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Emerging waste streams – Challenges and opportunities

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List of Abbreviations

BEV	Battery Electric Vehicle
Cd	Cadmium
CENELEC	European Committee for Electrotechnical Standardization
CF	Carbon Fibre
CRM	Critical Raw Materials
CO_2	Carbon Dioxide
Co	Cobalt
DIN	German Institute for Norming (Deutsches Institut für Normung)
EC	European Commission
EEA	European Environment Agency
EEE	Electrical and Electronic Equipment
ELV	End-of-Life Vehicle
EN	European Norm
EPR	Extended Producer Responsibility
ESS	Energy Storage Systems
EoL	end-of-life
EU	European Union
EU-27	27 countries of the European Union (without UK)
EU28	28 countries of the European Union (incl. UK)
EUROSTAT	Statistical Agency of the European Union
EV	Electric Vehicle
ETIP	European Technology and Innovation Platform
GF	Glas Fibre
GHG	Greenhouse Gas
HEV	Hybrid Electric Vehicle
HF	Hydrofluoric Acid
ICPE	Installation Classified for the Protection of the Environment
IEC	International Electrotechnical Commission
IEEP	Institute for European Environmental Policy
IRENA	International Renewable Energy Agency
ISO	International Organisation for Standardization

JRC	Joint Research Centre
KfW	Kreditanstalt für Wiederaufbau
LCA	Lifecycle Assessment
LFP	Lithium Iron Phosphate
LIB	Lithium Ion Batteries
Li-ion	Lithium-ion
NDC	Nationally Determined Contributions
Ni	Nickel
NMC	Lithium-Nickel-Manganese-Cobalt-Oxide
O_2	Oxygen
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
Pb	Lead (lat. Plumbum)
PHEV	Plug-in Hybrid Electric Vehicle
PoM	Put-on-Market
PV	Photovoltaic
QR	Quick Response (QR-Code)
R&D	Research and development
RFID	Radio Frequency Identification
RoHS	Restriction of Hazardous Substances Directive
SHS	Solar Home Systems
Si	Silicon
Te	Tellurium
UNEP	United Nations Environment Programme
VAT	Value Added Tax
WEEE	Waste of Electrical and Electronic Equipment
WSR	Waste Shipment Regulation

Summary

Objective and approach of this study

Renewable energy technologies like wind turbines, solar photovoltaic (PV) panels or energy storage systems are essential for Europe's transition towards climate neutrality. At the same time, these "green" technologies should also be in line with the environmental objectives of the European Green Deal. With many of them installed decades ago and probably at that time not designed according to circular economy principles, it is inevitable that their waste generation will not only be rapidly increasing in the coming years but that these emerging waste streams will also be posing challenges for the current recycling infrastructure both from a qualitative and quantitative perspective. This study aims at (i) mapping and selecting the most relevant emerging waste streams related to the energy transition and specifically the renewable electricity sector; (ii) analysing the key challenges for their waste management but also opportunities related to these waste streams; (iii) identifying existing or potential business models and solutions addressing the challenges; as well as (iv) discussing key drivers and framework conditions necessary to realise the identified opportunities and solutions for moving toward greater circularity in the coming years.

Based on a mapping of key technology areas related to the energy transition and renewable energy sector, 13 technology fields were initially analysed regarding waste-related information such as **current amounts and expected trends,** as well as **challenges and opportunities for their end-of-life management**. Based on this initial analysis, photovoltaics, lithium-ion batteries for energy storage and electromobility as well as wind turbines appeared to have the highest relevance for emerging waste streams in Europe until 2030 and thus were examined in further detail regarding their challenges and opportunities for waste management and approaches to increase circularity.

Emerging waste streams in the field of photovoltaics

Photovoltaic is currently the fastest emerging technology among the technologies for renewable electricity production in Europe. In 2020, about 50 000 tonnes of waste PV panels are estimated in Europe; the amount will significantly increase to more than 350 000 tonnes in 2025; in 2030, the volumes are expected to exceed 1 500 000 tonnes.

Glass is the most relevant component in terms of weight with about two-thirds of the total waste stream. Photovoltaic modules also contain highly valuable materials of economic interest, such as silver, copper, aluminium with about 15 % of the total weight. Furthermore, critical raw materials such as indium or germanium in the waste stream are of high relevance but technically difficult to recover. About 95 % of the mass of resources in PV modules (e.g. glass, copper, aluminium, etc.) have the potential to be recycled, however, apart from aluminium and glass, the remaining module scrap, including silicon, silver contacts, tin, and heavy metal containing solder (lead) usually undergoes thermal treatment in incineration plants.

Main challenges in PV recycling, both in economic and technological terms, are the delamination, separation and purification of the silicon from the glass and the semiconductor thin film. Further challenges for the recycling of photovoltaic modules are hazardous substances such as cadmium, arsenic, lead, antimony, polyvinyl fluoride and polyvinylidene fluoride. Also, at the end of life of photovoltaic systems, logistic constraints arise due to necessary work on a panel at a height of 20 metres which is often not anticipated at the design or installation stage of PV modules.

Approaches to increase the circularity of photovoltaic systems do not include waste prevention as a priority strategy as waste from the PV production does not seem to be relevant. Ecodesign and

design for recycling could significantly improve the durability, reparability and recyclability of future PV modules. Refurbishment and/or reuse of well-working second-hand PV panels are in principle technically feasible, however, so far, they have not been subject to legal frameworks and are hardly profitable. Current circular business models applied to photovoltaics in Europe are, for example, an integrated production where the recycling is conducted by the manufacturing company; disclosure of the material composition to facilitate recycling; and mobile recycling devices, also offered as rental or leasing system, which reduce the distance between collection and recycling sites and employ mechanical processes instead of thermal or chemical ones.

Some policy gaps and market barriers for increasing circularity of photovoltaics were identified: The policy process of the European Commission elaborating mandatory requirements for durability, reparability and design for recycling under the Ecodesign regulatory framework is still ongoing and the effects on increased circularity will only be visible at the end of life of future installed PV modules. Repair and reuse approaches are impeded, as in order to maintain the (expensive) inverter warranty, only inverter providers or companies commissioned by them are allowed to intervene for repair. Second-hand inverters and PV modules are only to a small degree or not at all covered by warranties. For proper repair and maintenance of PV modules, there also seems to be a lack of highly qualified technicians. Finally, some national legislation might impede circular business models such as mobile recycling systems.

As the collection has improved over the past ten years (several return schemes started working) and also the recycling capacities are growing (for example, a recycling plant in the south of France started operation in 2018), the recycling system for photovoltaics seems to be on track, but there is still room for improvement. Modules are being exchanged before they reach their technical end of life, because the new ones are more efficient, and they bring the companies a financial benefit. The reuse of cells is currently not widely applied, since the refurbishment is more costly than a new and more efficient cell. Also, for example, the Waste of Electrical and Electronic Equipment (WEEE) directive has no specific recycling targets for certain metals. Further policy options would be useful to improve the chances of reuse and to increase recycling.

Emerging waste streams in the field of lithium-ion batteries

Lithium-ion batteries (LIBs) are mainly produced for electric vehicles whereas stationary storage only accounts for about 3 % of the lithium-ion battery market. In the coming decade, depending on the year that new production lines become operational and near-term market projections, Europe may serve between 7 % and 25 % of global demand with most of the manufacturing capacity located in Sweden, Germany and Poland. In 2020, a total volume of almost 40 000 tonnes per year of all waste lithium-ion batteries (energy storage systems, traction batteries, and portable batteries) were expected with forecast to rise to about 75 000 tonnes per year in 2025 and 240 000 tonnes per year in 2030. Due to long lifetimes of 20 years for *energy storage system* applications, their share is rather low with around 2 500 tonnes in 2020, 13 800 tonnes per year by 2025 and 26 200 tonnes of end-of-life lithium-ion stationary energy storage batteries per year by 2030.

In addition, production waste from the manufacturing of lithium-ion batteries is emerging, especially in the beginning due to the necessary adjustments of the production parameters. Assuming that 1 % of the produced output is faulty and ends up as production waste, significant volumes will emerge, approximately in the same range as the expected waste stream of stationary energy storage batteries. The take-back of faulty traction batteries will lead to a previously unanticipated increase in end-of-life lithium-ion batteries in 2021.

The strongly growing number of lithium-ion batteries and production sites in the EU is demanding major action concerning the recycling and circularity of end-of-life batteries and the waste arising during the battery production. Currently, the recycling market is still waiting for the waste stream of batteries to grow. On the other hand, the volume of production scrap and the number of retracted batteries is supposed to grow faster than expected in the coming years without a real solution for the resulting gap in recycling capacities.

Currently, there is a lack of recycling technologies and large-scale recycling capacities in Europe (only pilot plants) to cope with the expected huge rise of waste streams from lithium-ion batteries in the next few years. Also, the infrastructure to transport and store the rising amount of waste batteries is often still missing and needs to be built up in the next years. Especially for lithium-ion batteries, measures to reduce safety risks of a "thermal runaway" during logistics and waste treatment are necessary but expensive, e.g. by special transport containers, temperature monitoring and a pre-treatment with salt-water or heat. The situation is aggravated due to the fact of a variety of different battery designs requiring each specific, costly, transport containers. Therefore, economic efficiency of lithium-ion battery recycling is yet difficult to achieve, mainly due to high safety risks during transport and recycling on the one hand, but also the material values (e.g. cobalt or nickel) not being high enough to cover costs of recycling. Cobalt and nickel could be valuable enough to make battery recycling profitable under certain circumstances, if conducted at large-scale, and depending on the future price for these resources and their content in the batteries. Especially for cells without cobalt or nickel inside, the recovered materials will probably never cover the costs of the recycling process.

Approaches to increase the circularity of lithium-ion batteries should be targeted at improving lifetime and keeping the products longer in the use phase. Information about the battery, modular design, harmonization of battery chemistry and design as well as the content of high impact materials are significant factors to reduce the challenges related to the battery waste stream. In December 2020, the European Commission proposed a new Battery Regulation yet to be adopted, which partly includes approaches on durability and material efficiency, and further proposals for recycling efficiencies and recycled content quotas for lithium-ion batteries. In some European countries, take-back systems for industrial batteries were established on a voluntary basis by industry initiative. Few companies are active in refurbishment of batteries with own quality procedures and certification by external organisations. Further, end-of-life batteries from electromobility could be reused in stationary applications, which is not common practice yet but investigated.

The implementation of innovative circular business models for lithium-ion batteries is slowed down because ecological benefits of recycled material is not yet priced. Secondary materials have to compete with primary material. Also, the market for batteries and material demand is growing too fast to sustain it with recycled materials only. Measures to increase the demand for recycled material could be legally determinations of a fixed rate of recycling material input (closed loop) or using the emerging waste streams in other applications (open loop). However, battery technologies and chemistries are still under development and changing which makes it difficult for new business models to make reliable assumptions regarding the future market development and demand.

