Cd	0.0002	0.008	0.003		0.01	0.0	95	10,832	0.004
Sn		0.0000001	0.001	0.00006	0.001	0.0	32	5,569	0.002
Pb		0.0003		0.004	0.005	0.0	96	9,642	0.004
Mo			0.001		0.001	0.0	18	2,720	0.001
Zn	0.00002	0.00000001	0.001	0.007	0.008	0.0	27	5,397	0.002
Ni				0.001	0.001	0.0	41	5,490	0.002
Cr	0.00003	0.001			0.001	0.0	20	2,315	0.001
Fe	0.00003				0.00003	0.0	90	17	<0.0001
Ti		0.00000001		0.000005	0.000	0.0	52	1.6	<0.0001
Mn	0.00004				0.00004	0.0	37	0.08	<0.0001

The share of c-Si panel waste amassed in the RL, LS scenario by 2030 is 86%. As new technologies enter the solar market, the percentage of c-Si waste subsequently drops to 72-83.6% (2030s) and 56-74.8% (2040s). There will be 5-9.8 MT and 15-21.7 MT of accumulated waste c-Si panels by 2040 and 2050, respectively. By 2019, a-Si had the second largest share in PV waste, 10.6–13.6%. This rate decreased to 3.4–4.2% in the 2020s and is projected to decrease further to 1.6–3.45% in the 2030s, and 0.3–2.1% in the 2040s. The total amount of a-Si waste generated will be 0.18-0.25 MT by 2040 and 0.3-0.31 MT by 2050, respectively. Prior to 2019, the CdTe share of waste panels was just 1.1-2.4%; following that, this waste stream gradually grew to 6.6-7.4% in the 2020s, and then lowered to 6.3-7.2% in the 2030s and 5.2-6.6% in the 2040s. The overall quantity of CdTe waste panels is expected to reach 1.3-2 MT and 0.4-0.9 MT by 2040 and 2050, respectively. By 2019, the average cumulative waste from CIGS panels was 0.2-0.5%. This will increase to 1.7-2.7% in the 2020s, 2.7-4.6% in the 2030s and 4.1-5.9% in the 2040s. Overall, 0.2-0.57 MT and 1-1.83 MT of CIGS panel waste will accumulate by 2040 and 2050, respectively. PV waste from advanced c-Si panels is estimated to be 0.8-4.7% in 2020-2040 and 6.6-18.5% in 2041-2050 (Kastanaki, 2025).

In the RL, HS scenario, the share of c-Si panel waste accumulated by 2030 is 88%, while it is almost 90% by 2040.

- Considering that the c-Si panels dominate the waste stream (Kastanaki and Giannis 2022), the primary technological and economic obstacle in the photovoltaic recycling process is the delamination, separation and purification of silicon from glass, as well as the semiconductor thin film of other module technologies from the front and backsheet glass (Franz, Piringer et al. 2020).

5.3.2 Manufacturing new panels in the EU: meeting material needs with recycling?

As the EU aims to boost the manufacturing of solar panels, extracting materials from accumulated waste can cover the demand for metals in new panels, if efficient recycling is ensured (Commission 2023). The manufacturing needs are calculated according to the NECPs, which are updated to the goals of the NZIA.

For example, to produce c-Si panels in 2030, there is an annual demand for 78,000 tonnes of Si in HS scenario. Annual Si content in c-Si waste panels can meet the demand by 9-23% in 2030 and 25-47% in 2035 (Figure 20).

Also, the annual silver demand in the production of new c-Si panels in 2030 is 482 tonnes, while the silver in c-Si waste panels in the EU-27 in the same year can cover 41-80% of the demand. It should be noted that older models contain higher amounts of precious metals and other metals than newer models. In 2035 silver in waste panels amounts to 132-164% of the annual demand for new panels.

Moreover, the yearly need for aluminium in the manufacturing of new c-Si PVs in 2030 will be 287,300 tons; however, 11-26% of this demand may be satisfied by Al found in c-Si waste PVs in 2030. By 2035 Al in waste panels will account for 30-51% of the annual Al demand for new panels.

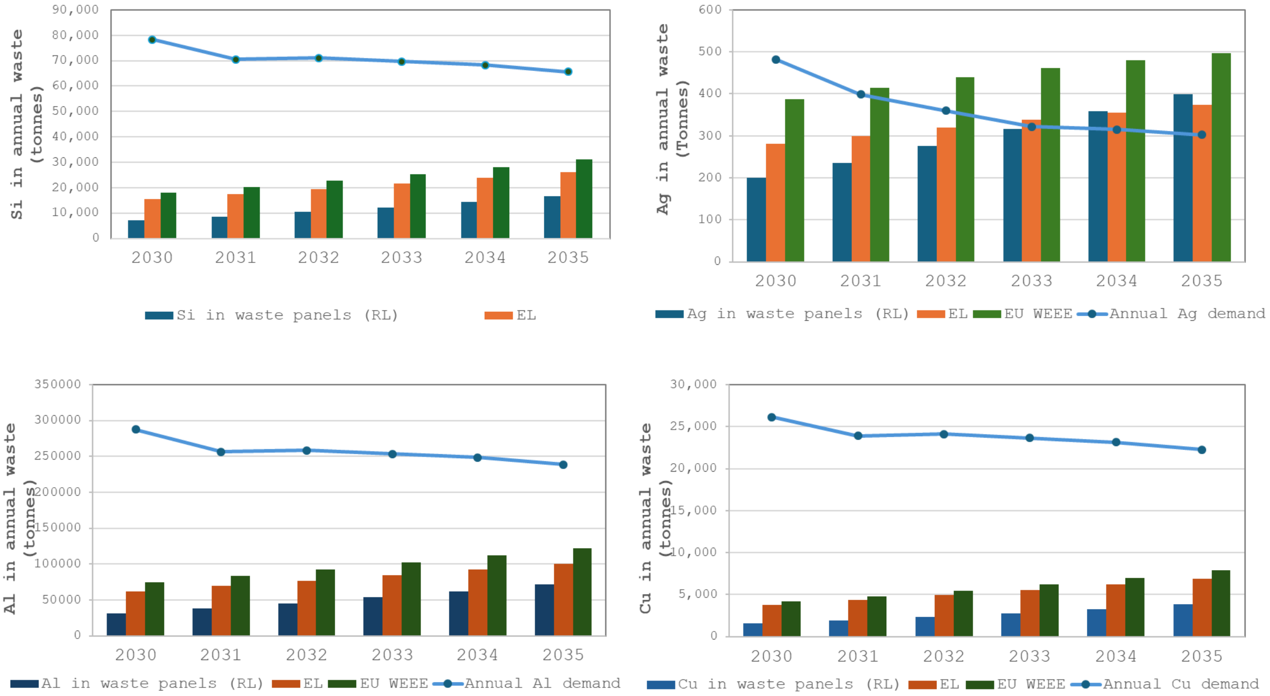
Cu has an estimated yearly requirement of 26,145 tonnes to produce new c-Si PVs in 2030; nevertheless, 6-16% of this demand may be met by Cu found in c-Si PV waste in 2030. By 2035, Cu in waste panels will amount to 17-35% of the annual demand. The reduction in metal composition in new PV panels reflects advances in material efficiency and technological changes in Si, Ag, Cu and Al i.e. smaller wafers, lower silver intensity and thinner module frames, which also results in lower costs (Ovaitt et al., 20222).

Thus, efficient recycling of waste panels can significantly contribute to the ambition of the EU for 40% domestic manufacturing of renewable energy systems (Commission 2023). In summary, there is a need to do the following:

- Recycle efficiently, at scale so that the existing waste PVs in the EU may provide many of the raw materials needed to meet demand for domestic manufacturing.
- Channel earlier PV models to dedicated PV recycling due to their higher metal and silicon content. Recycling techniques must focus on optimising material recovery, while minimising expenses and environmental impact. Life cycle analysis (LCA) can assist in optimising the potential solutions (Stolz, Frischknecht et al. 2017).

The current analysis for the EU is in alignment with the global analyses by the IEA, which states, “If panels were systematically collected at the end of their lifetime, supplies from recycling them could meet over 20% of the solar PV industry’s demand for aluminium, copper, glass, silicon and almost 70% for silver between 2040 and 2050 in the IEA’s Roadmap to Net Zero Emissions by 2050. However, existing PV recycling processes struggle to generate enough revenue from the recovered materials to cover the cost of the recycling process.”(IEA 2022)

Figure 20: Annual amounts of metals in c-Si waste PVs (High c-Si penetration scenario and RL, EL, EU WEEE scenarios for PV lifetime) and annual estimated metal demand (blue line) in 2030-2035 to produce new c-Si modules.



Source: Own elaboration.

5.4 What policies are needed to increase circularity?

Since 2012, the Waste Electrical and Electronic Equipment Directive, Directive 2012/19/EU, has required the collection and recycling of PV panels and their materials. Each MS has adopted the Directive into national law. An extended producer responsibility (EPR) scheme requires producers to finance the end-of-life management of PVs they put on the market in the EU. Producers can take back the PVs themselves or outsource to takeback organisations.

Takeback is geared towards materials recycling. It is mandatory for contract operators to comply with EU standards (CENELEC or WEEELABEX) for collection, processing, storage and recycling. Throughout the thermal, chemical and mechanical treatments of PV panels, special care must be taken to eliminate dust and other potentially dangerous materials as well as exhaust (Tesar 2021). On the other hand, refurbishment and reuse of PVs is possible and is increasing as older and less efficient models are replaced (Tsanakas, van der Heide et al. 2020). PV Cycle, which implements the EPR for PVs in the EU, finds that reuse of PVs presents a regulatory gap. Their 2021 research on PV reuse found that “Overall, the unclear legislation, the lack of control of the WEEE (Waste from Electrical and Electronic Equipment) directive, and the nearly complete lack of similar legislation outside the EU raises serious environmental and safety concerns about the re-use of PV modules”, chiefly outside the EU.

The Horizon Europe FutuRaM plans to distribute a dynamic dataset on materials arising from PV panels (which are part of WEEE) in the EU, considering distributions of lifetimes and distribution in Member States in 2025. The WEEE Directive currently under review and the revisions to the EU Ecodesign Directive (Polverini, Espinosa et al. 2023) now underway are two other opportunities to increase the circularity of PVs.

5.4.1 Collection targets

Contract operators are required to adhere to EU standards (CENELEC or WEEELABEX) for collecting PVs. Regulations forbid mixed solar panel and construction/demolition waste collection and raises specific de-pollution requirements for metals including Cd, Se and Pb. Nevertheless, because recycled module collection points are spread across many locations around Europe, they are not able to adhere to the same evaluation, recycling or reuse guidelines (Komoto, Held et al. 2022).

Currently PVs are included in the WEEE Directive under large EEE category 4, photovoltaics 4(b). As PV panels have an extended lifespan and their market penetration is still expanding, the 85% collection objective (based on sales in 3 preceding years) set by the WEEE Directive is unrealistic and unachievable. Therefore, separate reference rules for collection should be established for PVs, not together with large EEE whose market is saturated (Baldé, Wagner et al. 2020, DODD, ESPINOSA et al. 2020). Moreover, taking into consideration the significant increase in PV deployment in the EU-27, as highlighted in Section 3.2, there will also be an increase in the volume of inverters in the future. It is emphasised that inverters are not separately mentioned in the WEEE Directive but seem to belong to the general category 5 (DODD, ESPINOSA et al. 2020). Considering their also expanding market and lifetime of 10-15 years (Sangwongwanich, Yang et al. 2017), questions are raised about their separate collection targets:

- The WEEE Directive’s large EEE category and its collection targets are not a good fit for PVs’ characteristics. A review of the EEE category for PV is needed.

5.4.2 Transportation of PV waste

The transfer of this waste to the few specialised commercial-scale treatment facilities in the EU will be facilitated by standardising the categorisation of PV panels and the passport of the materials. Harmonising solar panel ID codes will facilitate export reporting and stop unauthorised shipments (Graulich K. 2021). Local pre-treatment, including collection, dismantling and storage, can be implemented until the volume of decommissioned PVs rises to the point at which economically viable recycling is achieved in some MS (Komoto, Held et al. 2022). Local pre-treatment followed by processing in a few commercial-scale dedicated recycling facilities is more sustainable from an environmental point of view (LATUNUSSA, MANCINI et al. 2016).

5.4.3 Recycling targets

The minimal mass-based recovery objectives for each category set forth by the EU WEEE Directive are readily met by recovering glass and aluminium from waste panels. However, materials like silver or CRMs, which are limited but have a high economic value, need to be extracted and repurposed, rather than wasted. As a result, regulations should be modified to promote material recovery based on the economic share as well as mass share of embedded materials (Kastanaki and Giannis 2022).

As stressed in Section 5.3.3, effective recycling of waste panels may contribute considerably to the necessary input materials for manufacturing (Kastanaki, 2025), which is relevant to the EU's aim of producing 40% of its own renewable energy systems by 2030 (Commission 2023). The European Critical Resources Management Act (CRMA) sets (non-binding) recycling targets requiring 25% of the EU's annual SRM consumption to come from recycled materials by 2030. The CRMA promotes the recovery of valuable materials, which is in line with EU’s 2030 manufacturing targets. This enhances the resilience of the EU by lowering reliance, boosting readiness, and encouraging sustainability as well as circularity in the supply chain (EU CRMA, 2024).