Especially the battery regulation of the European Commission includes several proposals to increase circularity which might lead to an improved battery waste management in future. However, the regulation is unlikely to immediately solve all the challenges related to the battery waste stream, also because practical implementation usually lags behind the legal requirements in time.

Emerging waste streams in the field of wind energy

In 2019, wind power made up 35% of the total electricity generated from renewable sources in Europe, with more than 3 000 wind turbines newly installed only in that year. Wind turbines are a highly relevant emerging waste stream because of their high demand of materials of about 400 000 tonnes per gigawatt wind power. In 2020 a total waste volume of about 2.5 million tonnes per year was expected, increasing to 3.3 million tonnes per year in 2025 and 4.7 million tonnes per year in 2030. Wind turbines consist of different parts such as the tower, the fundament and cables which are made of materials that have a well-established waste treatment, such as steel, aluminium, copper, cast iron and concrete, which is why about 90% of a wind turbine´s mass can be recycled.

The experience with end-of-life treatment is very limited because by 2020 only few of the first installed wind turbines have reached their end-of-life stage. Critical raw materials in magnets (neodymium, praseodymium, boron, dysprosium and niobium) could be valuable enough to make recycling of permanent magnet generators of wind turbines profitable, depending on the future price and their concentration in the waste stream. Rare earth elements as a crucial part of magnets are expected to add up to more than 500 tonnes per year in 2030.

For turbine blades, made of lightweight like carbon fibre (CF), glass fibre (GF), and composite material, the recycling infrastructure is still under development and research is ongoing or further research and implementation needed. The huge size of the blades would make transportation costs prohibitive for long-distance hauls to far-away recycling facilities. Around 14 000 wind turbine blades that could be decommissioned by 2023 are expected, equivalent to between 40 000 and 60 000 tonnes, difficult to recycle due to composite materials. Downcycling of carbon fibres as plastic moulded Euro pallets and polymer concrete as well as other construction applications such as noise proof barriers or thermal insulation materials is partly applied.

As approach to increase the circularity of wind turbines, waste prevention regarding production waste of wind turbines seems not seen as relevant. End-of-life waste prevention is tackled by extending the overall lifetime of wind turbines, e.g. through digital solutions facilitating preventive maintenance and repair or modular / upgradeable design with more easily accessible components for replacement of broken parts. Gear boxes and generators can be upgraded for reuse. Reusing turbine blades, e.g. as replacements for blades on similar (usually older) models of turbines is applied, however challenging due to their diversity in size and shape, which makes it harder to find the right types. A common way to trade these is by using e-platforms. Lifetime monitoring or fatigue testing of the blade might be necessary to ensure the safety of re-using the blade.

A significant portion of decommissioned wind turbines are exported for reuse, e.g. to Eastern Europe or outside of Europe, e.g. Latin America, however with no data on the respective share. Overall, current research efforts with regard to circularity seem to be predominantly focused on finding recycling solutions for the existing wind turbines to be decommissioned rather than on exploring material improvement or ecodesign approaches facilitating future dismantling, remanufacturing or recycling of wind turbines.

Some policy gaps and market barriers for increasing circularity of wind turbines were identified. For example, there is limited legislation both at EU and national levels regulating the treatment of composite or blade waste. European authorities use different regulatory instruments to incentivise recycling. Lack of regulation is one aspect why the disposal in landfills continues in many European countries. Also, costs of recycling composite waste are considered too high compared to the levels of landfill taxes for wind turbine blade waste, to trigger substantial changes towards more recycling. Extended producer responsibility for end-of-life management is rather not applied in the wind sector.

Stakeholders are pursuing EU wide dialogue to consider a ban on landfilling turbine blades. At the same time, some actors suggest considering landfilling at sea as an option to find a solution for the shrinking space in limited landfills.

Further, composite waste arising from the wind turbine blades is often classified as plastic waste from construction and demolition, i.e. it may therefore become mixed with other types of plastics. Differing waste classification may limit efficient separate collection and sorting. On the other hand, so far low volumes of composite wind blade waste make it challenging to build a recycling business based only on this waste stream. Also, lack of information and standardization in the composition of the different components hampers the development of a specified treatment process. Sector specific guidelines could spread the application of design for recycling in the industry. Cooperation of all composite-using sectors could facilitate finding cost-effective solutions and value chains for the combined volumes. Legally determined recycling targets, as introduced in France, or quotas of recycled content in some might stimulate recycling and the market for secondary materials. Finally, financial support for research and development (R&D), would be beneficial to encourage industry, private companies, academia and others to share their knowledge and work together on future circular solutions.

Potential side effects related to the emerging waste streams of energy transition technologies

Especially for lithium-ion batteries, but also for photovoltaics and wind turbines, due to the high costs of recycling and disposal in Europe, there could be a risk that actors will externalise these costs by exporting near end-of-life technologies and electric vehicles for further reuse to non-OECD (Organisation for Economic Co-operation and Development) countries. This could be triggered by a demand of these countries for renewable energies and electromobility to achieve rural electrification, better air quality in urban environments, and their greenhouse gas emission targets under the Paris Agreement. Whereas the EU usually has best-practice approaches for hazardous waste treatment, the export of used lithium-ion batteries, either in electric vehicles and/or as energy storage systems, to non-OECD countries with no stringent enforcement of environmental regulations may have severe environmental impacts in those countries.

For example, whereas for transport of lithium-ion batteries specific safety requirements are foreseen, this might not be necessary if the export goods to non-OECD countries are classified as electric vehicles or energy storage systems; this might still impose transport risks (thermal run-away). Also, in contrast to lead acid batteries which provide a net value for recyclers, i.e. being collected and recycled, there is no value from but high costs of the waste management of lithium-ion batteries. This imposes the risk that lithium-ion batteries will not be collected and recycled at all at their end of life but rather disposed of with the municipal waste or landfilled. Finally, although lithium-ion batteries have a lower toxicity compared to lead acid batteries, all hazardous substances (e.g. harmful, corrosive hydrofluoric acid) would end up in the environment if the whole lithium-ion battery will be improperly disposed of; and, if improperly disposed of there is also the risk of thermal run-aways during transport, storage, as well as in landfills.

The export of used battery electric vehicles to non-OECD countries for externalizing high costs for recycling and disposal of lithium-ion batteries in Europe, is currently not in focus of the EU waste shipment and end-of-life vehicle (ELV) legislations. Additional requirements would be needed for the export of used lithium-ion batteries in electric vehicles such as quality standards (“at least as good as new” regarding quality, i.e. residual capacity or lifetime), appropriate packaging and/or safety measures for transports, labelling of hazardous substances etc. In some countries, lithium-ion is already classified as hazardous waste, and transport must be notified, when crossing borders.

At the same time, policy instruments, R&D and funding to facilitate environmentally sound battery recycling and additional circularity approaches of lithium-ion batteries waste streams emerging from electric vehicles in Europe are necessary and should be encouraged to avoid those side effects of externalising environmental impacts as outlined above and keep valuable resources in Europe.

Policy options for the emerging waste streams

For photovoltaics, the collection and treatment of PV modules that are not falling under EPR should be tackled. Material-specific recycling targets should be put up to recover critical materials. The infrastructure for recycling still needs to be further built up and processes to recycle e.g. silicon need further development, so research should be funded. New regulations like for recycling targets or the ban of certain treatment methods as the thermal treatment would be useful to improve the chances of reuse and to increase recycling. The standardization of the panels may be an option to establish design for recycling, facilitate reuse and the recycling of the panels at the end of their life. A treatment standard, a harmonized classification of the waste as well as end-of-waste criteria could also help in recycling PV modules. Additionally, more information can be put on the panels (e.g. by a tag) to give recyclers more information, thus making recycling easier, because the different types of PV cells could be sorted before the treatment. New financing models to recover the costs of collection, treatment, recovery, recycling and disposal seem to be necessary such as producer-financed or consumer-financed models (upfront or at end of life) or a carbon tax.

For lithium-ion batteries used for energy storage and electromobility, apart from the upcoming European Battery regulation, the most important policy options should be targeted at a swift setting up of the battery waste logistics and recycling infrastructure. The amount of batteries put on the market is rising, the new battery cell production in the EU is connected to large amounts of production waste and retractions of faulty batteries lead to a major increase of battery related waste. If the EU will not be able to build up recycling capacities fast enough, this waste has to be stored until capacities are sufficient, or otherwise might be shipped to Asia. Both possibilities are connected to safety risks and high storage and transportation costs, respectively. The latter also leads to a loss of valuable critical raw materials connected to the export of these battery cells necessary for the battery industry in the EU.

In the field of wind energy, most OEMs and recycling facilities are based in Europe. In view of the emerging waste streams, however, there is no or only limited legislation regulating the take-back and treatment of composite or blade waste, neither at EU nor at national levels. Moreover, no extended producer responsibility scheme is applied. Industry has started own initiatives such as take-back schemes, research on recycling technologies for the composite materials, platforms for the trade of reused turbines, or initiating a voluntary initiative for a ban of landfilling waste blades. Legally determined recycling targets (so far only adopted in France), recycling targets for specific metals / critical raw materials, or quotas for recycled content could further stimulate recycling and secondary material markets. Besides further R&D activities in the field of recycling technologies for composite carbon fibre materials, especially incentives or financial support for a swift building up of the wind turbine recycling infrastructure would be necessary to manage the huge waste stream expected in the coming years.

Finally, for some of the information compiled for this study, e.g. related to the emerging waste volumes, broken down by type of valuable or critical raw materials, there is a lack of regular and consistent data. Therefore, it is also recommended to refine the existing monitoring and reporting system in order to gain a better information basis facilitating a priority setting for further policy options.

1 Introduction

Renewable energy technologies like wind turbines, solar photovoltaic panels or electrochemical and electrical energy storage systems are essential for Europe's transition towards climate neutrality. At the same time, these "green" technologies should also be in line with the environmental objectives of the European Green Deal. With many of them installed decades ago and probably at that time not designed according to circular economy principles, it is inevitable that their waste generation will not only be rapidly increasing in the coming years but that these emerging waste streams will also be posing challenges for the current recycling infrastructure both from a qualitative perspective, like new waste types with specific characteristics, and a quantitative one, such as waste generated in significant amounts in the years to come, for which separate collection, sufficient treatment capacity and facilities or new recycling technologies may be needed.

Objectives of this study are (i) to map and select the most relevant emerging waste streams related to the energy transition and specifically the renewable electricity sector; (ii) to analyse the key challenges for their waste management but also opportunities related to these waste streams; (iii) to identify existing or potential business models and solutions addressing the challenges; as well as (iv) to discuss key drivers and framework conditions necessary to realise the identified opportunities and solutions for moving toward greater circularity in the coming years.

The first step is a mapping of technologies related to the energy transition and renewable energy sector. For this "long list" of technologies (see section 2), initial waste-related information is gathered such as **current amounts and expected trends,** as well as **challenges and opportunities for their end-of-life management**. This includes topics like logistics (e.g. location, transport, or volume of the waste streams), recycling infrastructure and technologies, valuable or critical raw materials providing opportunities and, on the other hand, composite materials and hazardous substances bearing challenges for the recycling. Upon this information, the relevance of these technologies is assessed. The focus is on the time horizon, i.e. the point in time at which the waste streams of the different technologies are expected to be emerging, the relevance of the waste stream in terms of quantity and/or volume, as well as challenges and opportunities for their waste management. For example, waste streams expected to emerge only after a longer period of time or for which the time horizon is still unclear, depending e.g. on the technology readiness level of current innovations, might be of future relevance, but do not require immediate political attention.

Based on the initial assessment, the most relevant emerging waste streams are selected ("short list"). This is followed by a more in-depth analysis based on interviews with industrial experts as well as an online consultation of representatives of European Environment Agency (EEA) member countries (see section 3). The findings of the interviews and the survey complement and validate the initial analysis by focusing on specific areas of interest such as waste prevention options, approaches for remanufacturing, reuse or repurposing, existing or necessary waste management infrastructure, technical, economic or policy barriers, opportunities and innovative circular business models as well as potential policy gaps.

Section 4 is a short excursus about potential unintended side effects related to the emerging waste streams, and finally, section 5 summarizes conclusions and provides recommendations for a proper management and increased circularity of these emerging waste streams.

2 Overview of energy transition technologies and their relevance of emerging waste streams

For an initial mapping of technologies related to the energy transition and renewable energy sector, an overview of seven key technology areas and related technology fields listed by Wuppertal Institut et al. (2018) is taken as basis for this study, see Table 2-1.

Table 2-1: Overview of technology areas and fields related to the energy transition

Technology areas	Technology fields
Renewable Energies	Bioenergy Deep Geothermal Energy Photovoltaics Solar Heating and Cooling Solar Thermal Power Plants Wind Energy (land / marine) Environmental Heat
Conventional power plants	Centralised large power plants Decentralised power plants (fuel cells) Decentralised power plants (engines and turbines) Carbon capture and storage CO_2 use
Infrastructure	Electricity transmission and distribution Heat transport and distribution Energy storage (electrical and electrochemical) Energy storage (thermal, thermochemical and mechanical) Use of natural gas and oil infrastructures and refineries for electricity-based fuels
Technologies for sector coupling	Power-to-gas (hydrogen) Power-to-gas (chemical-catalytic methanation) Power-to-gas (biological methanation) Power-to-liquids/chemicals Process for the separation of CO_2 from digester gases and ambient air
Energy- and resource-efficient buildings	Building envelope and structural engineering Building systems engineering
Energy and resource efficiency in industry	Energy-efficient process technologies Energy-efficient cross-sectional technologies Power generation technologies for waste heat recovery Low-carbon and resource-efficient industry
Integrative aspects	Electromobility - Cars Electromobility - Hybrid Overhead Line Trucks Information and communication technologies

Source: Wuppertal Institut et al. 2018

Note: For the technologies marked red, it was decided to exclude them from further analysis for the purpose of this study.

The technology areas taken from Wuppertal et al. (2018) as listed in the table are not limited to the focus of this study, i.e. renewable energy production or the electricity grid, but also cover further technology areas and fields related to energy transition. Therefore, in an initial step, the variety of technology areas and fields was narrowed to the context and resources of this study without considering the following areas or fields for further analysis (marked red font in the table above):

- “Conventional power plants”: Although waste streams will be emerging due to the switching off of fossil power plants in the context of energy transition, these are neglectable compared to the waste stream of usual construction waste. They include valuable materials like the (high-) alloyed steel or aluminium, as well as hazardous materials like asbestos, which need to be demolished and landfilled properly. Facilities and infrastructure for the proper waste management of the buildings and machinery are well established; therefore, this stream is not further examined. However, decentralised power plants (fuel cells) may become important for future energy storage representing a new kind of waste stream. Hence, this technology field is included in the further analysis.
- “Technologies for sector coupling”: Sector coupling covers a large range of different technology fields for which a full analysis is not possible within the scope of this study. However, as a counterpart to fuel cells, electrolysers that might be essential for converting electricity into hydrogen which must be stored before being used to generate electricity will be further analysed.
- “Energy and resource efficiency in industry”: This technology area is an important pillar of energy transition, however, being very diffuse and only slightly connected to the focus of this study; thus, this technology area is not included in the further analysis.
- “Deep geothermal energy”, “heat transport and distribution”, “use of natural gas and oil infrastructures and refineries for electricity-based fuels” and “system integration, innovation and transformation”: in these technology fields, either it is not expected that there will be any emerging waste streams requiring special attention or these are not in the focus of the study, thus not being further analysed.
- “Energy and resource efficiency of buildings”: according to Wuppertal Institut et al. 2018, the technology field “building envelope and structural engineering” subsumes for example high-performance thermal insulation, functional optical surfaces, transparent and translucent façade elements, resource-saving construction, or multifunctional building envelope. Although emerging waste streams from insulation materials might become highly relevant, especially with challenges like hazardous substances, this technology field will not be further analysed as the focus of this study is related to renewable energies and the electricity grid.

The remaining technology fields are further detailed for their different technologies and examined for their relevance regarding emerging waste streams. A summary is given below in Table 2-2, the detailed matrix is provided in Annex I.

Table 2-2: Long list of technology fields analysed for their relevance regarding emerging waste stream

Technology fields	Technologies (based on Wuppertal Institut et al. 2018)	Short assessment of the relevance of emerging waste streams
Bioenergy	• Biochemical conversion: Anaerobic fermentation to ethanol / biogas • Thermochemical conversion: combustion gasification and hydrothermal processes • Physicochemical conversion: physical preparation, catalytic conversion	Bioenergy plants have small to no relevant substances in use that need to be recovered. The total amount of waste is of low relevance compared to demolition waste and is treated similarly. Even a significant growth would have little effect, but it can be expected that the number of biomass plants will decrease. Therefore, this technology field is not further examined.
Photovoltaics	• Solar cells and modules • PV manufacturing and systems engineering and production equipment • Systems engineering (i.e. photovoltaic inverter technology, network connection and network management) • Related technologies, e.g. building-integrated photovoltaics	Photovoltaics have a rapid growth and a high-volume waste stream. They will be even more important in the future for the energy transition and contain relevant materials that need to be recycled and/or need to be treated due to their hazard characteristics. The recycling infrastructure needs to be further developed to properly treat the waste streams.
Solar Heating and Cooling	• Solar thermal heating • Solar thermal cooling	Solar heating and solar cooling have mixed trends. While the glazed water collectors decline in capacity, the photovoltaic thermal hybrid collector market grows. Due to their long lifetime, the volume of the waste stream is not important. Moreover, the only interesting material in the stream is copper. Challenges in the collection are similar to those for photovoltaics, thus can be tackled by the more detailed analysis for photovoltaics. Therefore, this waste stream has not been selected for further analysis.
Solar Thermal Power Plants	• Parabolic trough or tower, Molten Salt as heat transfer and storage medium • Hybrid biomass cogeneration plants for fuel saving, parabolic trough with thermal oil or direct evaporation	Solar thermal power plants have a lifetime of 25 years and have been caught in a declining trend since 2008. They include some interesting materials which, however, are neglectable due to their small volume. Treatment facilities are in place and there are no problems in the treatment of the waste. Therefore, this stream is not further examined.
Wind Energy (land / marine)	• Permanent magnet generators • Synchronous generators • Asynchronous generators	Wind energy displayed a strong growth trend and a high-volume waste stream. Wind turbines will be even more important for the energy transition in future, and they contain

Technology fields	Technologies (based on Wuppertal Institut et al. 2018)	Short assessment of the relevance of emerging waste streams
	• Direct drive • Reluctance generators • High-temperature superconducting generators • Rotor blades • Wiring • Windmill base	relevant materials that need to be recycled. Windmill blades with carbon fibre become hazardous in normal incineration processes (asbestos like). The recycling infrastructure needs to be further developed to treat the waste streams properly. Therefore, this waste stream will be further examined in this study.
Environmental Heat	• Near-surface geothermal energy and development of air-technology • Electric heat pumps and chillers with components refrigerant circuit • Compressor technology • Gas sorption heat pump technology • Thermoelectric energy conversion • Urban waste heat sources (sewerage, transport systems) • Organic Rankine Cycle	Electric heat pumps have experienced consistent growth, but their waste volume is rather small. The geothermal energy is not expected to reach high volumes. The treatment may be challenging because of special refrigerants, but the technology for treatment is already applied. There are few relevant materials to recycle. Therefore, this stream is not further examined.
Decentralised power plants (electrolyzers and fuel cells)	• Polymer electrolyte membrane fuel cell • Solid oxide fuel cell • Alkaline water electrolysis • Polymer electrolyte membrane electrolysis	Fuel cells and electrolysers are still in development, so no waste stream is expected to emerge within the coming years. Therefore, this stream is not further examined in the context of this study.
Electricity transmission and distribution	• Power lines • Transformer stations	Power lines and transformers are well established. The electricity transmission grid will be extended, but the long lifetime of power lines and transformer stations will not lead to growth of emerging waste streams in the near future. Therefore, this stream is not further examined.
Energy storage (electrical and electrochemical)	• Lithium-based technologies • Sodium-based technologies • Redox flow technologies	From all energy storage technologies in this field, only lithium-ion batteries will have a relevant growth in the near future. They contain critical materials and need to be treated properly, also due to the risk of thermal run-away causing fire. The recycling capacities need to be developed because they do not currently match the upcoming waste streams. Therefore, the emerging waste stream of lithium-ion batteries will be analysed in further detail.

Technology fields	Technologies (based on Wuppertal Institut et al. 2018)	Short assessment of the relevance of emerging waste streams
Energy storage (thermal, thermochemical and mechanical)	• Thermal energy storage like water storage tanks, high temperature salt storage tanks, low temperature storage tanks • Central power storage (mechanical and thermal) like heat storage, adiabatic compressed air energy storage, adiabatic liquid air energy storage, pumped storage tanks, flywheel accumulators	The listed technologies have a long lifetime of about 25 years, and the market development is declining. No scarce materials are used, but hazardous wastes may emerge in the future. These can be treated by available methods and there is enough waste management capacity to treat them. Therefore, this stream will not be further analysed.
Building systems engineering	• Building automation • Heat accumulator • Power storage • Heating, ventilation and air-conditioning systems	Building automation is an increasing market, but the overall number of new buildings is rather small. Since the lifetime of buildings is long, no relevant mass stream is expected to emerge in the coming years. Moreover, materials are of low relevance (comparable to waste of electrical and electronic equipment, WEEE) and can be treated in existing recycling facilities. Therefore, this stream will not be further analysed.
Electromobility	• Batteries • Vehicle to grid systems (including charging infrastructure)	The waste stream of batteries for electromobility is comparable to that of lithium-ion batteries for stationary energy storage and needs the same treatment facilities. To gain a better understanding of the recycling challenges and capacities needed for energy storage batteries, also the emerging waste stream of lithium-ion batteries used in the electromobility sector will be considered.
Information and communication technologies	• Smart meters	The market of smart meters is expected to grow, but there is no experience yet, how long their lifetime is. They are similar to WEEE and can be treated in facilities for WEEE, but they are not covered by the scope of the WEEE directive. No high-volume waste stream is expected to emerge, and the relevant treatment capacities are available. Therefore, this technology is not further analysed.