5.4.4 Improving recyclability of modules

The implementation of design for recycling and disassembly, as well as a reduction of hazardous components, are necessary to enable the recycling of modules.[22] Hazardous materials such as cadmium, lead, antimony and polyvinyl fluoride create difficulties in the recycling of photovoltaic modules (Graulich K. 2021). Standardised labelling and material passports (e.g. type of module, metals, and materials) can be implemented to increase the recyclability of PV modules. This way, modules can be grouped to facilitate more effective recycling and recovery procedures (Komoto, Held et al. 2022).

The proposed EU Ecodesign regulatory framework for solar PV panels and inverters, which begun in 2020, with a follow-up study in 2021 and 2023, is envisaged to set standards and requirements to promote the recyclability, reparability and durability of modules (Graulich K. 2021, Commission 2024). In this framework, it is stressed that, to ensure quality, the PV module production process must be carefully controlled. It is proposed, to ensure the durability criteria described in the Ecodesign Directive, to require producers to have an additional third party-validated quality assurance system (Commission 2021). The Directive also proposes guidelines on data requirements for dismantling (removal of the frame, glass, encapsulation, backsheet, etc.); reparability (e.g. access to bypass passages in the junction box); and design measures to avoid breakage and facilitate clean separation of glass, contacts and internal layers during operations (Commission 2021).

- Upcoming eco-design criteria for PVs placed on the market help to ensure better environmental performance and recycling at end-of-life.

5.4.5 Refurbishment and/or reuse

In theory, reuse delivers the highest value and involves the fewest processing steps, making it the easiest and least expensive method of 'recycling' panels (Crownhart 2021). Although theoretically feasible, the refurbishment and/or reuse of operational used photovoltaic panels does not yet have legal protection and is not particularly profitable due to the design of the modules which does not facilitate repair. The current lamination and encapsulation design in photovoltaics limits the ability to repair, reuse or remanufacture the modules without extensive processing (Farrell, Osman et al. 2020). Due to this design, refurbished PV panels are more expensive to produce than new ones, especially as the cost of producing new panels is decreasing (Graulich K. 2021) or because replacement parts are difficult to find.

Reuse regulations are lacking in terms of certification requirements, safety measures and warranties for the safe development or export of used modules. The International Electrotechnical Commission's (IEC) solar photovoltaic energy systems committee has launched a project in 2023 on "Reuse of PV modules and circular economy, IEC TR 63525 ED1"to fill this gap (IEC, 2024). At this writing, the IEC has announced that it will publish on reuse of PV modules in September 2025.[13] Reuse requires access to information on the panel materials, which could be ensured with a material passport. To make reuse realistic, manufacturing should be established in the EU, since the EU promotes design for disassembly (DfD) (Commission 2021). However, currently most panels are imported from China (Statista), which does not comply with DfD requirements. The EU has determined that PV production in the EU is desirable because it will build resilience and create independence along the entire PV value chain. The European Commission has set a target for at least 40% of new solar PVs to be produced in the EU by 2030 (Commission 2023). Whether the EU succeeds in being competitive will depend on the prices of materials, power and labour and achieving economies of scale (Bórawski, Holden et al. 2023).

Prematurely retired solar panels retain 80% of their original capacity (Kennedy 2022). If reuse is an option, the estimation of potential quantities for reuse is important, to assess whether economies of scale may permit solar manufacturers to invest in panel repairs for a second life. Using the assumption that only prematurely retired modules (before 12 years of life) can be reused, to require minimum repair, a waste stream for second-life PVs can be calculated:

- Quantifying the second life waste stream will help determine if investments in PV repair are economically viable.

5.5 Solar Power Waste: Key learnings and policy strategies

A significant part of the transition to a majority of low- and net-zero-energy sources for supplying electricity is played by photovoltaic solar energy. Since 2019, the EU solar market has grown at an exponential rate that has surpassed all prior projections. It is anticipated that significant amounts of solar waste will eventually occur due to the rapid deployment of PVs. A detailed analysis of expected waste quantities is necessary for planning the management of photovoltaic waste.

The key learnings about solar PV waste quantities and challenges are summarized below. These are followed by potential strategies to better manage these waste in the EU drawing from these insights. The strategies in bold are noted for further exploration and potential implementation.

- PV waste volumes will rise significantly as the EU has just increased its aim for renewable energy deployment to 42.5% from 32.5% by 2030.
- Compared to the 135 GW deployed in total by 2020, the total installed PV capacity in the EU-27 in 2022 reached 200 GW, a rise of 50% in just 2 years (IRENA 2022).
- **The EU-27 will amass 6-13 MT of PV waste by 2040 and 21-35 MT of PV waste by 2050, if recycling is not implemented at an earlier stage.**

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[13] Source: https://www.iec.ch/dyn/www/f?p=103:38:706405266035236::::FSP_ORG_ID,FSP_APEX_PAGE,FSP_PROJECT_ID:1276,23,120892

- Currently installed PVs will become waste in the medium-term future; therefore, ongoing research focuses on efficient recycling of the old-technology PVs to harvest the embedded materials.
- Recycled materials can be used to manufacture new PVs within the EU, closing the material cycle, and strengthening the economy. **Policies to achieve this can be further investigated at the EU level.**
- Reuse can also be promoted to meet growing PV demand. **There are no regulations to promote reuse or control the export of reused modules. This regulatory gap needs attention in the short term.**
- **New PV designs are needed that eliminate the use of hazardous materials to promote recycling and the elimination or substitution of CRMs to facilitate manufacturing in the EU**.
- **Product regulation may also address some elements of product requirements for improved environmental and circular performance of PVs on the market**.

6 Waste from decommissioning fossil fuel power plants in the EU

This section presents a method for quantifying the volume of wastes from decommissioning fossil fuel power plants in the EU when they reach their end-of-life. To this end, (i) the topic of fossil fuels decommissioning is described, (ii) a contribution to fill the data gap to estimate the volume of waste for the 27 EU countries is presented, and (iii) further research needs are outlined. The following research questions are discussed:

- What technologies, infrastructures, and materials are included in the composition of decommissioning fossil fuel power plants that require a circular economy perspective?
- Can all fossil fuel power plant decommissioning waste be recycled?
- How much waste is generated from decommissioning?
- What policies are needed to increase circularity

6.1 Which technologies, infrastructures, and materials?

This section answers the research question, “What technologies, infrastructures, and materials are included in decommissioning fossil fuel power plants in future that require a circular economy perspective?”

As of 2021, the largest category of net electricity generation in the EU is combustible fuels (42%), which are fossil fuels such as natural gas, coal and oil (Eurostat 2024). Thermal fossil-fuel-burning power plants are the majority of electricity generation infrastructure, which is defined as facilities that generate, process and distribute electricity (Kalt, Thunshirn et al. 2021). Fossil fuel power systems are concentrated in certain locations and need distribution, unlike renewables - (excluding large hydro) - which are widely distributed. For non-renewable electricity supply, the following system components are required to produce and distribute power to end users:

1. power plants (coal/oil/gas);
2. transmission grids;
3. distribution grids; and
4. transformers (Kalt, Thunshirn et al. 2021).

A fossil-fuel-fired power station is a multifaceted operation requiring a wide range of materials and parts. To build a power plant, large quantities of structural steel, concrete, different metals (such as copper and aluminium) for electrical components, and a variety of mechanical parts for turbines and generators are needed. Other plant infrastructure includes cooling towers, boiler, steam turbine and other auxiliary facilities as part of the plant. The quantities and types of materials required also depend on the particular design and technology employed in the plant, such as fluidised bed combustion, integrated gasification combined cycle, or pulverised coal combustion (Fernando 2004).

The technologies and infrastructures of fossil-fuel-powered plants tend to be described in the literature as financial losses due to the stranded assets perspective. This raises the question, what are the drivers for fossil fuel decommissioning that are not solely driven by climate change mitigation? There are several examples worldwide where the aging fleet of coal and oil power plants are closing because they have become uncompetitive with alternatives such as natural gas or renewables. Whether the underlying reasons for plant closures are lack of competitiveness or solely the transition away from electricity generated with fossil fuels, these plants are on a downward trend. Currently, the stranded assets literature sees them as financial losses. The circular economy perspective sees them as assets with economic and environmental value at their first end-of-life. Some of these facilities can be repurposed after refurbishment. Most former fossil fuel plant buildings and structures are made of useful recyclable material that can enter the secondary materials markets.

6.1.1 Methods

The method of this analysis starts with three important assumptions. First, this Strategies Report focuses on areas of problematic or unknown waste volumes; therefore, materials due to the retirement and demolition of fossil fuel plants are included. The current analysis focuses only on end-of-life, not the continuous waste streams during operation or fossil fuel plant replacements. Second, transformers and transmission and distribution grids retain their functions and economic value during and after the transition to renewable electricity. Therefore, the complete retirement of transformers and transmission and distribution infrastructure is not envisioned under this analysis. Readers interested in the global material stocks of these types of infrastructure should see (Kalt, Thunshirn et al. 2021). Third, the current analysis does not account for batteries and energy storage technologies. In future, batteries and other forms of energy storage will be critical components of the transmission and distribution infrastructure. Batteries already receive significant research and policy attention (Bobba, Mathieux et al. 2019, Grijelmo 2022, Latini, Vaccari et al. 2022). These three assumptions narrow the analysis to potential waste streams at decommissioning.

Data is based on inputs rather than observable waste. As there is little information available on the volume of wastes that could be generated due to deconstructing and demolishing fossil fuel power plants, we use the volume of material and the material intensities in the literature for power plant construction as the basis for waste estimation.

Material Stock - The material intensity (tonnes/MW of electricity generation capacity) for power plant construction is used to estimate the material stock in fossil fuels plants. The material intensities differ for coal, oil and gas power plants. Because the exact material quantities vary considerably depending on the power plant technology and the size of plant, low, average and high estimates are given, based on the relevant scientific literature, in Table 8 (Elshkaki and Graedel 2013, Singh, Bouman et al. 2015, Beylot, Guyonnet et al. 2019, Li, Ye et al. 2020, Kalt, Thunshirn et al. 2021, Kalt, Thunshirn et al. 2021). In this way, uncertainties related to the material composition of distinct types of plants are considered. Assigning low, average and high values for the material intensities, the results presented are given as averages with a sensitivity range. The material intensity is significantly higher for coal power plants, as depicted in Table 8.

Table 8: Material intensities for constructing electricity-producing power plants by type of fossil fuel technology.

		Material intensity (tonnes/MW)			
Technology		Steel	Concrete	Copper	Aluminium
Coal	Low	30	100	0.7	0.2
	Med	65	275	2	1.6
	High	100	450	3.3	3

Gas	Low	10	45	0.6	0.1
	Med	30	60	1.1	0.9
	High	50	75	1.6	1.7
Oil	Low	15	50	0.6	0.6
	Med	33	63	0.9	1
	High	51	76	1.2	1.4

General Recovery Rate - Once the material “in” is calculated, we assume a general recovery rate for all wastes to come “out” of facilities. The material intensity (in tonnes per MW of capacity) is multiplied by the installed capacity (MW) of the coal- or oil or gas-fired power plant to obtain the materials (tonnes). The materials analysed are steel, concrete, copper, and aluminium based on the literature review. In practice, the percentages of these materials that can be recovered for recycling can vary. Metals, such as structural steel, copper and aluminium, are often highly recoverable and are recycled at high percentages. For example, the aluminium recycling rate in the building sector in Europe exceeds 90% (zu Castell-Rudenhausen, Margareta et al. 2022). Copper and steel are also highly recyclable materials. In the EU, the construction sector is the number one user of steel and 90% is recycled. Concrete accounts for the largest percentage of materials from building demolition. It is recycled to mostly low-cost aggregates for use in the construction of roads, etc. (Caro, Lodato et al. 2024). Mechanical parts, insulation and wiring may have varying recyclability depending on their specific composition. The percentage of materials harvested during the decommissioning of a fossil fuel plant varies depending on the specific facility, its state and the planned use of the land (Raimi 2017). In short, the reality of industrial building construction and demolition is more complex than can be captured in a simple statistical analysis.

Due to the complexity of construction, there is no specific percentage of generated waste material that can be recycled/reused as this depends on many factors (Bowyer, Bratkovich et al. 2015). The waste volumes calculated in this report demonstrate only the potential (100%) for recycling from the decommissioning of fossil fuel plants. Based on the Monticelli et al. (2019) decommissioning case study of a coal power plant, the collection and recycling rate of waste materials was calculated at 85%. We agree that 85% of the waste materials generated during decommissioning can be intended for use as raw material for other uses, as a reasonable and conservative estimate (Monticelli 2019).

Number of decommissioned plants - To calculate the materials from decommissioned plants, first data on retired plants in each of the 27 EU countries were retrieved from the Global Plant Tracker (Monitor 2024).[14] As reported on the Global Coal Plant Tracker website, the data **were** last updated in January 2024. For each country, data on coal plants retired from 2014 to 2023 were extracted (Monitor 2024). For oil- and gas-fired power plants, data for the retired plants are grouped together in the Global Oil and Gas Plant Tracker (Monitor 2024).[15] More detailed data could be found in Global Energy Monitor’s ‘Europe Gas Tracker’ distinguishing between retired oil and gas plants (Monitor 2024).[16] GEM.wiki provides information for each plant in the regions of the EU countries. The wiki

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[14] Global Coal Plant Tracker, Tracker Map. Global Energy Monitor. https://globalenergymonitor.org/projects/global-coal-plant-tracker/tracker/

[15] Global Oil and Gas Plant Tracker, Tracker Map - Global Energy Monitor. https://globalenergymonitor.org/projects/global-oil-gas-plant-tracker/

[16] Europe Gas Tracker, 2024. Global Energy Monitor. https://globalenergymonitor.org/projects/europe-gas-tracker/tracker-map/ (accessed 6.5.24).

page includes further information such as capacity of oil or gas plant and retirement year. Data were retrieved at NUTS2 level, separately for retired oil and gas plants.