Source: Initial analysis of Oeko-Institut e.V. based on a structure of technology fields and technologies by Wuppertal Institut et al., 2018

Based on this initial analysis, the following energy transition technologies with the highest relevance regarding emerging waste streams in Europe until 2030 (marked green in the table above) are selected and examined in further detail regarding their challenges and opportunities:

- Photovoltaics
- Wind Energy
- Lithium-ion batteries for energy storage and electromobility

3 Most relevant waste streams emerging from energy transition technologies: challenges and opportunities

In the following sections, each of the three selected technology fields, i.e. photovoltaics, lithium-ion batteries for energy storage and electromobility, as well as wind turbines, are analysed in more detail regarding the specific challenges and opportunities of their emerging waste streams.

The first section on *market developments and emerging waste streams* gives an introduction with a first overview of the technologies which are in the scope of this study. Characteristics indicating the relevance of a waste streams for this study will be analysed, e.g. the technology's lifetime which influences the throughput time and how soon a technology will reach the end-of-life stage. Information on the past, current and predicted future deployment of a technologies from statistical reports and scenario-based outlooks are laid out to complement the first overall picture for a better understanding of the following subchapters.

In the subsequent chapter on *End-of-life challenges and opportunities,* the most significant challenges are analysed in more detail together with the chances that come along with them. This analysis is broken down to the aspects of *high impact material and supply chain*, *logistics and safety in waste handling* and *recycling infrastructure*.

All these above-mentioned challenges implicate different demands and types of action needed by the stakeholders, including designers, producers, users, recyclers, politicians and agencies in the sector and many more. Therefore, an outlook on identified *approaches to increase circularity* is described under the captions of waste prevention, ecodesign and design for recycling, as well as remanufacturing and reuse. The section is supported by the subsequent part on selected *best practice examples and business models from EEA member countries*.

Reasons why some of these chances are not yet developed are diverse. Partly, this can be due to a lack of demand or too strong competition on the market against pricy virgin material, lacking recycling infrastructure or hazardous material in the waste stream. The *policy gaps and market barriers* which contribute to the current state or the ones that are identified as needed, refer to the challenges, chances and approaches that were pointed out in the previous sections.

After the comprehensive study of each of the emerging waste streams under the subchapter *Conclusions,* the most significant findings and the most promising approaches to deal with the waste stream in the future are summarized.

3.1 Emerging waste streams in the field of photovoltaics

3.1.1 Market developments and emerging waste streams

- Photovoltaic is currently the fastest emerging technology among the technologies for renewable electricity production in Europe. The majority of the current capacity has been installed in the past 10 years; waste streams will largely emerge in 2030 and beyond.
- In 2020, about 50 000 tonnes of waste PV panels are estimated in Europe; the amount will significantly increase to more than 350 000 tonnes in 2025; in 2030, the volumes are expected to exceed 1 500 000 tonnes.
- Glass is the most relevant component in terms of weight with about two-thirds of the total waste stream. Mass metals such as copper and aluminium play a significant role with about 15 % of the total weight. Furthermore, critical raw materials such as indium or germanium in the waste stream are of high relevance.

The European Commission has set itself goals to reach climate neutrality by 2050, to decarbonize Europe's economy and to improve the competitiveness of strategic value chains. Solar power, as one of the key drivers among other renewable energy technologies, has been emerging on a global scale during the past 10 years. Most of the capacity being in operation in 2020 has been installed in the last decade, and, according to scenario analyses, the growth trend in the sector will continue. Considering the lifetime expectation of PV modules of about 30 years, (Weckend et al., 2016) waste streams are about to emerge largely in 2030 and beyond.

As regards the time horizon chosen for the analysis of the PV market sector and the related waste streams in Europe, a clear trend of growth can be seen. When the technology overcame its pioneer status in the beginning, a rapid expansion occurred. In 2019, with a share of 13 %, solar power accounted for the third largest share in renewable electricity production in Europe, ranging behind water and wind powered electricity with each share representing 35 %. Taking into account the market development of solar power, jumping from a contribution of 7.4 TWh in 2008 to 125.7 TWh in 2019, solar power has been identified as the fastest-growing energy source among the renewable electricity sources (EUROSTAT, 2020). This development makes Europe already now one of the 'traditional markets'.

According to a pioneering company for PV collecting and recycling, there were about 8.1 million tonnes of PV modules installed in Europe by 2020 (Fraunhofer ISE, 2020). The classification as highly relevant waste stream is based on the projection that the sector's current growth will be continuing or even increasing. If PV modules will achieve their 30 years expected lifetime, Weckend et al. (2016) expect Europe to become the second largest PV waste market with up to nearly 2 million tonnes per year of PV waste by 2030 (see Table 3-1). For the PV market projections, the scientists developed two scenarios, one with a regular loss and one with an early loss in which the modules reach the end of their life faster. Taking into account the current developments, the actual waste stream is expected to be most likely somewhere in between these two scenarios (Weckend et al., 2016).

According to Fraunhofer ISE (2020), the BIFA Environment Institute forecasts a similar trend. Based on the figures of approximately 10 000 tons of end-of-life PV modules in 2017, by 2022/2023, about

100 000 tonnes per year are expected showing a further increasing trend. Franz and Piringer (2020) share the expectation on this development and highlight that in Europe the first large-scale generation of PV modules will reach its end of life by 2035.

Table 3-1: Modelled estimated waste volumes of EoL PV panels [1000 t/year]

Year	2015/2016	2020	2030
Projected PV Waste globally (regular loss / early loss)	43.5 / 250	100 / 850	1 700 / 8 000
Projected PV Waste (Europe) (regular loss / early loss)	5.5 / 100	27.7 / 325	626 / 1 970

Source: Weckend et al., 2016.

Material composition of PV waste volumes

Based on IRENA report data and PV material compositions of the European Commission´s Joint Research Centre (JRC), own calculations regarding the development of the total waste stream and a breakdown to the material composition have been made (Carrara et al., 2020; IRENA, 2020). Historic figures for PV installations starting from 2000 until 2019 have been used in the calculation. The projection until 2030 is based on the medium demand scenario developed by the JRC (Carrara et al., 2020). Assuming a lifetime of 25 years for PV panels, end-of-life volumes have been estimated on the basis of a Weibull distribution. The material composition is based on JRC figures. Results are displayed in Table 3-2.

According to these calculations, the overall waste stream becomes relevant in the near-term future. While waste PV panels are estimated at about 50 000 tonnes in 2020, the amount will grow significantly to more than 350 000 tonnes in 2025. In 2030, the volumes are expected to exceed 1 500 000 tonnes. The results are in line with Weckend et al. (2016) projections of Table 3-1 above, ranging between the regular and the early loss scenario.

Table 3-2: Expected mass of contained glass, metals and silicon with high impact in PV waste stream in Europe in tonnes/year

	2020	2025	2030
Total panel	50.137	363.260	1.532.810
Glass	32 792	237 592	1 002 539
Aluminium	5 300	38 404	162 048
Copper	3 251	23 554	99 390
Silicon (crystalline)	2 697	19 540	82 450
Silver	13.48	97.70	412.25
Tellurium	1.61	11.67	49.26
Cadmium	1.44	10.45	44.08
Selenium	0.81	5.84	24.63
Indium	0.36	2.63	11.08
Germanium	0.10	0.74	3.11
Gallium	0.09	0.68	2.87

Source: Calculation by Oeko-Institut e.V. based on Carrara et al., 2020; IRENA, 2020.

Glass is by far the most relevant component in terms of weight, accounting for approximately two-thirds of the total waste stream. Mass metals such as copper and aluminium play a significant role, accounting for approximately 15 % of the total weight. Technology metals such as indium or germanium, included in the European list of Critical Raw Materials (CRM) 2020, are only accounting for small fractions of the total waste stream and may appear to be comparatively small. However, comparing it to the global production of about 130 tonnes in 2018, the 3.11 tonnes of germanium contained in the European waste stream in 2030 become more relevant (USGS, 2020).

It is highly important that such metals are recovered. On the one hand the EU, only produces small volumes of the critical raw materials and is therefore dependant on imports, on the other hand recycling has significant environmental effects, as summarised in the next subsection.

3.1.2 End-of-life challenges and opportunities

- Photovoltaic modules contain highly valuable materials of economic interest, such as silver, copper, aluminium, and critical raw materials like indium and germanium which are technically difficult to recover.
- About 95 % of the mass of resources in PV modules (e.g. glass, copper, aluminium, etc.) have the potential to be recycled, however, apart from aluminium and glass, the remaining module scrap, including silicon, silver contacts, tin, and heavy metal containing solder (lead) usually undergoes thermal treatment in incineration plants.
- Main challenges in PV recycling, both in economic and technological terms, are the delamination, separation and purification of the silicon from the glass and the semiconductor thin film.
- Challenges for the recycling of PV modules are hazardous substances such as cadmium, arsenic, lead, antimony, polyvinyl fluoride and polyvinylidene fluoride. Furthermore, according to lifecycle assessments, cadmium (Cd) and tellurium (Te) are the main contributors to the negative impact on mineral, fossil and renewable resource depletion.
- Logistic constraints arise due to necessary work on a panel at a height of 20 metres which is often not anticipated at the design or installation stage of PV modules.

High impact materials and supply chain

By recycling the cover glass (70-75% of the weight) and the aluminium frames (10-15 % of the weight) the legally prescribed recycling quota is already reached; however, the separated remaining portion of silicon, silver contacts, tin, and heavy metal containing solder (lead) is usually burned together with the plastic foil. (Fraunhofer ISE, 2020). This means that there is still high potential for the PV sector to recover further valuable and scarce resources, including silver, copper, indium, gallium, tellurium, silicon etc. (Weckend et al., 2016; Pavel et al., 2017).

Table 3-3: Crystalline Si modules: Proportion of different material components per ton of waste modules

	Average proportion per ton of module scrap
Glass	700 - 750 kg
Aluminium (frame)	100 - 150 kg
Silicon	25 - 50 kg
Copper	5 - 10 kg
Silver	0.5 - 1 kg
Tin	0.5 - 1 kg
Plastic	Remainder

Source: Fraunhofer ISE, 2020.

One of the most pressing issues for PV modules is the use of critical raw materials (CRM). To secure the supply and price continuity for the increasing demand, they should either be replaced by other types of raw materials, or, more likely, be reextracted from photovoltaic modules at their end of life to feed them back into the market. This might be the chance for circular business models to seize these opportunities; but at the same time, it appeared that technology and infrastructure have to be developed soon in order to deal with such quantities arising. If the EU does not take immediate action to develop capacity for desirable treatment for the emerging PV waste stream, in the future the risk increases to handle the major part of the waste with less desirable practices that are currently quite common, such as incineration and landfilling. (Aryan et al., 2018) This would potentially put a higher risk on the environment and human health, for example by leaching. Besides, valuable materials like rare metals such as indium, gallium, germanium and silver would be lost (Pavel et al., 2017).

A special focus should be on cadmium (Cd) and tellurium (Te) as life cycle assessment (LCA) identified the extraction of these two elements as main contributors to the impact categories mineral, fossil and renewable resource depletion (Sinha and Wade, 2018). A possibility to reduce these impacts is to use recycled secondary material instead of virgin material. According to Weckend et al. (2016), further purification offers the potential to increase the application of secondary cadmium and tellurium in the solar industry. Another chance to reduce these materials' impact is the reduction of the respective quantities used. In CdTe thinfilm panels, the thickness of the CdTe layer has the potential to be reduced to one third (Weckend et al., 2016). To enable the recovery of such valuable and critical materials, standardisation in PV panels will play a key role, but one has to keep in mind that this measure can show results only after the end of life, which means in 30 years, if standardisation were already applied today.

Logistics and safety in waste handling

In Germany, which represents one of the biggest European PV markets, according to the opinion of recyclers, the return systems were already well established and sufficient infrastructure was available when approximately 30 000 t of PV waste were recycled in 2019.

A challenge in the recycling of PV modules are hazardous substances which are a threat to the environment and human health. These include cadmium, arsenic, lead, antimony, polyvinyl fluoride and polyvinylidene fluoride etc. Aryan et al. (2018) summarize that the three major environmental problems related to the improper disposal of PVs would be, firstly, toxic metals such as lead and cadmium that are leaching, secondly, the loss of conventional resources such as glass and aluminium and lastly, the loss of critical raw metals such as silver, indium, gallium, and germanium.

According to Weckend et al. (2016), a great opportunity for the improvement of product safety lies in the significant reduction of hazardous substances such as indium, gallium, selenium, cadmium, tellurium and lead. This opportunity is currently researched and offers the additional benefit to improve the recyclability and resource recovery potential of EoL panels.

Another, very practical logistic barrier mentioned in the interviews conducted in the context of this study arises when it becomes necessary to work on a panel and repair it, often at a height of 20 metres. The logistical constraints are strong and were apparently not anticipated during the design or installation stage. Therefore, it is recommended to create a stronger network between the designer and the maintenance teams.

Recycling infrastructure

Challenges related to the waste stream of PV technologies can be derived from the currently common practice. Although the disassembly and delamination of PV modules is possible, it is hardly suited for an industrial process because of high intensity of time and costs. Apart from aluminium and glass, the remaining module scrap, including silicon, silver contacts, tin, and heavy metal containing solder (lead), usually undergoes thermal treatment in incineration plants together with the plastic foil (Fraunhofer ISE, 2020). Nevertheless, EoL PV modules of different types still have a high potential to recover valuable and scarce resources as mentioned before. Franz and Piringer (2020) see the main technological challenge of the PV recycling process that becomes an economic barrier for recycling, in the delamination, separation and purification of silicon from glass and the semiconductor thin film of other module technologies from the front- and backsheet glass.

From the perspective of technical possibility, recyclers can achieve recycling rates of 90 % for glass and 95 % for semiconductors (esp. because of tellurium), whose materials are reused in the process. Aluminium can be recycled to 100 %, the junction box is recycled as WEEE. For the single parts anyway, the material gets shipped around the globe for treatment (e.g. USA, Asia).

A further possibility for improving material recovery is the recovery of metals from the filter cake in those cases where the filter cake contains a high concentration. For the majority of materials deployed in PVs, the application of these materials after recycling in new PVs is not yet possible. To develop a stand-alone recycling plant for PV modules, producing companies estimate a minimum demanded waste stream of about 10 000 tonnes to be economical. Additionally, the difficulties with recycled materials lie in the fact that there is a constant demand of raw materials on the part of manufacturers, while the production of recycled materials is not constant.

3.1.3 Approaches to increase circularity

- Production waste does not seem to be relevant, thus waste prevention is not a priority strategy for increasing the circularity of PV modules.
- Ecodesign and design for recycling could significantly improve the material efficiency (durability, reparability) and the recyclability of PV modules. The European Commission is currently elaborating mandatory requirements under the EU Ecodesign regulatory framework.
- Refurbishment and/or reuse of well-working second-hand PV panels in principle are technically feasible, however, so far have not been subject to legal frameworks and are hardly profitable.
- Circular business models for photovoltaics in Europe are, for example, an integrated production where the recycling is conducted by the manufacturing company; disclosure of the material composition to facilitate the recycling; and mobile recycling devices, also offered as rental or leasing system, which reduce the distance between collection and recycling sites and employ mechanical processes instead of thermal and chemical ones.

In the following sections, possible options relating to circularity principles such as waste prevention, ecodesign and design for recycling, remanufacturing and reuse approaches are analysed for photovoltaics, and examples of circular business models are presented.

Waste prevention

In Europe, producing companies confirm that waste streams emerging from the production of photovoltaic modules are relatively small and therefore, the vast majority of PV waste derives from end-of-life PV modules. No significant chances or challenges in waste prevention were identified for EoL PV modules.

Ecodesign and design for recycling

Manufacturers report that the sector's main problem is not necessarily recycling in general but rather the missing compatibility of the design of some PV module when they reach the recycling phase. Therefore, a design for the recycling approach could significantly improve the conditions for the development of circular business models, when PV modules can perform their 30 years of service without degradation some day. This can be partially influenced in the design phase.

An approach to improve efficient resource management and identify the environmentally most critical materials and processes along the value chain is called integrated life cycle management. Lifecycle assessment enables design to take into account the recycling phase. This option is especially interesting for suppliers when they do the recycling themselves and benefit from the improved recyclability.

Recently, the European Commission has conducted a preparatory study to assess the feasibility of applying Ecodesign, Energy Label, Ecolabel and Green Public Procurement instruments to solar photovoltaic modules, inverters and systems (Dodd et al., 2020). In November 2020, in a stakeholder webinar, initial potential ecodesign and energy labelling measures were presented. Related to waste and material efficiency, these include, inter alia, draft performance requirements on quality, durability and circularity for PV modules, such as durability product testing or a declaration of the degradation rate expected over a service lifetime of 30 years. Also, information requirements on reparability (access to bypass diodes in the junction box, possibility to replace the whole junction box) and dismantlability (potential to separate and recover the semiconductor from the frame, glass, encapsulants, and backsheet; design measures to prevent breakage and enable a clean separation of the glass, contacts and internal layers during the operations) are proposed. Finally, the draft proposals include requirements on material disclosure (antimony, cadmium, gallium, indium, lead, silicon metal, silver and tellurium) to facilitate the recycling of PV modules. For PV inverters, also durability testing, but also slightly different material efficiency requirements under EU Ecodesign are proposed. These include information requirements on reparability (circuit boards being replaceable onsite; provision of a preventive maintenance and replacement cycle). Moreover, requirements on material disclosure to facilitate the recycling of PV modules are proposed (lead, cadmium, silicon carbide, silver, indium, gallium, and tantalum) for inverters (EC, 2020d).

Remanufacturing and reuse

Currently, in many cases, still well-working PV panels are being replaced by more efficient and cheaper ones, i.e. the financial approach in such instances seems to be of primary significance. This is a typical case where remanufacturing and reuse of the decommissioned modules could be considered as circularity principle.

Repair or remanufacturing for the reuse of PV panels typically involves applying a new frame, new junction box, diode replacement, new plugs and sockets and more. Solar cells may even be replaced, and panels relaminated. They can be resold as used panels at a reduced market price of approximately 70 % of the original sales price (Weckend et al., 2016).

According to manufacturers, this is in principle possible but hardly economically viable and therefore not an appealing business case for producers. For silicon, the cost of purifying old silicon results in total costs being four times higher than the purchase price of new silicon. When planning to refurbish PV panels, labour is involved, too, specifically in order to sort out faulty components and for quality control reasons. Unfortunately, the costs for refurbished PV panels exceed production costs of new panels, especially with new panels becoming cheaper in manufacturing. Nevertheless, some companies specialized on such return systems for PV modules to be recycled.

According to recyclers, the return rate of PV modules based on warranty within the first 10 years lifetime is very low at 0.048 % and 0.2 % later on. By now, the life expectancy of PV modules is 30 years with a nominal performance of 90 %, while 80 % are guaranteed. Sinha and Wade (2017) support the option of reuse in general but point out that economic incentives for the re-use of end-of-life photovoltaic panels are not sufficient to lead to a large shift of the EoL streams in the re-use direction.

Examples of circular business models in Europe

In the following, some examples of circular business models for photovoltaics retrieved from literature review as well as reported either in the interviews or the survey conducted within this study are presented. The overview might not be exhaustive.

For example, one producer reported that he considered the addition of tags at the back of PV panels that would summarise the material composition in order to facilitate easier disassembly and recycling. This tag would also include other information such as the production year and location. In India, this approach is already common practice.

Another producer in Europe applies an integrated production, which means that the production and recycling are executed by the same company. This also allows recycling of waste streams emerging from the maintenance of the infrastructure, such as dust from laser scribes.

Furthermore, with support of EU funding, an Italian consortium developed a device especially for recycling solar panels through innovative and environmentally friendly technologies (Photovoltaic panels Mobile Recycling Device). Based on the experience that the usual process for recycling photovoltaic panels uses thermal and chemical technologies, with disadvantages in terms of costs, sustainability and portability, for example, the mobile recycling device enables the treatment of panels right where they are located. Its complete portability thus reduces the distance between the collection and the recycling sites; and it employs mechanical processes instead of thermal and chemical ones, which improves the recovery of PV panels by lowering its cost and environmental impact by reducing CO_2 emissions, waste production and energy consumption. The company sold its first device in summer 2017. The business model considered the rental/lease of the device as well. (EASME, 2017)

3.1.4 Policy gaps and market barriers for circular business models

- In order to maintain the (expensive) inverter warranty, only inverter providers or companies commissioned by them are allowed to intervene for repair. Second-hand inverters and PV modules are only to a small degree or not at all covered by warranties. For proper repair and maintenance, there seems to be a lack of highly qualified technicians. This impedes repair and reuse approaches.
- The policy process of the European Commission elaborating mandatory requirements under the EU Ecodesign regulatory framework for ecodesign (durability, reparability) and design for recycling requirements is still ongoing.
- National legislation might impede circular business models such as mobile recycling systems.
- For a proper end-of-life treatment of photovoltaic systems, new financing models to recover the costs of collection, treatment, recovery, recycling and disposal have to be applied, such as producer-financed or consumer-financed (upfront or at end-of-life) models or a carbon tax.
- To facilitate recycling and the supply of secondary resources, specification of end-of-waste criteria is seen as a necessary step. The WEEE directive has no specific recycling targets for certain metals. To increase circularity, the implementation of a regulation or requirements for treatment at EU level and the definition of recycling targets for certain metals are recommend-ded.