The historical plant data include the GW of electricity generation capacity for each plant; therefore, material intensity estimates could be applied. The annual GW from the GEM.wiki pages for retired natural gas (and oil) power plants were compared and were in line with the country-by-country (2020-2023) retired plant summary tables included in the Global Oil and Gas Plant Tracker ("Global Oil and Gas Plant Tracker (GOGPT) Summary Tables - 2024) (Monitor 2024).

In addition to the historical decommissioning data for the EU analysed from the sources given herein, in future work we will use the same method to project future wastes from future plant decommissioning. The analysis will be similar; however, we will apply an updated scenario from the POTenCIA model. We expect to estimate the forecasted waste streams until 2070. This work is the next step in refining the analysis for future forecasts with additional modelling data and will be carried out by the JRC.

6.2 Can all waste from fossil fuel power plant decommissioning be recycled?

Fortunately, collection and preparing for reuse and recycling of construction and demolition waste (CDW) from buildings and infrastructure are common practice in the EU. This is because CDW is the largest waste stream of all waste generated in the EU, at 40%. The analysed materials resulting from fossil fuel electricity supply decommissioning are all traded on established secondary materials markets for collection, reuse and recycling in the EU. As discussed above, the recycling rates vary depending on the type of materials and countries. **There are technical barriers to recycling, such as materials that are fused together**. Furthermore, the presence or potential presence of hazardous materials in some components of fossil fuel plants could impede recycling.

In addition, there are economic barriers to recycling construction and demolition waste (**CDW)**. The EEA reports that "CDW consists of numerous materials that can be recycled. However, the economically most valuable fractions (e.g. metals, plastics, and glass) represent only a small percentage of all CDW waste" (zu Castell-Rudenhausen, Margareta et al. 2022). As a result, the metals, etc. tend to have higher recycling rates for higher value applications. In contrast, the mineral fraction of CDW, including concrete, encounters economic barriers. The EEA concludes that "There is a market for aggregates derived from CDW waste in roads, drainage, and other construction projects. But the recycling potential of such waste is still under-used and varies among Member States. The market for aggregates from CDW waste generally does not meet the criteria to be well-functioning" (López Ruiz, Roca Ramón et al. 2020).

6.3 How much waste will be generated?

This section discusses the volume and composition of PV waste by 2023. As the estimates are based on

6.3.1 Coal plant decommissioning

Estimations of the total waste stream from the decommissioning of coal plants for the EU-27 are shown in Figure 22 and Table 8 (material intensities). According to the analysis of the publicly available sources discussed herein, **by 2023, around 84.9 GW of coal-fired power plants had been phased out in the EU-27. It is estimated that this would correspond to about 5.52 million tonnes of steel, 23.36 million tonnes of concrete (assuming 15% cement[8]), 169,000 tonnes of copper and 136,000 tonnes of aluminium contained in the facilities.** Two of the principal factors to consider when defining the potential for urban mining are the amounts and geographical distribution of retired metal stocks. As observed in Figure 23, the highest uncertainty is found in aluminium estimations. This may be explained by the different content in the various coal-fired power plant designs. Using gigawatts of electricity generation capacity by retired coal power plants as a metric, approximately 30% of retired plants are in Germany, 13% in Spain, 8.6% in Poland, 7.8% in France, 5.6% in Romania and 5% in Italy, as seen in figure 23. Croatia, Estonia, Ireland, Latvia, Lithuania, Luxembourg and Malta did not have any decommissioned coal installations (Monitor 2024). It is important to remember that the current analysis does not account for standby or cold storage mode. However, it is possible that coal power plants placed in standby mode were or could be used again. For example, it is reported that "In a bid to avert gas shortages due to the energy crisis fuelled by Russia's war on Ukraine, Germany temporarily reopened some recently decommissioned and other soon-to-be decommissioned coal power plants in 2022 and 2023" (Wettengel 2024). The data of this analysis reflect permanent plant closures and demolitions.

6.3.2 Gas plant decommissioning

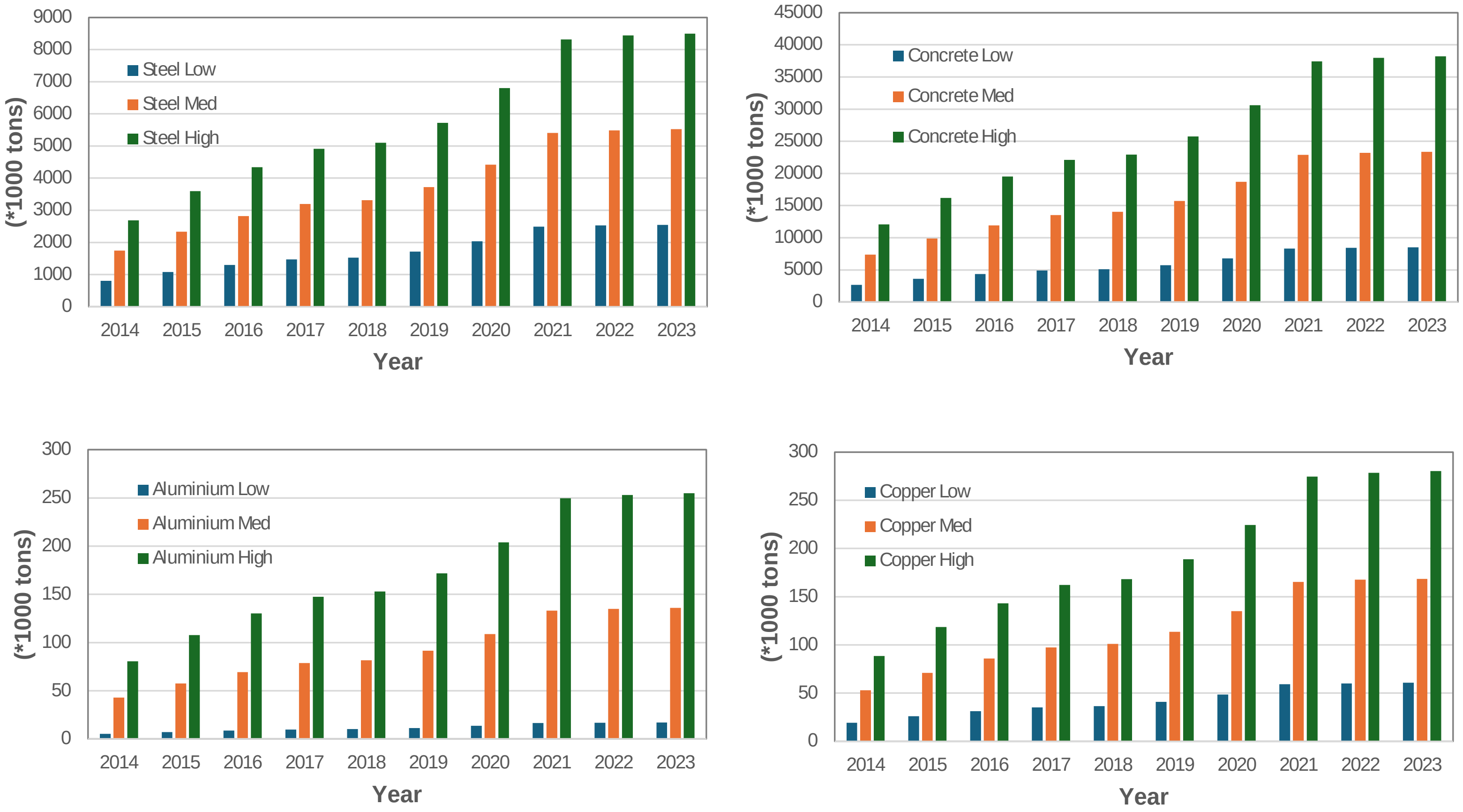
Over the period 2016-2023, 2.53 GW of gas power plants had been retired in the EU-27, amounting to 76,000 tonnes of steel, 152,000 tonnes of concrete, 2,800 tonnes of copper and 2,300 tonnes of aluminium, as seen in Table 9. Of the units withdrawn, 11.8% are in Germany, 18.7% in Italy, 14.2% in Greece, 14.22% in Lithuania, 11.85% in Romania, 10.7% in Ireland, 6.1% in the Netherlands and 3.3% in Spain. The retired units in Austria, Finland, Slovenia and Portugal account for 1.7-3.2% (Monitor 2024).

6.3.3 Oil plants decommissioning

Only a few countries have decommissioned oil plants in the EU-27, Germany, Slovenia and Spain (Jinamar power station in Jinamar, Las Palmas). Retired oil plants in the EU-27 accounted for 0.44 GW by 2020-2023, corresponding to 14,550 tons of steel, 27,800 tonnes of concrete, 400 tons of copper and 440 tonnes of aluminium (Table 10). Of the oil-powered units withdrawn, 67.6% are in Germany, 5.2% in Slovenia and 27.2% in Spain (Las Palmas).

The volumes of waste materials are significant, and their recycling and reuse is important to support the construction of new energy plants in the EU. The amount of materials acquired from the decommissioned coal plants is much greater than that from oil and gas power plants. For metals, the amounts are 60-73 times higher and for concrete 154 times higher than the materials from decommissioning gas power plants. Table 11 lists the total amounts of materials from retired fossil fuel plants (coal, gas and oil) in the EU-27. Cumulatively, by 2023, decommissioning fossil fuels power plants (coal, gas, and oil) were predicted to provide a total of 5.6 million tonnes of steel, 172,000 tonnes of copper, 139,000 tonnes of aluminium and 23.5 million tonnes of concrete.

Figure 21: Estimated amounts of materials from decommissioning coal power plants.

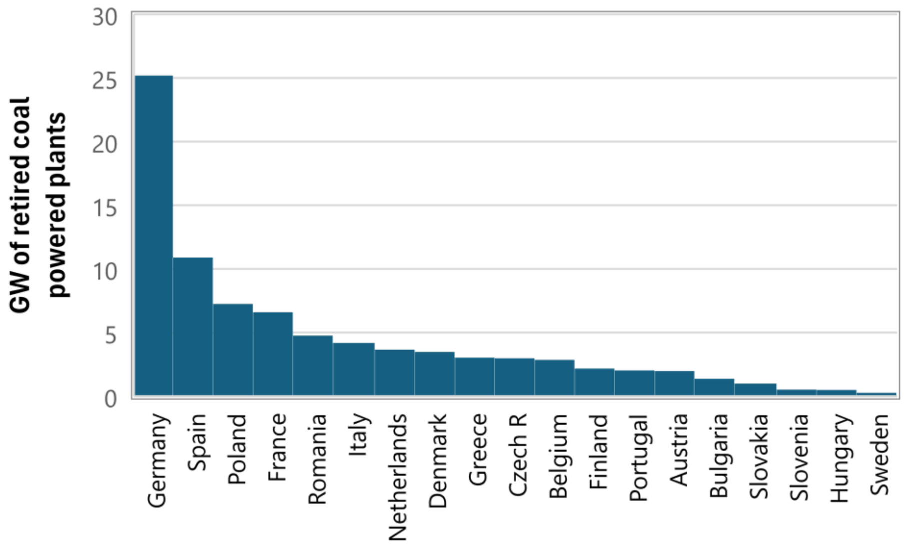


Source: Own elaboration.

Table 9: Estimated cumulative waste material stream from decommissioning of coal power plants in the EU-27.

(*1000 tonnes)		2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Steel	Low	805.6	1078.8	1301.3	1474.6	1529.1	1716.8	2039.6	2494.9	2531.4	2547.9
	Med	**1745.5**	**2337.5**	**2819.4**	**3195**	**3313.1**	**3719.6**	**4419.2**	**5405.6**	**5484.6**	**5520.4**
	High	2685.4	3596.1	4337.6	4915.4	5097.1	5722.5	6798.7	8316.3	8437.9	8492.9
Concrete	Low	2685.4	3596.1	4337.6	4915.4	5097.1	5722.5	6798.7	8316.3	8437.9	8492.9
	Med	**7384.9**	**9889.3**	**11928.4**	**13517.4**	**14017**	**15736.9**	**18696.4**	**22869.8**	**23204.2**	**23355.5**
	High	12084.3	16182.5	19519.2	22119.3	22937	25751.3	30594.2	37423.4	37970.6	38218.1
Copper	Low	19.4	26.1	31.3	35.3	36.6	41.0	48.6	59.2	60.1	60.7
	Med	**53.1**	**71.0**	**85.9**	**97.4**	**101.0**	**113.5**	**135.0**	**165.3**	**167.7**	**168.6**
	High	88.6	118.7	143.1	162.2	168.2	188.8	224.4	274.4	278.5	280.3
Aluminium	Low	5.4	7.2	8.7	9.8	10.2	11.4	13.6	16.6	16.9	17
	Med	**43**	**57.5**	**69.4**	**78.6**	**81.6**	**91.6**	**108.8**	**133.1**	**135**	**135.9**
	High	80.6	107.9	130.1	147.5	152.9	171.7	204	249.5	253.1	254.8

Figure 22: Gigawatts of electricity generation capacity by retired coal power plants in the EU-27



Note: (This analysis does not account for plants that were on standby / cold storage status that could have been or could be reactivated).

Source: Own elaboration.

Table 10: Estimated annual waste material flow from decommissioning gas power plants in the EU-27 in 2016-2023. Cumulative total in last column.

(*1000 tonnes)		2016	2017	2018	2019	2020	2021	2022	2023	total (2016-2023)
Steel	Low	3.6	0	1.54	0	4.86	2.15	5.93	7.23	25.31
	Med	**10.8**	**0**	**4.62**	**0**	**14.58**	**6.45**	**17.79**	**21.69**	**75.93**
	High	18	0	7.7	0	24.3	10.75	29.65	36.15	126.55
Concrete	Low	16.2	0	6.93	0	21.87	9.675	26.685	32.535	113.90
	Med	**21.6**	**0**	**9.24**	**0**	**29.16**	**12.9**	**35.58**	**43.38**	**151.86**
	High	27	0	11.55	0	36.45	16.125	44.475	54.225	189.83
Copper	Low	0.216	0	0.0924	0	0.2916	0.129	0.3558	0.4338	1.52
	Med	**0.396**	**0**	**0.1694**	**0**	**0.5346**	**0.2365**	**0.6523**	**0.7953**	**2.78**

	High	0.576	0	0.2464	0	0.7776	0.344	0.9488	1.1568	4.05
Aluminium	Low	0.036	0	0.0154	0	0.0486	0.0215	0.0593	0.0723	0.25
	Med	**0.324**	**0**	**0.1386**	**0**	**0.4374**	**0.1935**	**0.5337**	**0.6507**	**2.28**
	High	0.612	0	0.2618	0	0.8262	0.3655	1.0081	1.2291	4.30

Table 11: Estimated cumulative waste material flow from decommissioning gas power plants in the EU-27 in 2016-2023.

(*1000 tons)		2016	2017	2018	2019	2020	2021	2022	2023
Steel	Low	3.60	3.60	5.14	5.14	10.00	12.15	18.08	25.31
	Med	**10.80**	**10.80**	**15.42**	**15.42**	**30.00**	**36.45**	**54.24**	**75.93**
	High	18.00	18.00	25.70	25.70	50.00	60.75	90.40	126.55
Concrete	Low	16.20	16.20	23.13	23.13	45.00	54.68	81.36	113.90
	Med	**21.60**	**21.60**	**30.84**	**30.84**	**60.00**	**72.90**	**108.48**	**151.86**
	High	27.00	27.00	38.55	38.55	75.00	91.13	135.60	189.83
Copper	Low	0.22	0.22	0.31	0.31	0.60	0.73	1.08	1.52
	Med	**0.40**	**0.40**	**0.57**	**0.57**	**1.10**	**1.34**	**1.99**	**2.78**
	High	0.58	0.58	0.82	0.82	1.60	1.94	2.89	4.05
Aluminium	Low	0.04	0.04	0.05	0.05	0.10	0.12	0.18	0.25
	Med	**0.32**	**0.32**	**0.46**	**0.46**	**0.90**	**1.09**	**1.63**	**2.28**

High	0.61	0.61	0.87	0.87	1.70	2.07	3.07	4.30

Table 12 Estimated annual waste material flow from decommissioning oil power plants in the EU-27 between 2020 and 2023.

(*1000 tonnes)		2020	2021	2022	2023	total (2020-2023)
Steel	Low	1.8	4.815	0	0	6.62
	Med	**3.96**	**10.593**	**0**	**0**	**14.55**
	High	6.12	16.371	0	0	22.49
Concrete	Low	6	16.05	0	0	22.05
	Med	**7.56**	**20.223**	**0**	**0**	**27.78**
	High	9.12	24.396	0	0	33.52
Copper	Low	0.072	0.1926	0	0	0.26
	Med	**0.108**	**0.2889**	**0**	**0**	**0.40**
	High	0.144	0.3852	0	0	0.53
Aluminium	Low	0.072	0.1926	0	0	0.26
	Med	**0.12**	**0.321**	**0**	**0**	**0.44**
	High	0.168	0.4494	0	0	0.62

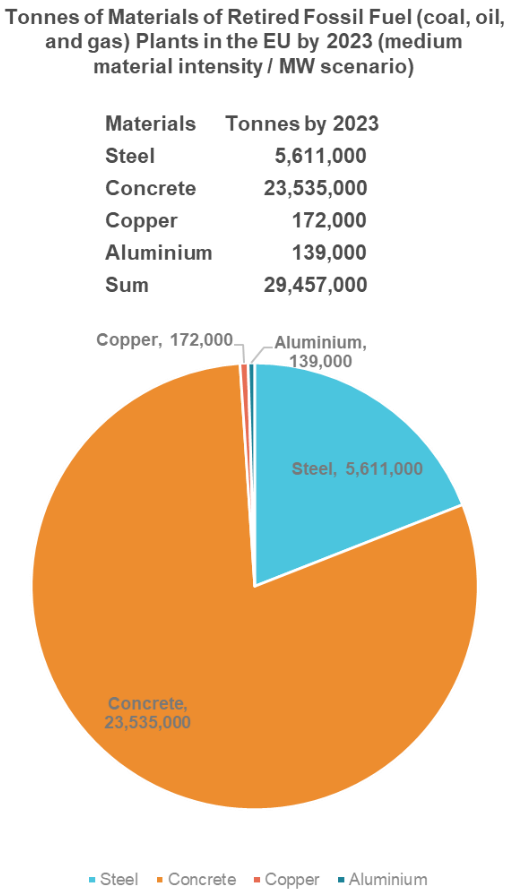
Table 13: Estimated cumulative waste material flow from decommissioning oil power plants in the EU-27 between 2020 and 2023.

(*1000 tonnes)		2020	2021	2022	2023
Steel	Low	1.80	6.62	6.62	6.62
	Med	**3.96**	**14.55**	**14.55**	**14.55**
	High	6.12	22.49	22.49	22.49
Concrete	Low	6.00	22.05	22.05	22.05
	Med	**7.56**	**27.78**	**27.78**	**27.78**
	High	9.12	33.52	33.52	33.52
Copper	Low	0.07	0.26	0.26	0.26
	Med	**0.11**	**0.40**	**0.40**	**0.40**
	High	0.14	0.53	0.53	0.53
Aluminium	Low	0.07	0.26	0.26	0.26
	Med	**0.12**	**0.44**	**0.44**	**0.44**
	High	0.17	0.62	0.62	0.62

Table 14: Total waste material flow from retired fossil fuel plants (coal, oil and gas) in the EU by 2023.

(*1000 tonnes)		Coal	Gas	Oil	Total
Steel	Low	2547.9	25.31	6.62	2580
	Med	**5520.4**	**75.93**	**14.55**	**5611**
	High	8492.9	126.55	22.49	8642
Concrete	Low	8492.9	113.90	22.05	8629
	Med	**23355.5**	**151.86**	**27.78**	**23535**
	High	38218.1	189.83	33.52	38441
Copper	Low	60.7	1.52	0.26	63
	Med	**168.6**	**2.78**	**0.40**	**172**
	High	280.3	4.05	0.53	285
Aluminium	Low	17	0.25	0.26	18
	Med	**135.9**	**2.28**	**0.44**	**139**
	High	254.8	4.30	0.62	260

Figure 23: An overview of materials from all decommissioned fossil fuel power plants. An estimated 5.6 million tonnes of steel, 23.5 million tonnes of concrete (assuming 15% cement), 172,000 tonnes of copper and 139,000 tonnes of aluminium were contained in the fossil fuel power plants decommissioned in the EU-27 by 2023.



Materials	Tonnes by 2023
Steel	5,611,000
Concrete	23,535,000
Copper	172,000
Aluminium	139,000
Sum	29,457,000

Source: Own elaboration.

The current analysis applies the methodology to facilities decommissioned in the EU by 2023. Figure 24 summarises the findings by estimating the tonnage of materials from all decommissioned fossil fuel power plants. There are no data available on the eventual fate of these waste streams for all MS, although individual cases are documented.

- Additional research is needed to determine if recovered materials are reused or recycled in future.
- The current analysis can be extended to future years through additional analysis of planned retirement dates in the EU.

6.4 What policies are needed to increase circularity?

Decommissioning is a demolition of an industrial facility that results in CDW. CDW is regulated by the Waste Framework Directive (European Parliament 2018). The norms that apply to CDW will apply to decommissioning fossil fuel plants. CEPRES asks the question of whether there is an additional benefit to focusing on the decommissioning of fossil fuel plants. This research has identified **four benefits to taking a systems approach towards waste from fossil fuel plant decommissioning to improve circularity which could be augmented by additional guidance or regulation in the EU**.

6.4.1 Guidance or regulation on repurposing and reuse of materials

Up to now, decommissioning has primarily followed a linear model. Thus, the assets that need to be decommissioned are viewed as a collection of waste fractions rather than potential products. Electricity suppliers that are planning the decommissioning of obsolete fossil fuel plants have the goal of keeping costs as low as possible (Monticelli 2019). Guidance or regulation could change this approach to emphasise repurposing and reusing materials and systems from already existing structures, machinery and buildings. A more circular approach could increase the financial return to companies and keep the power plant's components within the economy in the EU. With pre-demolition planning, the components that cannot be reused can be recycled as secondary raw materials, with the greatest emphasis on avoiding landfill and incineration (Monticelli 2019).

6.4.2 Survey locations and materials

A circular economy approach would increase the value of the facility as an asset with reusable and recyclable components rather than solely a monetary loss as waste. Fossil fuel power plants could be thought of as "mines" or "banks" of valuable materials whose uses have environmental and economic benefits. To tap this potential, knowledge of the locations, quantity, value and recoverability are needed (Morlet, Blériot et al. 2016, Mohammadiziazi and Bilec 2022).

6.4.3 EU-level guidance, knowledge-sharing

Closer scrutiny to decommissioning can incite knowledge-sharing and skills-sharing which may increase benefits and reduce costs. The global move towards no unabated coal power plants is a strong existing political commitment, reiterated again by the G7 Ministers of Climate, Energy and Environment in April 2024.[17] Research to identify best practice techniques for better environmental outcomes of decommissioning and the sharing of these are necessary. There has been similar knowledge-sharing for safe decommissioning of nuclear power plants.

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[17] G7-Climate-Energy-Environment-Ministerial-Communique_Final.pdf (g7italy.it)

6.4.4 Incentives and requirements

Finally, as public funding may be involved in repurposing, dismantling or demolishing former power plants, projects may consider incentivising or requiring more circular treatment options over disposal, particularly concrete.

6.5 Fossil Fuel Decommissioning Waste: Key learnings and policy strategies

The key learnings about fossil fuel plant decommissioning waste quantities and challenges are summarized below. These are followed by potential policy strategies discussed herein to better manage these waste in the EU drawing from these insights. The strategies in bold are noted for further exploration and potential implementation.

- Coal-fired plants are the main source of potential waste today.
- The fate of these materials is unknown for two reasons. Some facilities were put on standby, whilst others were permanently closed and demolished. Wastes from decommissioning are not tracked.
- So far, Germany, Spain, Poland, France and Romania have retired the majority of coal-fuelled electricity generation capacity (i.e. in terms of GW).
- Decommissioning is essentially demolition of an industrial facility that results in CDW regulated by the Waste Framework Directive. **EU-level guidance and knowledge-sharing could improve circular outcomes.**
- Concrete and steel make up the majority of the waste material. Concrete waste is not sufficiently recycled. **EU-wide policies aimed at increasing concrete recycling would also impact plant decommissioning.**

7 Discussion and Conclusions

Discussion of the Results

The growing volume of future waste streams created by renewable electricity supply infrastructure accelerated by the EU's climate change mitigation ambitions and the Net-Zero Industry Act are inevitable. The transition to renewable electricity creates diverse waste streams of recyclable materials, including steel, copper, aluminium, concrete, fibreglass and glass.

Solar PV modules and wind turbine blades are currently not routinely reused and recycled and represent technical and economic barriers to well-functioning recycling markets in the EU.

Wastes from decommissioned fossil fuel power plants are primarily construction and demolition wastes such as concrete that have limited recycling outlets today.

Each of these waste streams presents a different conundrum that is addressed in the Strategies Report.

- Wind turbines possess a particularly challenging key component, wind turbine blades. Blades are large-volume and have limited commercial-scale recycling and reuse possibilities. Hence, the chapter discusses all components of wind turbines and focuses on the issue of blade waste estimation and management. Second, estimating the amount of wind turbine and blade waste more accurately depends on the new observed and estimated data presented in the Strategies Report.
- The solar photovoltaic chapter offers a detailed bottom-up analysis of all materials in PV panels. The chapter not only answers the key research questions but determines that existing PV panels, if properly recycled, contain enough materials to meet the supply needs of the EU PV manufacturing industry.
- The chapter on the decommissioning of fossil fuel burning power plants estimates bulk waste streams due to actual plant closures. This new analysis applies material intensities from the literature to estimate waste.

The report estimates that future waste volumes from the renewable technologies will be generated in far greater quantities and at faster rates than previously estimated overall. However, the picture is complicated by the previous underestimation of reuse and repowering of wind turbines.

The report estimates the volume of accumulated materials in the three sectors by 2023. The time frames are different for each sector because they were rolled out and decommissioned in different eras and available data varies. The data for decommissioned power plants is collected for 2014 to 2023. The updated estimates of the volumes and types of wastes from new and obsolete includes some unexpected results.

Steel, aluminium, and copper are resources shared by the three sectors analysed in the Strategies report. They are present throughout the electricity supply. The volume of accumulated steel in solar PVs (10,940 tonnes), wind turbines (274,194 tonnes), and decommissioned fossil fuel plants cumulatively by 2023 is estimated at 5,896,134 tonnes of which renewables account for 285,000 tonnes. Theoretically, approximately 7,000 passenger trains could be made with 285,000 tonnes of steel, using the average weight of 40 tonnes for a passenger train car.