So far, second-hand photovoltaic panels are not subject to legal frameworks; this means that there are no guarantees or insurance for manufacturers who repurpose them. More specifically, also inverter repair on the field is less common; mostly, faulty inverters are replaced. In order to maintain the (expensive) inverter warranty, only the inverter providers or a company commissioned by them are allowed to intervene for repair. Similar to PV modules, second-hand inverters are only to a small degree or not at all covered by warranties (Dodd et al. 2020). Therefore, manufacturers rather prefer to destroy PV panels. If a relevant legal framework existed, PV panels would not have to be recycled straight away but could be refurbished first. According to Dodd et al. (2020), also weaker options for cell recycling exist, e.g. refurbishing second-hand modules with less invasive steps such as inspection, glass cleaning and coating, replace the bypass diode, etc. which can extend the insitu cell lifetime beyond the 30 years. However, although manufacturers are technically already capable of refurbishing PV panels, also customers seem to prefer new panels. According to the interviews conducted in this study, the implementation of a carbon tax might help supporting a business model in which refurbished PV panels with lower environmental impacts are a better option than new ones manufactured in and imported from another continent.

From an investment perspective of consumers (households or companies) of PV panels, leasing is often the most attractive solution in financial terms. This shifts the responsibility of new versus refurbished photovoltaic panels entirely onto the manufacturer. In Germany, there is an emerging market of refurbished photovoltaic panels for large roofs. For many consumers, it is a way of becoming more autonomous in terms of electricity provision. In other countries, such an evolution appears to be more difficult.

A lack of highly qualified technicians which should demonstrate some form of certification attesting their qualification proved to be a hindrance to the proper repair and maintenance of PV systems. In this context, certification schemes can be used. However, these schemes may vary across Europe or even be inexistent in some countries, even though training for PV installers exists. Still, different eligibility requirements and qualifications may exist for the training courses (Dodd et al., 2020).

Only recently, requirements on ecodesign for photovoltaic systems and inverters, addressing material efficiency like durability, reparability and design for recycling, were developed at European level, and might be fed into a mandatory EU Ecodesign regulation, thus to be applied by all photovoltaic systems entering the European market, and/or into voluntary instruments such as Green Public Procurement criteria or the development of an Ecolabel. At the end of 2020, this regulatory process was still ongoing.

With regard to the circular business model of a mobile recycling device presented in the previous section, it seems that in France, the ICPE (Installation Classified for the Protection of the Environment) legislation on environmental protection has made mobile recycling more challenging insofar as it is highly restrictive. The status “treated and purified waste” is nearly impossible to achieve for a mobile installation. Currently it is legally prohibited to automatically feed the treatment line with PV modules instead of feeding it manually into the thermal treatment. This undeveloped potential for higher throughput in the treatment hampers the second-hand market.

Due to the fact that the end-of-life treatment of photovoltaic panels leads to costs for collection, treatment, recovery, recycling and disposal, for example, Weckend et al. (2016) suggest financing models that can recover these costs by different approaches such as producer-financed compliance cost, a consumer-financed upfront recycling fee or a consumer-financed end-of-life disposal fee.

Also suggested by Weckend et al. (2016), voluntary takeback or producer responsibility programmes can be designed as direct management, where the manufacturer operates his own recycling infrastructure and refurbishment or recycling programmes to process his own panels. Another approach in form of indirect management suggests that manufacturers contract service providers for the collection and treatment of their panels.

To facilitate recycling and the supply of secondary resources, recyclers interviewed in this study see a necessary step in the further specification of end-of-waste criteria not only for glass, but also for other materials. An example are metal containing filter cakes which have a higher metal content than ores and are considered as waste until they are refined. Given that refineries are located in other countries than the recycling facilities, a major effort is needed to transport the material to its final destination.

According to Dodd et al., 2020, the WEEE Directive requires the establishment at Member State level of schemes to ensure the separate collection and 'proper treatment' of Electrical and Electronic Equipment (EEE). Since 2018, the scope of EEE has been extended to include solar photovoltaic modules, and they are also identified in the Directive as a priority for separate collection. Annexes I to IV of the Directive specifically identify solar photovoltaic 'panels' (modules) under EEE category 4(b). However, no specific collection rate for modules is specified, instead, an overall collection rate for EEE is set at 85 % from 2019 onwards. From 2018 onwards, for EEE category 4 products, an 85 % recovery rate and an 80 % re-use and recycling rate shall be achieved. Other system components such as inverters are not specifically identified in the existing EEE categories but could be interpreted to fall under the new EEE category 5 'Small equipment (no external dimension more than 50 cm)' which refers to equipment 'for the generation of electric currents'. The Directive also states that Member States shall encourage co-operation between product manufacturers and recyclers in order to facilitate the re-use, dismantling and recycling of WEEE at product, component and material level. However, it is understood that some Member States are considering specific references in legislation to the treatment of photovoltaic modules (Dodd et al., 2020).

As one part of a regulatory approach towards more circularity, recyclers recommend the implementation of a regulation stipulating requirements for treatment on EU level and the definition of recycling targets for certain metals. Another problem is a lack of clear responsibilities, structure and standardization for take-back and collection of used modules, in both qualitative and quantitative terms, in Germany, for example (and presumably in other member states as well), which could be incentivized via regulatory approaches.

Furthermore, to improve the cross-border transport of PV waste to other European countries, a harmonization of waste declaration in this field is seen as necessary. To address this problem, the European Committee for Electrotechnical Standardization (CENELEC) developed supplementary standards (EN50625-2-4 and TS50625-3-5) specifically to address PV panel collection and treatment. Besides the aspects of environmental, health, and safety requirements for PV recycling, the standards address the recovery of metals in PV modules (Sinha and Wade, 2018). To enable the recovery of valuable and critical raw materials, standardisation in PV panels will be key, but even if applied today this measure will only become fully effective after the end of life of photovoltaic panels, which means in about 30 years.

According to stakeholder information, illegal exportation of waste PV modules already exists and might be increasing. It needs, for example, more (unannounced) checks especially at harbors by responsible authorities so that EoL modules will not be exported anymore. One solution in this regard is seen in the EU support of member states through harmonization of identification numbers of PV panels in export reporting and statistics. Further, a clear definition of criteria to distinguish PV panels for reuse from waste PV panels could facilitate detecting attempts to circumvent the cost and effort of EoL treatment and disposal in Europe (see also section 4).

3.1.5 Conclusions

As laid out in this chapter, several challenges have to be faced with regard to the waste streams in the field of photovoltaics. On the one hand there are relevant as well as critical resources in the photovoltaic cells (e.g. silicon, indium, copper), on the other hand they are not easy to recycle because they are only used in small quantities covered by a large quantity of glass. There are several cell technologies that need to be recycled differently, e.g. CdTe cells need a different process compared to silicon-based cells. Some metals are hazardous (e.g. Cd) and may cause problems when not recycled properly. As the collection has improved over the past ten years (several return schemes started working) and also the recycling capacities are growing (for example, a recycling plant in the south of France started operation in 2018), the recycling system seems to be on track, but there is still room for improvement. Modules are being exchanged before they reach their technical end of life, because the new ones are more efficient, and they bring the companies a financial benefit. The reuse of cells is currently not widely applied, since the refurbishment is more costly than a new and more efficient cell. Still, there are some companies that buy cells and sell them to countries that have no access to new cells and therefore have no other options. New regulations would be useful to improve the chances of reuse and to increase recycling. The standardization of the panels may be an option to establish design for recycling, facilitate reuse and the recycling of the panels at the end of their life.

3.2 Emerging waste streams in the field of batteries for energy storage and electro-mobility

3.2.1 Market developments and emerging waste streams

- In the coming decade, depending on the year that new production lines become operational and on the basis of near-term market projections, Europe may serve between 7 % and 25 % of global demand with most of the manufacturing capacity located in Sweden, Germany and Poland. Lithium-ion batteries (LIBs) are mainly produced for electric vehicles whereas stationary storage only accounts for about 3 % of the lithium-ion battery market
- In 2020, a total volume of almost 40 000 tonnes per year of all waste lithium-ion batteries (energy storage systems, traction batteries, and portable batteries) was expected. Due to long lifetimes of 20 years for energy storage system applications, the volumes of end-of-life batteries are rather low. In 2020, around 2 500 tonnes per year were expected. This volume is forecast to rise to 13 800 tonnes per year by 2025 and to double to 26 200 tonnes per year of EoL lithium-ion stationary energy storage batteries by 2030.
- In addition, production waste from LIB manufacturing is emerging, especially in the beginning, due to the necessary adjustments of the production parameters. Assuming that 1 % of the produced output is faulty and ends up as production waste, significant volumes will emerge, approximately in the same range as the expected waste stream of stationary energy storage batteries.
- The take-back of faulty traction batteries will lead to a previously unanticipated increase in EoL lithium-ion batteries in 2021.
- High impact metals in stationary and portable batteries are lithium, nickel, cobalt and copper.

The European Commission has set itself the goals to reach climate neutrality by 2050, to decarbonize the European economy and to improve the competitiveness of strategic value chains. In these fields, renewable energy sources and especially batteries will play a key role in achieving the goals, since the application of batteries functions as temporary storage of renewable energy and will help to decarbonize the transport and mobility sector by electrification. Furthermore, the improvement in the battery design along their entire lifecycle is a lever to reduce their CO_2 footprint.

Lithium-ion (Li-ion) batteries are deemed as the only relevant battery technology for the purpose of this study, since they are deployed on a larger scale for stationary electrochemical energy storage, as home storage or grid stabilization. On the other hand, the recycling of lead acid batteries used as energy storage system is already well established. The demand of lithium-ion batteries for stationary energy storage systems (ESS), and especially for electric mobility will surpass any demand for batteries seen in the past. Based on the analysis that the lifetime of a LIB lies between 5 and (more realistically) 20 years and depending on the usage profile, highly relevant waste streams will emerge from lithium-ion batteries in the coming years (Buchert et al., 2019; Bulach et al., 2020; Dühnen et al., 2020).