- **For a general comparison of scale to other significant electricity supply wastes, Eurostat's 2021 estimate of cumulative collected waste portable batteries and accumulators (all materials) between 2012 and 2021 is 883,812 tonnes.**[18]
- **Key materials such as silver that exist in PV panels, if collected and recycled appropriately, could supply new PV manufacturing demand if produced in the EU.**
- **Potential recyclable materials from decommissioning fossil fuel plants (by volume), particularly coal plants, dwarf the potential recyclable materials from renewable technologies by 2023. This indicates that more attention is needed to ensure these materials are recirculated in the economy.**
- **As fossil-fuel is phased out, secondary material markets can be made ready to recycle new renewable waste streams.**

The cumulative amount of waste highlights how much materials would be waste without recycling in 2023 as a benchmark. Up to now, only a small percentage of photovoltaic and wind turbines have retired, while the opposite is true for fossil fuels plants, particularly coal. These estimates are based on the actual number and locations of retired plants in the EU. See Table 15. Future estimates (2050) as shown in Table 16, indicate that wind power will generate an annual volume of bulk material waste higher than solar power. See Table 16.

Table 15: Estimated Cumulative Decommissioned Large Volume Waste Materials by 2023

Estimated Cumulative Decommissioned Large Volume Waste Materials by 2023 in the transition from fossil fuels to renewable electricity generation (tonnes)				
Materials	**Photovoltaics (regular loss conservative scenario)**	**Wind Turbines**	**Coal, Gas & Oil Plants (medium scenario)**	**Tonnes by 2023**
Steel	10,940	274,194	5,611,000	**5,896,134**
Glass	79,100			**79,100**
Fibreglass		50,000		**50,000**
Cast iron		40,860		**40,860**

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[18] Source: Eurostat: https://doi.org/10.2908/ENV_WASPB

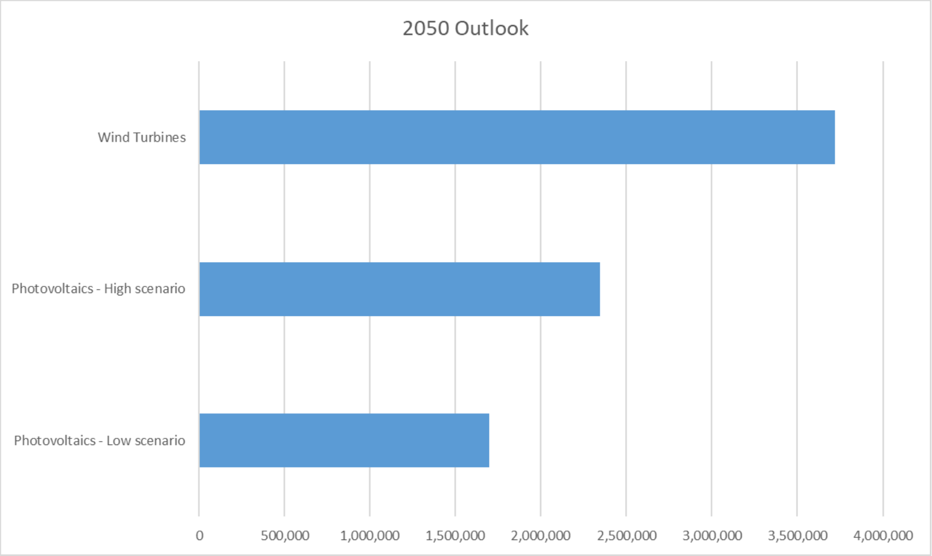
Aluminium	20,510	3,226	139,000	**162,736**
Ethylene vinyl acetate	7,860			**7,860**
Copper	3,763	1,120	172,000	**154,883**
Silicon	4,380			**4,380**
Concrete	not estimated	not estimated	23,535,000	**23,535,000**

Table 16: Estimated Annual Waste (Recyclable) Large Volume Waste Materials in 2050

Estimated Annual Waste (Recyclable) Large Volume Waste Materials in 2050 in the transition from fossil fuels to renewable electricity generation (*Coal, Gas & Oil Plants not included in 2050 estimates*)				
Materials	**Photovoltaics (regular loss conservative scenario & Low and High c-Si penetration scenario)**	**Wind Turbines**		**Tonnes / year in 2050**
Steel	122,154 – 191,290	2,741,935		2,864,090
Glass	1,268,707 – 1,719,692			1,268,707
Fibreglass		500,000		500,000
Cast iron		408,602		408,602
Aluminium	159,269 – 230,818	32,258		191,527
Ethylene vinyl acetate	89,038 – 120,700			89,038
Copper	15,240 – 18,554	37,634		52,874
Silicon	40,999 – 64,250			40,999

Table 16 notes: Material calculations for PV waste in Table B include only c-Si (59% of annual waste in 2050), CdTe (5.2%), CIGS (5.9%) and a-Si (0.2%) technologies. Advanced c-Si (17%) and "Other" (12.9%) technologies are not included due to lack of specific composition data.

Figure 24: Estimated Annual Large-Volume Waste (Recyclable) Materials in 2050 in tonnes



Source: Own elaboration.

Conclusions

We learned that a comprehensive circular economy perspective on the transition to renewable electricity unearths important similarities and differences in how wastes are managed in both the solar power and wind power, and fossil-fuel decommissioning sectors. In addition, decommissioning fossil fuel power plants presents significant wastes and significant material recovery opportunities.

These cases demonstrate that the industries of the EU electricity supply system are not fully prepared to become circular. However, steps towards this goal could be achieved if regulatory and knowledge gaps identified herein are addressed. The Strategies Report offers policymakers useful data and actionable policy strategies for further consideration when developing future regulation and budgets. The main policy themes common to all sectors are harmonising waste management legislation, examining reuse options, and drive recycling as shown in Table 17.

The Strategy Report emphasises the importance of waste policies and incentivising the secondary materials markets to keep up with the levels of useful and valuable recyclable material that are present in emerging waste streams.

Table 17: Overview of policy themes

Overview of policy themes in the Circular Economy Strategies for the EU's Renewable Electricity Supply Report		
Harmonising waste management		
For wind turbines	**For Solar PVs**	**For Fossil Fuel Decommissioning**
Sharing information on blade structures and materials	Product regulation for improved environmental and circular performance	Guidance on repurposing and reuse of materials
New waste code for wind turbine blade materials	Review of the suitability of the EEE category for PV in WEEE	
Establish an EU-wide registry of wind turbine decommissioning	Modify recycling targets to also include valuable materials with low mass share	
Encouraging reuse		
For wind turbines	**For Solar PVs**	**For Fossil Fuel Decommissioning**
Continuous estimation of where and when future wind turbine blades will become available	Explore certification for PV reuse and control the export of reused modules with product regulation	Guidance and knowledge-sharing on dismantling to improve circular outcomes
Incentivising recycling		
For wind turbines	**For Solar PVs**	**For Fossil Fuel Decommissioning**
Sharing information on blade structures and materials	Encourage manufacturing PVs within the EU to use EU-recycled panels as inputs	Survey locations and materials
Guidance on decommissioning procedures	Encourage new PV designs with structures that allow disassembly for recycling.	Increasing concrete recycling in general

References

Ardente, F., C. E. Latunussa and G. A. J. W. M. Blengini (2019). "Resource efficient recovery of critical and precious metals from waste silicon PV panel recycling." **91**: 156-167.

Atasu, A., S. Duran and L. N. Van Wassenhove (2021). "The dark side of solar power." Harvard Business Review.

Baldassarre, B. and H. Saveyn (2023). "A systematic analysis of EU publications on the Circular Economy."

Baldé, C., M. Wagner, G. Iattoni and R. J. U. U. B. Kuehr (2020). "In-depth review of the WEEE Collection Rates and Targets."

Beauson, J., A. Laurent, D. Rudolph and J. P. Jensen (2022). "The complex end-of-life of wind turbine blades: A review of the European context." Renewable Sustainable Energy Reviews **155**: 111847.

Beylot, A., D. Guyonnet, S. Muller, S. Vaxelaire and J. Villeneuve (2019). "Mineral raw material requirements and associated climate-change impacts of the French energy transition by 2050." Journal of Cleaner Production **208**: 1198-1205.

Bobba, S., F. Mathieux and G. A. Blengini (2019). "How will second-use of batteries affect stocks and flows in the EU? A model for traction Li-ion batteries." Resources, Conservation and Recycling **145**: 279-291.

Bórawski, P., L. Holden and A. Bełdycka-Bórawska (2023). "Perspectives of photovoltaic energy market development in the european union." Energy **270**: 126804.

Bowyer, J., S. Bratkovich, K. Fernholz, M. Frank, H. Groot, J. Howe and E. Pepke (2015). "Understanding steel recovery and recycling rates and limitations to recycling." Dovetail Partners Inc.: Minneapolis, MN, USA: 1-12.

Cahen-Fourot, L., E. Campiglio, A. Godin, E. Kemp-Benedict and S. Trsek (2021). "Capital stranding cascades: The impact of decarbonisation on productive asset utilisation." Energy Economics **103**: 105581.

Caro, D., C. Lodato, A. Damgaard, J. Cristóbal, G. Foster, F. Flachenecker and D. J. S. o. t. T. E. Tonini (2024). "Environmental and socio-economic effects of construction and demolition waste recycling in the European Union." **908**: 168295.

Carrara, S., P. Alves Dias, B. Plazzotta and C. J. P. O. o. t. E. U. L. Pavel (2020). "Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system."

Carrara, S., S. Bobba, D. Blagoeva, P. A. Dias, A. Cavalli, K. Georgitzikis, M. Grohol, A. Itul, T. Kuzov and C. E. Latunussa (2023). Supply Chain Analysis and Material Demand Forecast in Strategic Technologies and Sectors in the EU: A Foresight Study, Publications Office of the European Union.

Commission, E. (2021). Discussion paper on potential Ecodesign requirements and Energy Labelling scheme(s) for photovoltaic modules, inverters and systems. Brussels.

Commission, E. (2023). DIRECTIVE (EU) 2023/2413 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652 (Renewable Energy Directive), European Parliament and Council. **32023L2413**.

Commission, E. (2023). Factsheet: Net Zero Industry Act: Making the EU the home of Clean Tech Industries. Luxembourg, Publications Office of the European Union. **NA-04-23-270-EN-N**.

Commission, E. (2023). A Green Deal Industrial Plan for the Net-Zero Age. COM(2023) 62 final. Brussels, EUR-Lex.

Commission, P. B.-J. R. C.-E. (2024). "Solar Photovoltaics." Retrieved Augut 8, 2024, from https://susproc.jrc.ec.europa.eu/product-bureau/product-groups/462/home.

Commission), D.-G. f. R. a. I. E. (2023). Factsheet: EU research and innovation support to reduce our dependency on materials and accelerate the roll-out of the EU's strategic net-zero technologies.

Crownhart, C. (2021). "Solar panels are a pain to recycle. These companies are trying to fix that." Retrieved March 13, 2024, 2024, from https://www.technologyreview.com/2021/08/19/1032215/solar-panels-recycling/.

Curtis, T. L., H. Buchanan, L. Smith and G. Heath (2021). A circular economy for solar photovoltaic system materials: drivers, barriers, enablers, and US policy considerations, National Renewable Energy Lab.(NREL), Golden, CO (United States).

Damgaard, A., C. Lodato, S. Butera, T. Fruergaard, M. Kamps, L. Corbin, D. Tonini and T. F. Astrup (2022). "Background data collection and life cycle assessment for construction and demolition waste (CDW) management."

Deng, R., Y. Zhuo and Y. Shen (2022). "Recent progress in silicon photovoltaic module recycling processes." Resources, Conservation and Recycling **187**: 106612.

Desing, H., R. Widmer, U. Bardi, A. Beylot, R. G. Billy, M. Gasser, M. Gauch, D. Monfort, D. B. Müller, M. J. R. Raugei, Conservation and Recycling (2024). "Mobilizing materials to enable a fast energy transition: a conceptual framework." **200**: 107314.

DODD, N., M. M. D. L. N. ESPINOSA, T. P. VAN, K. PEETERS and A. SOARES (2020). Preparatory study for solar photovoltaic modules, inverters and systems. Luxembourg, Publications Office of the European Union. **EUR 30468 EN**.

Dragan, M. (2019). Accelerating wind turbine circularity. WindEurope Workshop on Accelerating Wind Turbine Circularity. Bilbao.

Elshkaki, A. and T. Graedel (2013). "Dynamic analysis of the global metals flows and stocks in electricity generation technologies." Journal of Cleaner Production **59**: 260-273.

European Parliament, C. o. t. E. U. (2018). EU Waste Framework Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance). Brussels, Belgium, European Commission.

European Parliament, C. o. t. E. U. (2021). REGULATION (EU) 2021/1119 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law'). L 243/1. C. o. t. E. U. European Parliament. Brussels, Official Journal of the European Union.

Eurostat. (2024, 1 July 2024). "Electricity production, consumption and market overview." Retrieved August 8, 2024, 2024, from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_production,_consumption_and_market_overview#Electricity_generation.

Fraunhofer ISE. (2024). Photovoltaics Report—Fraunhofer ISE. Fraunhofer Institute for Solar Energy Systems ISE. https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html

Fankhauser, S., S. M. Smith, M. Allen, K. Axelsson, T. Hale, C. Hepburn, J. M. Kendall, R. Khosla, J. Lezaun and E. Mitchell-Larson (2022). "The meaning of net zero and how to get it right." Nature Climate Change **12**(1): 15-21.

Farrell, C. C., A. I. Osman, R. Doherty, M. Saad, X. Zhang, A. Murphy, J. Harrison, A. S. M. Vennard, V. Kumaravel, A. H. Al-Muhtaseb and D. W. Rooney (2020). "Technical challenges and opportunities in realising a circular economy for waste photovoltaic modules." Renewable and Sustainable Energy Reviews **128**: 109911.

Fernando, R. (2004). Current design and construction of coal-fired power plant, IEA Coal Research.

Franz, M., G. Piringer and Society (2020). "Market development and consequences on end-of-life management of photovoltaic implementation in Europe." Energy, Sustainability **10**: 1-21.

IEC. (2024). IEC Technical Report for reuse of PV modules and circular economy | CEB-BEC. https://www.ceb-bec.be/nl/nieuws/iec-technical-report-for-reuse-of-pv-modules-and-circular-economy

Gauß, R., C. Burkhardt, F. Carencotte, M. Gasparon, O. Gutfleisch, I. Higgins, M. Karajić, A. Klossek, M. Mäkinen, B. J. A. r. b. t. R. E. M. Schäfer and M. C. o. t. E. R. M. Alliance (2021). "Rare earth magnets and motors: A European call for action."

Gautam, A., R. Shankar and P. Vrat (2022). "Managing end-of-life solar photovoltaic e-waste in India: a circular economy approach." Journal of Business Research **142**: 287-300.

Gautam, A., R. Shankar, P. Vrat and Consumption (2021). "End-of-life solar photovoltaic e-waste assessment in India: a step towards a circular economy." Sustainable Production **26**: 65-77.

Ghisellini, P., R. Passaro and S. Ulgiati (2023). "Environmental assessment of multiple "cleaner electricity mix" scenarios within just energy and circular economy transitions, in Italy and Europe." Journal of Cleaner Production **388**: 135891.

Graulich K., J. B., and P. Dolega, C. Hermann, A. Manhart, V Bilsen, F. Bley and E. Watkins, T. Stainforth (2021). Emerging waste streams–challenges and opportunities. Freiburg, Germany, Oeko-Institut e.V.

Grijelmo, T. M., Lluís; Sanz, Javier (2022). Wind, PV and batteries recycling in Europe, EIT InnoEnergy and Naturgy Foundation.

Grubert, E. (2020). "Fossil electricity retirement deadlines for a just transition." **370**(6521): 1171-1173.

Heath, G. A., T. J. Silverman, M. Kempe, M. Deceglie, D. Ravikumar, T. Remo, H. Cui, P. Sinha, C. Libby, S. Shaw, K. Komoto, K. Wambach, E. Butler, T. Barnes and A. Wade (2020). "Research and development priorities for silicon photovoltaic module recycling to support a circular economy." Nature Energy **5**(7): 502-510.

Held M. et al., “Status of PV Module Take-Back and Recycling in Germany. Report IEA-PVPS T12-27:2024” (IEA-PVPS, 2024), https://iea-pvps.org/wp-content/uploads/2024/03/IEA-PVPS-T12-27-Report-PV-Recycling-in-Germany.pdf.

IEA. (2022). "Solar PV Global Supply Chains." Retrieved November 15, 2024, 2024, from https://www.iea.org/reports/solar-pv-global-supply-chains.

Invernizzi, D. C., G. Locatelli, A. Velenturf, P. E. Love, P. Purnell and N. J. J. E. P. Brookes (2020). "Developing policies for the end-of-life of energy infrastructure: Coming to terms with the challenges of decommissioning." **144**: 111677.

IRENA, I. R. E. A.-. (2022). "Solar Energy Data." from https://www.irena.org/Energy-Transition/Technology/Solar-energy.

Kalt, G., P. Thunshirn and H. Haberl (2021). "A global inventory of electricity infrastructures from 1980 to 2017: Country-level data on power plants, grids and transformers." Data in Brief **38**: 107351.

Kalt, G., P. Thunshirn, D. Wiedenhofer, F. Krausmann, W. Haas and H. Haberl (2021). "Material stocks in global electricity infrastructures – An empirical analysis of the power sector's stock-flow-service nexus." Resources, Conservation and Recycling **173**: 105723.

Kastanaki, E. (2025). “Dynamic Assessment of Photovoltaic Waste Streams in the EU-27 Countries under the Circular Economy Principles of ‘Reduce, Reuse and Recycle." Submitted to Journal of Resources, Conservation & Recycling. **214**: 108033.

Kastanaki, E. and A. Giannis (2022). "Energy decarbonisation in the European Union: Assessment of photovoltaic waste recycling potential." Renewable Energy **192**: 1-13.

Kefford, B. M., B. Ballinger, D. R. Schmeda-Lopez, C. Greig and S. Smart (2018). "The early retirement challenge for fossil fuel power plants in deep decarbonisation scenarios." Energy Policy **119**: 294-306.

Kennedy, R. (2022). "A Majority of New Solar Panels Will Retain 80% Production after 30 Years." 2024, from https://pv-magazine-usa.com/2022/11/07/a-majority-of-new-solar-panels-will-retain-80-production-after-30-years/.

Komoto, K., M. Held, C. Agraffeil, C. Alonso-Garcia, A. Danelli, J. Lee, F. Lyu, J. Bilbao, R. Deng and G. J. R. I.-P. T.-. Heath (2022). "Status of PV Module Recycling in Selected IEA PVPS Task12 Countries."

Kramer, K. J. A., Asger Bech; Beauson, Justine; Hansen, Ulrich Elmer; Clausen, Niels-Erik; Velenturf, Anne P. M.; Schmidt, Matthias (2024). " Quantifying Circular Economy Pathways of Decommissioned Onshore Wind Turbines: The Case of Denmark and Germany." Sustainability Research & Policy Network.

Latini, D., M. Vaccari, M. Lagnoni, M. Orefice, F. Mathieux, J. Huisman, L. Tognotti and A. Bertei (2022). "A comprehensive review and classification of unit operations with assessment of outputs quality in lithium-ion battery recycling." Journal of Power Sources **546**: 231979.

LATUNUSSA, C., L. MANCINI, G. BLENGINI, F. ARDENTE and D. PENNINGTON (2016). "Analysis of material recovery from silicon photovoltaic panels."

Le Boulzec, H., L. Delannoy, B. Andrieu, F. Verzier, O. Vidal and S. J. A. E. Mathy (2022). "Dynamic modeling of global fossil fuel infrastructure and materials needs: Overcoming a lack of available data." **326**: 119871.

Li, F., Z. Ye, X. Xiao, J. Xu and G. Liu (2020). "Material stocks and flows of power infrastructure development in China." Resources, Conservation and Recycling **160**: 104906.

Liang, Y., R. Kleijn, A. Tukker, E. J. R. van der Voet and S. E. Reviews (2022). "Material requirements for low-carbon energy technologies: a quantitative review." **161**: 112334.

Lichtenegger, G., A. A. Rentizelas, N. Trivyza and S. Siegl (2020). "Offshore and onshore wind turbine blade waste material forecast at a regional level in Europe until 2050." Waste management **106**: 120-131.

Liu, P. and C. Y. Barlow (2017). "Wind turbine blade waste in 2050." Waste Management **62**: 229-240.

López Ruiz, L. A., X. Roca Ramón and S. Gassó Domingo (2020). "The circular economy in the construction and demolition waste sector – A review and an integrative model approach." Journal of Cleaner Production **248**: 119238.

Maani, T., I. Celik, M. J. Heben, R. J. Ellingson and D. J. S. o. T. T. E. Apul (2020). "Environmental impacts of recycling crystalline silicon (c-SI) and cadmium telluride (CDTE) solar panels." **735**: 138827.

Mackie, C., Lobregt, M., Velenturf, A., Vasudevan, K., Frid, G., Najib, H., Agirregomezkorta, A., Barcelo Basanez, A., Monnaie, F., Krüger, B., Straarup Skygebjerg, L., Spring, P., Marchante Jiménez, M., Travia, W. F., & Beauson, J (2024). IEA Wind Task 45 - Deliverable 4.1 - Preliminary summary of policies, legislation, guidelines and initiatives that address the end-of-life of wind turbine blades. . Zenodo, EU Open Research Repository.

Mahmoudi, S., Huda, N., & Behnia, M. (2019). Photovoltaic waste assessment: Forecasting and screening of emerging waste in Australia. Resources, Conservation and Recycling, 146, 192–205. https://doi.org/10.1016/j.resconrec.2019.03.039Mahmoudi, S., N. Huda and M. Behnia (2021). "Critical assessment of renewable energy waste generation in OECD countries: Decommissioned PV panels." Resources, Conservation and Recycling **164**: 105145.

Majewski, P., N. Florin, J. Jit, R. A. J. R. Stewart and S. E. Reviews (2022). "End-of-life policy considerations for wind turbine blades." **164**: 112538.

Mathieux, F., F. Ardente, S. Bobba, P. Nuss, G. A. Blengini, P. A. Dias, D. Blagoeva, C. T. De Matos, D. Wittmer and C. J. P. O. o. t. E. U. B. Pavel, Belgium (2017). "Critical raw materials and the circular economy."

Mohammadiziazi, R. and M. M. Bilec (2022). "Building material stock analysis is critical for effective circular economy strategies: a comprehensive review." Environmental Research: Infrastructure Sustainability **2**(3): 032001.

Moné, C., M. Hand, M. Bolinger, J. Rand, D. Heimiller and J. Ho (2017). "2015 cost of wind energy review."

Monitor, G. E. (2024). Europe Gas Tracker.

Monitor, G. E. (2024). Global Coal Plant Tracker.

Monitor, G. E. (2024). Global Oil and Gas Plant Tracker.

Monticelli, G. C. L. M. A. (2019). Circl-e from decommissioning to regeneration. Ciruclar strategies for energy power plants. ARUP. Milan, Italy, Arup, Enel, and Intesa Sanpaolo.

Morlet, A., J. Blériot, R. Opsomer, M. Linder, A. Henggeler, A. Bluhm and A. J. E. M. F. Carrera (2016). "Intelligent assets: Unlocking the circular economy potential." 1-25.

Mulvaney, D., R. M. Richards, M. D. Bazilian, E. Hensley, G. Clough and S. Sridhar (2021). "Progress towards a circular economy in materials to decarbonize electricity and mobility." Renewable Sustainable Energy Reviews **137**: 110604.

Norgren, A., A. Carpenter and G. J. J. o. S. M. Heath (2020). "Design for recycling principles applicable to selected clean energy technologies: crystalline-silicon photovoltaic modules, electric vehicle batteries, and wind turbine blades." **6**(4): 761-774.

Nyffenegger, R., Ä. Boukhatmi, T. Radavičius and M. Tvaronavičienė (2024). "How circular is the European photovoltaic industry? Practical insights on current circular economy barriers, enablers, and goals." Journal of Cleaner Production **448**: 141376.

Ovaitt, S., Mirletz, H., Seetharaman, S., & Barnes, T. (2022). PV in the circular economy, a dynamic framework analyzing technology evolution and reliability impacts. iScience, 25(1), 103488. https://doi.org/10.1016/j.isci.2021.103488astuszak, J. and P. Węgierek (2022). "Photovoltaic cell generations and current research directions for their development." Materials **15**(16): 5542.

Paiano, A. (2015). Photovoltaic waste assessment in Italy. Renewable and Sustainable Energy Reviews, 41, 99–112. https://doi.org/10.1016/j.rser.2014.07.208

Polverini, D., N. Espinosa, U. Eynard, E. Leccisi, F. Ardente and F. Mathieux (2023). "Assessing the carbon footprint of photovoltaic modules through the EU Ecodesign Directive." Solar Energy **257**: 1-9.

Raimi, D. (2017). Decommissioning US power plants. R. f. t. F. Report, Resources for the Future Report.

Raugei M., Isasa M., and Palmer P. F., “Potential Cd Emissions from End-of-Life CdTe PV,” The International Journal of Life Cycle Assessment 17, no. 2 (February 1, 2012): 192–98, https://doi.org/10.1007/s11367-011-0348-9.

Sangwongwanich, A., Y. Yang, D. Sera and F. Blaabjerg (2017). "Lifetime evaluation of grid-connected PV inverters considering panel degradation rates and installation sites." IEEE transactions on Power Electronics **33**(2): 1225-1236.

Semieniuk, G., P. B. Holden, J.-F. Mercure, P. Salas, H. Pollitt, K. Jobson, P. Vercoulen, U. Chewpreecha, N. R. Edwards and J. E. J. N. C. C. Viñuales (2022). "Stranded fossil-fuel assets translate to major losses for investors in advanced economies." **12**(6): 532-538.

Singh, B., E. A. Bouman, A. H. Strømman and E. G. Hertwich (2015). "Material use for electricity generation with carbon dioxide capture and storage: Extending life cycle analysis indices for material accounting." Resources, Conservation and Recycling **100**: 49-57.

Sommer, V., J. Stockschläder and G. Walther (2020). "Estimation of glass and carbon fiber reinforced plastic waste from end-of-life rotor blades of wind power plants within the European Union." Waste Management **115**: 83-94.

Statista. "Regional Distribution of Solar PV Cells Production." Retrieved March 13, 2024, 2024, from https://www.statista.com/statistics/268682/regional-distribution-of-solar-cell-manufacturing/.