LIBs are very diverse concerning their cathode materials. Apart from other non-lithium-containing technologies like lead (Pb), mainly lithium iron phosphate ($LiFePO_4$; LFP) has been used for stationary energy storage systems so far, although the market share of nickel (Ni)- and cobalt (Co)-containing cell chemistries, e.g. with a Lithium-Nickel-Manganese-Cobalt-Oxide ($LiNi_xMn_yCo_zO_2$; NMC) cathode like NMC 622, has increased in the last few years (Fraunhofer ISI, 2015). The number of stationary storage units sold until 2018 lies in the range of 125 000 for Germany alone, with the energy storage capacity mostly below 10 kWh (Figgener et al. 2020, Fraunhofer ISI, 2015).

According to Tsiropoulos et al. (2018), while the future market share of Li-ion cell manufacturing belongs to Asian players, steepest growth is expected in Europe, owing to the still limited domestic capacity. By 2022, the global share of European Li-ion battery cell manufacturing capacity is expected to increase from about 3 % today to 8 %. By 2028, due to additional capacity and plant expansions in Europe, total Li-ion cell manufacturing capacity may reach about 105 GWh. In the coming decade, depending on the year that the new production lines become operational and on the basis of near-term market projections, Europe may serve between 7 % and 25 % of global demand with most of the manufacturing capacity located in Sweden, Germany and Poland.

It is not possible to separate the production of LIBs for stationary storage from the production for electric cars, as they are produced in the same plants with similar chemistries, and the demand for stationary storage only makes up a fraction of the demand of LIBs for electric vehicles. Especially battery electric vehicles (BEVs), but today also plug-in hybrid electric vehicles (PHEVs) and hybrid electric vehicles (HEVs) incorporate a lithium-ion battery. A battery in a BEV weighs between 150 and 650 kg (Buchert et al., 2019). For BEVs, the lithium-ion batteries are usually guaranteed to last either eight years or 160 000 kilometres driven. A car battery has a probable lifetime of between 8 and 15 years. (Wallner, 2020). Until 2020, about 550 000 BEVs, 550 000 PHEVs and over 2.4 million HEV have been sold in the EU, whereby growth was strongest in BEVs (Buchert et al., 2019).

As sales have risen sharply only in the last few years, it will take several years for the waste stream to evolve, which is then expected to rise steadily. However, also in the meantime, the waste stream might significantly increase, for example if car batteries must be recalled due to technical problems or safety risks. Furthermore, also the production of batteries evolving in the EU produces scrap material which has to be recycled as well.

A differentiation of the relevant resources related to the waste stream is shown below in Table 3-4. The table shows the total volume of end-of-life lithium-ion batteries from stationary storage as well as the lithium, nickel, cobalt and copper content for the years 2020, 2025 and 2030. The numbers are based on calculations produced by VITO and Fraunhofer (2019) and on own assumptions. The volume of EoL batteries has been calculated on the basis of projected new installations. It is assumed that the lifetime is 20 years and that 5 % of the stock is replaced per annum. The forecast was based on the assumption that NMC 622 cell chemistry will be used, as it is likely to remain the dominant cell chemistry until the mid-2020s (Wood Mackenzie, 2020).

It should be noted that there is no clear picture regarding the market growth. Although a rapid increase from today’s low volumes is forecast by most predictions, the projections vary significantly. Lowest estimates for global stationary storage installed in 2030 range between 8 to 100 GWh, while more optimistic calculations assume up to 400 GWh (Tsiropoulos et al., 2018).

Due to long lifetimes of 20 years for energy storage system applications, the volumes of end-of-life batteries are rather low in the near-term future. For 2020, around 2 500 tonnes have been forecast, increasing to 13 800 tonnes in 2025 and doubling to 26 200 tonnes of EoL Li-ion storage batteries in 2030.

Table 3-4: Expected mass of waste stream of lithium-ion batteries for energy storage systems and the contained metals with high impact in EU-28

	2020	2025	2030
Lithium-ion batteries / t	2 500	13 800	26 000
Copper	350	1 932	3 668
Nickel	212	1 172	2 225
Cobalt	71	391	742
Lithium	38	210	399

Source: based on VITO and Fraunhofer, 2019; and own assumptions.

Compared to total expected volumes of EoL lithium-ion batteries in the EU, the stationary batteries are a rather small waste stream. The total numbers are extracted from Oeko-Institut's own model. It takes into account traction batteries, industrial batteries as well as portable applications. Based on different lifetimes for the applications, end-of-life volumes are derived. It should be noted that energy storage systems are part of the industrial batteries in the model. However, this application is not modelled separately. Therefore, in Table 3-5, a different reference has been used.

For the year 2020, a total volume of almost 40 000 tonnes of waste lithium-ion batteries has been forecast. In 2025, this number is forecast to almost double to about 75 000 tonnes and, based on predictions, it will significantly grow to almost 240 000 tonnes by 2030. It becomes evident that compared to stationary energy storage systems, the overall volumes are significantly larger. This is both an effect of higher volumes placed on the market and shorter lifetimes.

Table 3-5: Expected mass of waste stream of all lithium-ion batteries (energy storage, traction batteries and portable batteries) and the contained metals with high impact in EU-27

	2020	2025	2030
Lithium-ion batteries / t	39 367	75 288	239 780
Copper	5 364	10 182	31 853
Nickel	1 253	3 425	15 401
Cobalt	3 310	4 720	8 600
Lithium	613	1 112	3 241

Source: based on Stahl et al., forthcoming.

Another important waste stream will be the production waste from LIB manufacturing. As production of LIBs is rising swiftly, also the production waste could be a huge challenge to cope with as it emerges especially in the beginning due to the necessary adjustments of the production parameters. Assuming that 1 % of the produced output is faulty and ends up as production waste somewhere along the production line, significant volumes will emerge which are in the same range as the expected waste stream of stationary energy storage batteries. It needs to be pointed out, however, that in this scenario, the put-on-market (PoM) volumes are assumed to be produced in the EU, which is highly unlikely.

Table 3-6: Expected mass of waste stream from production waste of lithium-ion batteries and the contained metals with high impact (assumption: 1 % production waste) in EU-27

	2020	2025	2030
Lithium-ion batteries / t	3 103	13 210	26 437
Copper	406	1 731	3 466
Nickel	184	1 039	2 284
Cobalt	107	271	416
Lithium	40	168	335

Source: based on Stahl et al., forthcoming.

3.2.2 End-of-life challenges and opportunities

- The infrastructure to transport and store the rising amount of batteries is still mostly missing and needs to be built up in the next years to cope with the high waste stream of EoL batteries to come.
- Current lack of recycling technologies and large-scale recycling capacities in Europe (only pilot plants) to cope with the expected huge rise of LIBs waste streams in the next few years
- Economic efficiency of LIB recycling is yet difficult to achieve, mainly due to high safety risks during transport and recycling on the one hand, and material values (e.g. cobalt or nickel) not being high enough to cover costs of recycling on the other hand. Cobalt and nickel could be valuable enough to make battery recycling profitable under certain circumstances, if conducted at large-scale, and depending on the future price for these resources and their content in the batteries.
- Measures to reduce safety risks of a "thermal runaway" during logistics and treatment, e.g. by special transport containers, temperature monitoring and a pre-treatment with salt-water or heat, are expensive, each measure having specific challenges.

High impact materials and supply chain

A key factor that influences the properties of waste is the material selection and composition. LIBs contain several materials, such as cobalt, for example, which are ranked as a critical raw material, which implies a high supply risk and high economic importance. As mentioned in the introduction, NMC batteries containing cobalt and nickel are the most common type of LIBs. The high cost intensity of these materials makes LIBs, compared to wind and solar power, especially vulnerable to price volatility (Pavel and Blagoeva, 2017).

On the other hand, the risks coming along with rare and critical raw materials also offer the opportunity to recover them from EoL batteries. This creates the demand for new business models for refining and recycling. Established recyclers as well as start-ups have perceived this trend, and several companies have built up pilot plants with larger facilities being planned (Dühnen et al., 2020). However, it is not sure if this will be enough to cope with the battery waste volumes expected in the coming years.

Not all batteries have a material value high enough to potentially cover the costs of recycling. This is especially the case for LFP containing cells, used in buses and stationary storage systems, which are not valuable enough to cover recycling and additional costs for disposal by their recovered value. Lithium, as well, is not yet valuable enough to make a large impact, as the amount and concentration in a battery cell is comparably small. Copper (and aluminium, often going to scrap) are in general materials of interest for the market, but their material share is not sufficient to cover the costs. Cobalt and nickel could be valuable enough to make battery recycling under certain circumstances profitable, if conducted at large scale, but this depends very strongly on the future price for these resources and the content of them in batteries.

In any case, in view of the sharply increasing waste streams in Europe that will have to be treated in the coming years, it does not seem reasonable to wait until recycling has become profitable. The infrastructure and recycling techniques must therefore be developed immediately. A benefit that comes along with resource conservation and economic benefits is the fact that, depending on the battery chemistry and the recycling process, the recycling of batteries has the potential to reduce GHG emissions of the batteries' life cycle and therefore reduces their overall environmental impact (Mohr et al., 2020). This is also supported by the TERM report from the EEA (Hampshire et al. 2018).

Logistics and safety in waste handling

A common challenge in logistics of LIBs is the condition of a "thermal runaway", which can start from a charge level of 30 % or higher for all LIBs. Higher energy densities of batteries lead to increased risks. As it can start with a delay, warehouses where old batteries are stored for a longer time are especially at risk. Measures to cope with the potential risk of thermal runaway are to store and transport batteries in containers, embedded in heat absorbing, isolating material, while monitoring the temperature of each container. This makes it relatively easy to recognise if and when a thermal event occurs in individual batteries. However, there is no one solution for all types of Li-ion batteries; a key challenge is that battery packs from electric vehicles have very different types of designs, each then requiring also different types of special transport boxes which could be very costly.

An alternative could be a pre-treatment with a saltwater bath, which, however, causes the problem of wastewater and often does not completely deactivate the cell. The alternative heat treatment comes with the disadvantages of high costs for the oven and the purification of the evolving gases that must be filtered. It can be summarized that measures to improve the security in logistics make the transport expensive, especially, if large and damaged but still energy-containing batteries are involved.

The storing and transportation of large amounts of batteries also require large areas, as putting them on top of each other is only allowed in special cases. The infrastructure to transport and store the rising amount of batteries is still missing and needs to be built up in the next years to cope with the high waste stream of EoL batteries to come.

More general challenges in terms of infrastructure lie in the fact that the collection is not driven by safety aspects, which reflects a trend of too high-risk acceptance on transportation. Improper practices in the logistics can be partly due to a lack of reverse logistics (tracking, data management), which puts a high pressure on existing structures. Therefore, the system of today must be developed for individual cases, if high volumes are expected, for example.