Stolz, P., R. Frischknecht, K. Wambach, P. Sinha and G. J. Heath (2017). Life cycle assessment of current photovoltaic module recycling, IEA PVPS Task 12, International Energy Agency Power Systems Programme. **13:** 2018.

Tao, J., S. Yu and S. Cells (2015). "Review on feasible recycling pathways and technologies of solar photovoltaic modules." Solar Energy Materials **141**: 108-124.

Tao, M., V. Fthenakis, B. Ebin, B. M. Steenari, E. Butler, P. Sinha, R. Corkish, K. Wambach, E. S. J. P. i. P. R. Simon and Applications (2020). "Major challenges and opportunities in silicon solar module recycling." **28**(10): 1077-1088.

Tesar, M., Karigl, B., Lampert, C. et al. (2021). Study on quality standards for the treatment of waste electrical and electronic equipment (WEEE) – Final report. D.-G. f. E. European Commission, Publications Office.

Tsanakas, J. A., A. van der Heide, T. Radavičius, J. Denafas, E. Lemaire, K. Wang, J. Poortmans, E. J. P. i. P. R. Voroshazi and Applications (2020). "Towards a circular supply chain for PV modules: Review of today's challenges in PV recycling, refurbishment and re-certification." **28**(6): 454-464.

Wang, S., Z. Hausfather, S. Davis, J. Lloyd, E. B. Olson, L. Liebermann, G. D. Núñez-Mujica and J. J. J. McBride (2023). "Future demand for electricity generation materials under different climate mitigation scenarios." **7**(2): 309-332.

Weckend, S., A. Wade and G. A. Heath (2016). End of life management: solar photovoltaic panels, National Renewable Energy Lab.(NREL), Golden, CO (United States).

Wettengel, J. (2024, March 25, 2024). "Germany to shut down seven more coal power plant units as country exits winter." Retrieved August 8, 2024, 2024.

WindEurope (2022). The EU Raw Materials Act WindEurope’s contribution to the European Commission consultation. Brussels, Belgium, Wind Europe.

WindEurope (2024). Wind energy in Europe: 2023 Statistics and the outlook for 2024-2030. G. B. Giuseppe Costanzo. Belgium, WindEurope.

WindEurope, C. a. E. (2020). Accelerating Wind Turbine Blade Circularity, WindEurope, Cefic and EuCIA.

Xie, J., Z. Xia, X. Tian and Y. Liu (2023). "Nexus and synergy between the low-carbon economy and circular economy: A systematic and critical review." Environmental Impact Assessment Review **100**: 107077.

Xu, C., Isabella, O., & Vogt, M. R. (2024). Future material demand for global silicon-based PV modules under net-zero emissions target until 2050. Resources, Conservation and Recycling, 210, 107824. https://doi.org/10.1016/j.resconrec.2024.107824zu Castell-Rudenhausen, M., W. Margareta, N. Dirk, D.

Yoko, P. Susanna, R. Zoboli, W. Henning and B. Ioannis (2022). Investigating Europe's secondary raw materials markets. Luxembourg: Publications Office of the European Union, European Environment Agency.

List of abbreviations and definitions

Abbreviations	**Definitions**
CEPRES	Circular Economy Pathway for Renewable Electricity Supply
CETO	Clean Energy Technology Observatory
CDW	Construction and Demolition Waste
CRMs	Critical Raw Materials
EC	European Commission
EEA	European Environment Agency
EGD	European Green Deal
EoL	End-of-Life
EU	European Union
EVA	Ethylene-vinyl acetate
GHGs	Greenhouse gases
ICT	Information and Communication Technology
IEA	International Energy Agency
ISO	International Organization for Standardization
JRC	Joint Research Centre – European Commission
LCA	Life Cycle Assessment
MS	Member State(s)
NECPs	National Energy and Climate Plans
OECD	Organisation for Economic Cooperation and Development
OJ	Official Journal of the European Union
PET	Polyethylene terephthalate
PV	Photovoltaic
UK	United Kingdom
US	United States of America

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Annexes

Annex 1: List of EU-funded projects on Wind Turbines and Blades

Overview of European projects dedicated to the recycling of fibre-reinforced polymer composite and wind turbine blades (prevention, reuse, repurpose, recycling and circular economy)

Acronym	Classification	Country coordinator	Name of coordinator	Kick-off year	Full title and link
KEMA project	Prevention	Netherlands	KEMA Nederland BV	1997	Technology for improved manufacture of blades from environmental resources https://cordis.europa.eu/project/id/JOR3960136
ENVIROCOMP	Prevention	UK (non-EU)	Halmatic Ltd	1997	Research, development and evaluation of environmentally friendly advanced thermoplastic composites for the manufacture of large surface area structures https://cordis.europa.eu/project/id/BRPR960228
REACT	Recycling	Netherlands	HEBO ENGINEERING	2003	Re-use of glassfibre reinforced plastics by selective shredding and re-activating the recyclate https://cordis.europa.eu/project/id/G1ST-CT-2002-50287
EURECOMP	Recycling	France	Plastic Omnium	2009	Recycling Thermoset Composites of the SST https://cordis.europa.eu/project/id/218609
LIFE-WGF-PP	Recycling	Spain	Befesa Plásticos S.L.	2009	Demonstration of a process to recycle glass fibre waste, placed on rubbish dump, producing Polypropilene composites https://webgate.ec.europa.eu/life/publicWebsite/project/details/2809
LIFE-GLASS FIBER	Recycling	Sweden	Stena Recycling AB	2009	Recycling of waste glass fibre reinforced plastic with microwave pyrolysis

					https://webgate.ec.europa.eu/life/publicWebsite/project/details/2834
LIFE-Composites Waste	Recycling	Denmark	Grymer Group ApS	2010	Demonstration of a new composites waste recycling process and of the use of the recycled materials in various industries https://webgate.ec.europa.eu/life/publicWebsite/project/details/3121
LIFE-BOATCYCLE	Recycling	Spain	LEITAT Technological Centre	2010	Management, recycling and recovery of wastes of recreational boat scrapping https://webgate.ec.europa.eu/life/publicWebsite/project/details/2961
SUSRAC	Recycling	Italy	CONSIGLIO NAZIONALE DELLE RICERCHE	2011	Sustainable recycling of aircrafts composites https://cordis.europa.eu/project/id/296546
GENVIND	Recycling	Denmark	Force Technology	2012	Recycling of composites and wind turbine blades https://www.dti.dk/genvind/35154
BME Clean Sky 027	Prevention	Hungary	MUSZAKI ES GAZDASAGTUDOMANYI EGYETEM	2012	Development of an innovative bio-based resin for aeronautical applications https://cordis.europa.eu/project/id/298090
IRECE	Recycling	Italy	CONSIGLIO NAZIONALE DELLE RICERCHE	2013	INDUSTRIAL RECYCLING OF CFRP BY EMULSIFICATION https://cordis.europa.eu/project/id/335277
LIFE-Enrich a poor waste	Recycling	Italy	Bra Servizi S.r.l.	2013	Original ennobling recycling process of GFRP waste to re-produce GFRP replacing energy-intensive construction elements https://webgate.ec.europa.eu/life/publicWebsite/project/details/3720
WALID	Prevention	Germany	Fraunhofer ICT	2013	Wind Blade Using Cost-Effective Advanced Composite Lightweight Design https://cordis.europa.eu/project/id/309985
LIFE-BRIO	Recycling	Spain	IBERDROLA	2014	Demonstration of wind turbine rotor Blade Recycling into the Coal Clough Wind Farm Decommissioning Opportunity

					https://webgate.ec.europa.eu/life/publicWebsite/project/details/4169
EFFIWIND	Prevention	France	Canoe Technology Platform	2014	EFFIWIND : DEVELOPMENT OF A NEW GENERATION OF WIND TURBINE BLADES BASED ON RECYCLABLE ACRYLIC MATERIALS http://www.plateforme-canoe.com/en/effiwind-project-first-25m-long-wind-blade-manufactured-using-elium-resin/
RECYBLADE	Recycling	Denmark	Danish Ministry for Environment	2016	Sustainable recycling of wind turbine blades into construction component https://www2.mst.dk/Udgiv/publikationer/2014/02/978-87-93178-17-5.pdf
ECO-COMPASS	Prevention	Germany	DEUTSCHES ZENTRUM FUR LUFT - UND RAUMFAHRT EV	2016	Ecological and Multifunctional Composites for Application in Aircraft Interior and Secondary Structures https://cordis.europa.eu/project/id/690638
ECOBLADE	Recycling	Denmark	FRANDSEN INDUSTRI HOLDING APS	2017	Eco-efficient decommissioning of wind turbine blades through on-site material shredding and separation https://cordis.europa.eu/project/id/778847
REROBALSA	Recycling	Germany	Fraunhofer WKI	2017	Recycling of Balsa RECYCLING VON ROTORBLÄTTERN ZUR VERWERTUNG VON BALSAHOLZ/SCHAUM FÜR DIE HERSTELLUNG VON DÄMMSTOFFEN
FIBEREUSE	Recycling	Italy	Politecnino Milano	2017	Large scale demonstration of new circular economy value-chains based on the reuse of end-of-life fibre reinforced composites. https://cordis.europa.eu/project/id/730323
LIFE-REFIBRE	Recycling	Spain	INSTITUTO DE LA CONSTRUCCIN DE CASTILLA Y LEN	2017	High value asphalt pavements with glass fibre from sustainable recycling of wind powered generator blades https://webgate.ec.europa.eu/life/publicWebsite/project/details/4633
ECOBULK	Prevention/ Recycling	Spain	UNIVERSITAT POLITECNICA DE CATALUNYA	2017	Circular Process for Eco-Designed Bulky Products and Internal Car Parts

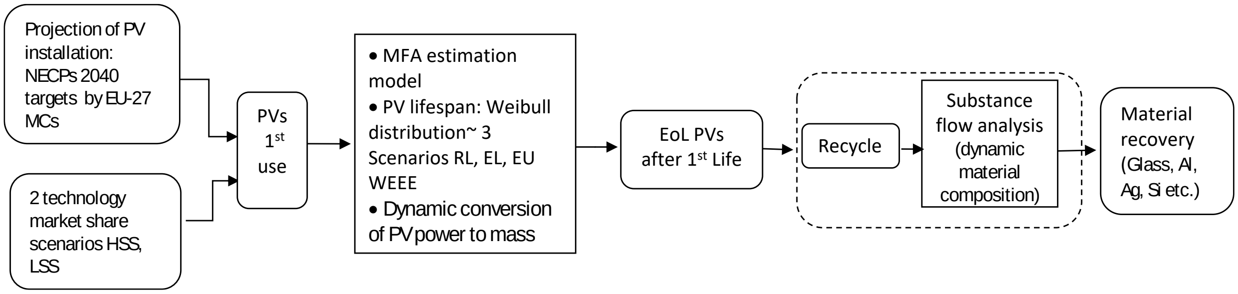
					https://cordis.europa.eu/project/id/730456
SSUCHY	Prevention	France	Université de Franche Comté	2017	Sustainable structural and multifunctional biocomposites from hybrid natural fibres and bio-based polymers https://cordis.europa.eu/project/id/744349
ECOXY	Prevention	Spain	Cidetec	2017	ECOXY - Bio-based recyclable, reshapable and repairable (3R) fibre-reinforced EpOXY composites for automotive and construction sectors. https://cordis.europa.eu/project/id/744311
RecycleWind	Recycling	Germany	Bremen Hochschule	2018	RecycleWind – Conception and application simulation of a self-learning recycling network for the resource-saving control of material flows for high-quality and especially long-lasting products using the example of wind turbines. https://www.iekrw.de/en/recyclewind-en/
R3FIBER	Recycling	Spain	BCIRCULAR COMPOSITES	2018	Eco-innovation in Composites Recycling for a Resource-Efficient Circular Economy https://cordis.europa.eu/project/id/809308
REINVENT	Prevention	Italy	Fiat	2018	Novel Products for Construction and Automotive Industries Based on Bio Materials and Natural Fibres https://cordis.europa.eu/project/id/792049
DACOMAT	Prevention	Norway	SINTEF	2018	Damage Controlled Composite Materials https://cordis.europa.eu/project/id/761072 ; https://www.sintef.no/projectweb/dacomat/
AIRPOXY	Prevention	Spain	Cidetec	2018	ThermoformAble, repaIrable and bondable smaRt ePOXY based composites for aero structures https://cordis.europa.eu/project/id/769274

Re-Wind	Repurpose	Ireland / US	University College of Cork	2019	REPURPOSING WIND BLADES DRIVING INNOVATION IN WIND FARM DECOMMISSIONING https://www.re-wind.info/
Green Insulation	Recycling	Denmark	Mijløskærm	2019	Green-Tech Fibre Insulation https://cordis.europa.eu/project/id/888396
ZEBRA	Prevention	France	IRT Jules Verne	2020	Zero wastE Blade ReseArch https://www.lmwindpower.com/en/stories-and-press/stories/news-from-lm-places/zebra-project-launched
CARBO4POWER	Prevention	Greece	ETHNICON METSOVION POLYTECHNION	2020	New generation of offshore turbine blades with intelligent architectures of hybrid, nano-enabled multi-materials via advanced manufacturing https://cordis.europa.eu/project/id/953192
WindLEDeRR	Repurposing	Ireland	University College Dublin	2021	WindLEDeRR A comprehensive decision support tool for end-of-life wind turbines of Ireland; Lifetime Extension, Decommissioning, Repowering, Repurposing https://www.marei.ie/project/windlederr/
DECOMBLADES	Recycling	Denmark	Ørsted	2021	A three-year project providing the basis for commercialization of sustainable recycling of wind turbine blades. https://decomblades.dk/
SUSWIND	Recycling	UK	NCC	2021	Accelerating sustainable composite materials and technology for wind turbine blades https://www.nccuk.com/what-we-do/sustainability/suswind/
CETEC	Prevention	Denmark	AU	2021	Circular Economy for Thermoset Epoxy Composites https://www.project-cetec.dk/uk/
VIBES	Prevention	Spain	AITIIP	2021	IMPROVING RECYCLABILITY OF THERMOSET COMPOSITE MATERIALS THROUGH A GREENER RECYCLING TECHNOLOGY BASED ON REVERSIBLE BIOBASED BONDING MATERIALS

					https://cordis.europa.eu/project/id/101023190
CIRCUBLADE	Repurpose	Sweden	Chalmers	2022	CIRCUBLADE – Holistic solutions to upcycle End-of-Life wind turbine blades https://chalmersindustriteknik.se/en/news/circublade-holistic-solutions-to-upcycle-end-of-life-wind-turbine-blades/
REKOVIND2	Repurpose	Sweden	RISE	2022	Rekovind2 - Digitization of wind blade streams https://www.ri.se/en/what-we-do/projects/rekovind2-digitization-of-wind-blade-streams
RECREATE	Recycling / prevention	Italy	Politecnino Milano	2022	REcycling technologies for Circular REuse and remanufacturing of fibre-reinforced composite mATErials https://cordis.europa.eu/project/id/101058756
EuReComp	Recycling	Greece	ETHNICON METSOVION POLYTECHNION	2022	European recycling and circularity in large composite components https://cordis.europa.eu/project/id/101058089
TURBO	Prevention	Denmark	DTU	2022	Towards tURbine Blade production with zero waste https://cordis.europa.eu/project/id/101058054
ESTELLA	Prevention	Spain	Fondacion Cidaut	2022	DESign of bio-based Thermoset polymer with rEcycLing capabiLity by dynAmic bonds for bio-composite manufacturing https://cordis.europa.eu/project/id/101058371
Wind Value	Decision support	Ireland	University College of Cork	2022	End of Life Decisions for Wind Farms: An Opportunity for Climate Action and for Energy Communities https://windvalue.ie/?page_id=2
EirBLADE	Repurposing	Ireland	Munster Technological University	2023	National repository of decommissioned WTBs to centralize information, such as origin of a blade, history, geometry, condition rating based on visual inspection, non-destructive and

					destructive testing, material characterization, and modelling. https://www.marei.ie/marei-researchers-receive-funding-from-the-sfi-national-challenge-fund/
EoLO-HUBs	Recycling	Spain	AITIIP	2023	Wind turbine blades End of Life through Open HUBs for circular materials in sustainable business models https://cordis.europa.eu/project/id/101096425
Blades2Build	Recycling	Denmark	DTU	2023	https://cordis.europa.eu/project/id/101096437 https://blades2build.com/
REFRESH	Recycling	Italy	RINA consulting	2023	Smart dismantling, sorting and REcycling of glass Fibre REinforced composite from wind power Sector through Holistic approach https://cordis.europa.eu/project/id/101096858

Annex 2: Methodology for PV waste flows in the EU-27



LSS: Low c-Si penetration scenario, HSS: High c-Si scenario, RL: Regular Loss; EL: Early Loss

Annex 3: Market share of PV panels technologies

Tables - (a) Low c-Si penetration scenario, LSS (Weckend et al., 2016; Mahmoudi et al., 2019; Kastanaki, 2025), (b) High c-Si penetration scenario, HSS (Ovaitt et al, 2022; Fraunhofer ISE, Photovoltaics Report, 2022)

(a) LSS

	c-Si	**a-Si**	**CdTe**	**CIGS**	**CPV**	**OPV**	**Advanced c-Si**	**Other**
1980	1.000	0	0	0	0	0	0	0
1985	0.780	0.220	0	0	0	0	0	0
1990	0.720	0.280	0	0	0	0	0	0
1995	0.880	0.110	0.010	0	0	0	0	0
2000	0.900	0.100	0.000	0	0	0	0	0
2005	0.950	0.030	0.020	0	0	0	0	0
2010	0.810	0.040	0.120	0.030	0	0	0	0
2015	0.680	0.040	0.180	0.080	0.010	0.003	0.005	0.003
2020	0.733	0	0.052	0.052	0.012	0.058	0.087	0.006
2025	0.591	0	0.050	0.058	0.010	0.073	0.172	0.048

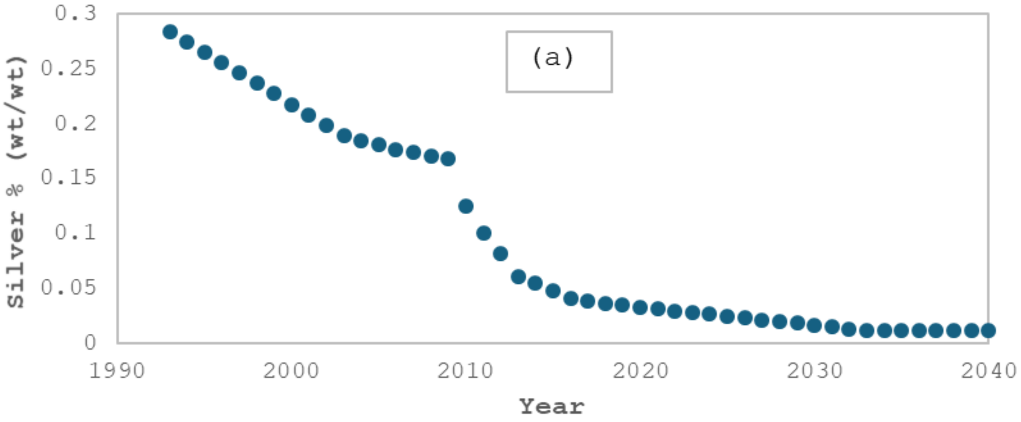
2030	0.448	0	0.047	0.064	0.006	0.087	0.256	0.092
2035	0.306	0	0.045	0.070	0.004	0.102	0.341	0.134
2040	0.163	0	0.042	0.076	0.001	0.116	0.425	0.177

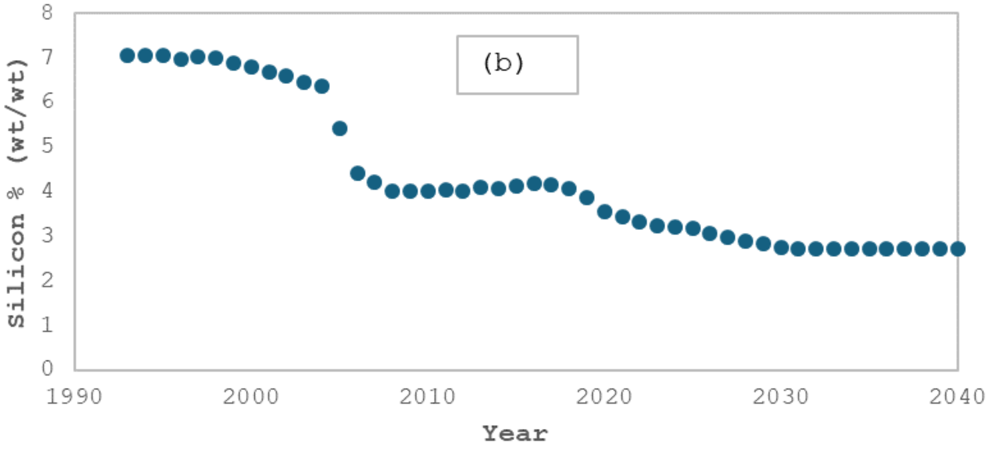
(b) HSS (Photovoltaics Report, Fraunhofer ISE, 2022)

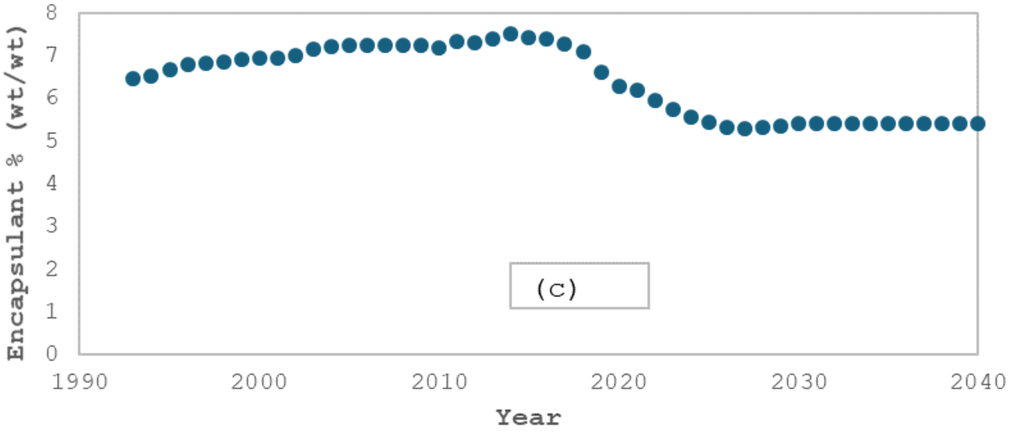
Year	c-Si,	Thin film
1980	100	0
1981	97	3
1982	92	8
1983	87	13
1984	79	21
1985	77	23
1986	71	29
1987	68	32
1988	68	32
1989	72	28
1990	73	27
1991	78	22
1992	80	20
1993	84	16
1994	86	14
1995	87	13
1996	86	14
1997	88	12
1998	88	12
1999	89	11
2000	90	10
2001	91	9

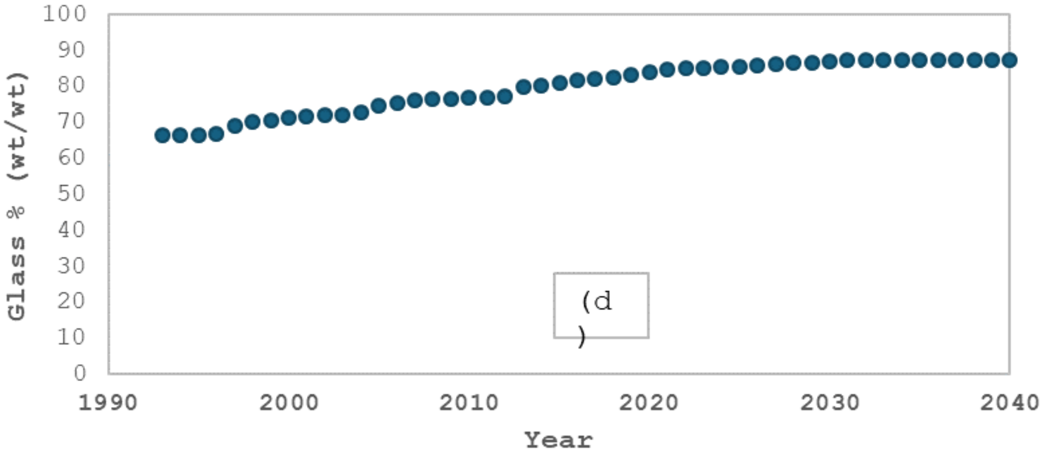
2002	94	6
2003	95	5
2004	95	5
2005	94	6
2006	93	7
2007	89	11
2008	86	14
2009	83	17
2010	88	12
2011	86	14
2012	91	9
2013	91	9
2014	92	8
2015	94	6
2016	94	6
2017	96	4
2018	96	4
2019	95	5
2020	95	5
2021	95	5
2040	95	5

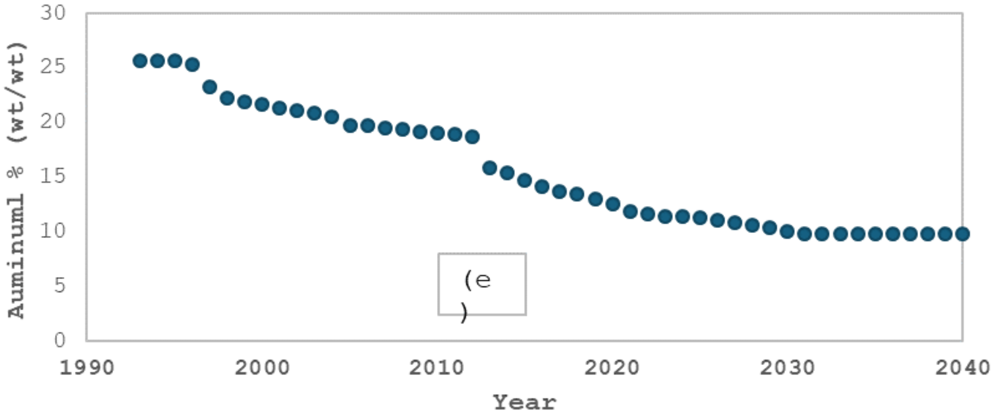
Annex 4: Graphics of data for the dynamic composition values for (a) Ag, (b) Si, (c) EVA encapsulant, (d) glass and (e) Al for c-Si PVs






Encapsulant % (wt/wt)
8
7
6
5
4
3
2
1
0
1990
2000
2010
2020
2030
2040
Year
(c)


Glass % (wt/wt)
100
90
80
70
60
50
40
30
20
10
0
1990
2000
2010
2020
2030
2040
Year
(d
)


Auminuml % (wt/wt)
30
25
20
15
10
5
0
1990
2000
2010
2020
2030
2040
Year
(e
)

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