A further safety risk related to the waste stream of LIBs lies in the hazardous substances used therein. These include the electrolyte, especially the conducting salt, as well as toxic metals. When in contact with humidity, the conducting salt decomposes easily to hydrofluoric acid (HF), a very toxic and corroding substance. Respondents to the online survey further pointed to a lack of current knowledge in treating hazardous materials of batteries, which has prompted some countries such as Spain and Algeria to repair rather than recycle batteries.

Design characteristics of batteries that recyclers recommend for improving logistics and safety address different life phases. With regard to the problems related to logistics and recycling discussed above, more specific data from the battery status could provide information on the condition of the individual modules to determine which modules are in poor chemical and electrical condition before storing and recycling them.

Recycling infrastructure

Although pilot plants like the one established by Umicore in Belgium with a capacity of 7 000 tonnes per year are available, this is not enough to cope with the emerging waste stream of batteries. Furthermore, also the necessary infrastructure for the logistics is still missing. These capacities might have been sufficient for the market so far, but as the battery landscape is changing so fast, it will no longer be sufficient in the future, especially if one of the existing recycling plants should temporarily not be able to work as intended. To transport and store great amounts of large batteries in a safe and cost-efficient way, solutions must be found urgently. As transportation is complicated, it is often the most expensive part of the battery recycling process. The recycling technology itself is also still under development (Dühnen et al., 2020).

To simplify the communication and management of several steps in the lifecycle, researchers propose to re-localise the steps of assembly and disassembly to the same place. This would also reflect the current trend of “lock-in strategy” being pursued by several producing companies like Tesla by not publishing their product composition and instead performing the EoL handling on their own, although, for globally engaged companies, this is nearly impossible to conduct for all their products.

3.2.3 Approaches to increase circularity

- Improving lifetime of a battery and keeping the products longer in the use phase gains time to develop the necessary infrastructure for recycling.
- Information about the battery, modular design, harmonization of battery chemistry and design and the content of high impact materials are significant factors to reduce the challenges related to the battery waste stream.
- The European Commission recently proposed a new Battery Regulation, which also includes proposals for recycling efficiencies and recycled content quotas for LIBs.
- In some European countries, take-back systems for industrial batteries were established on a voluntary basis by industry initiative.
- Few companies are active in refurbishment of batteries with own quality procedures and certification by external organisations.
- End-of-life batteries from electromobility could be reused in stationary applications, not being common practice yet but being under investigation.

In the following sections, possible options along circularity principles such as waste prevention, ecodesign and design for recycling, remanufacturing and reuse approaches are analysed for lithium-ion batteries, and examples of circular business models are presented.

Waste prevention

By achieving durability and a longer lifetime of batteries through a better design, it is possible to postpone the entry of a battery to the end-of-life stage, also resulting in more time to get prepared for developing the necessary infrastructure for the waste treatment and recycling of LIBs.

According to VITO and Fraunhofer ISI, (2019b) the Battery Management System and sensoring of the cells might be improved e.g. by measuring more than one physical range to improve the cell management and increase the service life of the battery system. Also, a sensor-less measurement is thinkable, which would reduce the wiring and therefore improve the energy density and reduce the costs (materials and production). Another step regarding improving the service life is to improve the thermal management to homogenize the cell temperature and thus to increase the whole battery system's service life. It has also to be considered that fast charging-capability will play a more prominent role in the future. Therefore, thermal management has to be able to deal with the high currents going along with that. These design options to increase the overall service life of the battery system are amongst the best technologies which, however, are not yet available, but expected to arise by 2025 (VITO and Fraunhofer ISI, 2019b). Also, to monitor the lifetime of batteries, more consecutive data collection would be helpful, which has not been developed yet.

On 10 December 2020, the European Commission (EC, 2020c) proposed a new Battery Regulation which also includes proposals for ecodesign requirements on durability and lifetime:

- Information requirement on the electrochemical performance and durability parameters for rechargeable industrial batteries and electric vehicle batteries with internal storage. From 2026 onwards, rechargeable industrial batteries shall meet certain minimum values.
- Rechargeable industrial batteries and electric vehicle batteries shall contain a battery management system that stores the information and data needed to determine the state of health and expected lifetime of batteries.

Along the battery manufacturing process, there are relevant waste streams emerging from every step, but especially in the end, a small ratio of the batteries has to be discarded. When this is the case for completely produced but faulty battery cells, they cannot just be used again, but have to be recycled as well in the same process as usually discarded cells, as they often present a safety hazard. In terms of the recycling process, it makes sense to keeping the materials of different chemistries like anode and cathode separated. Developing a direct recycling for the well separated cathode/anode materials from production scraps could be a solution to prevent further waste, but this would cover only a small volume compared to the overall production output.

Ecodesign and design for recycling

To increase circularity, ecodesign and design for recycling are generally well-established approaches. For example, when targeting a second-life application, the design should right from the beginning consider using electronics suitable for both, automotive and stationary applications.

Battery design also makes a significant contribution to recycling, determining the degree of recyclability at the EoL phase. According to recycling firms that are piloting battery recycling processes, however, the potential in this aspect has not been fully exploited yet. For batteries, so far only ideas for financial and fiscal incentives and ecodesign rules exist, e.g. by the Global Battery Alliance[1]. The

1 "A Vision for a Sustainable Battery Value Chain in 2030" by Global Battery Alliance

European Battery Alliance[2], on the other hand, has a focus on promoting a European battery industry without giving clear guidance about production or recycling. By now, there are no mandatory guidelines on how to integrate a design for recycling approach for batteries, although it appears to be very promising. A reason for this lack of guidance documents could be the relatively low priority given to the recycling of batteries so far.

These idle opportunities also affect other aspects, such as modular design for remanufacturing and accessibility of high impact materials to be recovered, which were addressed in more detail in previous passages. If packs are not easy to disassemble, this generates extra costs and puts the possible economic disassembling balance under pressure. Recyclers even go so far as to predict that the disassembling of battery packs one day could be potentially financed by the so-called ‘pack material value’, which contains aluminium, steel, copper and more pure material fractions. In general, different material scraps must be kept separate as far as possible, as recycling them separately makes everything easier. For the design process of batteries, recyclers recommend a modular design of large batteries. This includes a housing that can also be recycled independently from the battery cell.

Research institutes estimate that, given the current design, about 50 to 60 % of materials can be recovered, but that a better design enables recycling rates of even 80 to 90 %. Recyclers confirm that all metals recovered by recycling can be used in LIB production again, if they have undergone thorough purification. However, environmental risks, challenges and impacts are not fully correlated to these fractions. Even where fractions are low, there can be large-scale potential challenges / impacts, depending on the substances involved.

Other processes, like direct recycling of the cathode and anode materials sound good on paper but have several problems. Firstly, the materials used in the batteries are outdated after 10 to 15 years of operation and do not provide comparable performance to the current materials even after being reconditioned. At the same time, the processes for direct recycling are complicated and expensive, requiring a defined input of battery chemistries and battery sizes to be able to win back the anode and cathode material separately, which is not realistic at all, since no standardization was in place in 2020. Regarding the harmonization of battery chemistry and design, researchers in the sector point out the current lack of willingness by many producing companies outside the EU (most in Japan, South Korea, China, USA) to share information on their applied substances. This will be challenging for producing as well as recycling companies in Europe to develop a harmonized process and infrastructure to deal with foreign products at the EoL phase.

Research institutions see the design of a battery as a highly relevant aspect for the later recycling. Hence, they suggest the involvement of more modern technologies relating to reverse assembly and robotics. More adequate information about a specific battery cell would offer the potential to improve the disassembly and recycling process, to monitor a battery’s components and to provide instruction information on the correct handling. The last aspect is especially relevant for logistics and safety in waste handling. A battery passport (e.g. with a QR-code) could therefore support the tracking of battery streams and provide relevant information for logistics, remanufacturing and recycling. An approach that is based on this product information proposed by researchers is to increase the consumers’ awareness about a product’s recyclability by implementing a label comparable to the ones already existing for energy efficiency (A+, A, B, C,..). The intention is thereby to increase the demand for recyclable products. This concept would nevertheless require a high degree of

2 https://www.eba250.com/

transparency about the product. Thus, the aforementioned aspects of handing down information along the value chain (e.g. by product passport or RFID technology) are necessary preconditions.

On 10 December 2020, the European Commission (EC, 2020c) proposed a new Battery Regulation which also includes proposals for ecodesign requirements:

- Rules on the carbon footprint of electric vehicle batteries and rechargeable industrial batteries. The requirements are staged; first, there is an information requirement in form of a carbon footprint declaration; next, batteries shall be subject to classification into carbon footprint performance classes; last, batteries will need to comply with maximum lifecycle carbon footprint thresholds.
- Use of recovered raw materials: The technical documentation for industrial and electric-vehicle batteries with internal storage that contain cobalt, lead, lithium or nickel in active materials shall contain information about the amount of the above materials that have been recovered, being present in each battery model and batch per manufacturing plant. As of 2030, those batteries shall contain minimum shares of recovered cobalt, lithium or nickel from waste: 12 % cobalt, 4 % lithium and 4 % nickel. As of 2035, the minimum shares of recovered metals shall increase to 20 % cobalt, 10 % lithium and 12 % nickel.
- Labelling and information requirements: as of 2027, batteries shall be labelled to provide information necessary for the identification of batteries and of their main characteristics. Various labels on the battery or the battery packaging shall also inform about lifetime, charging capacity, requirement on separate collection, presence of hazardous substances and safety risks.

Remanufacturing and reuse

An extended use-phase of EoL-batteries from mobile applications appears to be generally possible by using them in other applications with less demanding requirements or refurbishing them without discarding the whole battery pack. They can find a second life in stationary applications. According to stakeholders in the energy supply sector, this option is not common practice yet, but is being investigated, e.g. in the form of several pilot projects, as the amount of EoL-batteries is still too small.

One challenge is that the replacement of batteries in electric vehicles currently costs several thousand Euros. Thus, most consumers most likely will not replace it but probably prefer driving with a battery with a residual capacity of only 70 % and use it until the vehicle is scrapped as a whole. Hence, most batteries from the electric vehicle waste stream will be quite old and be of a comparably poor quality compared to new batteries. In addition, handling costs for remanufacturing or preparation for reuse are also substantial and liability issues are not always clear.

Although there seems to be a demand for secondary batteries, the financial benefit remains a key factor, since first-life batteries are steadily decreasing in price terms, which puts a greater financial pressure on batteries aged over several years, to compete with new batteries. Currently, first-life LFP cells are preferred and cheaper compared to first-life NMC cells, which could be due to overproduction in China. In the long run, NMC batteries, mainly used in the automotive sector, could become more economical, also due to economies of scale. The costs per absolute stored energy is the most important factor for the stationary storage. The energy sector is only a small consumer of batteries compared to the automotive sector, which means that, in the event of an interim battery shortage, batteries could be hard to come by or would probably be more expensive than those provided to the automotive sector with its large volumes and strong supply chains.

Second-life batteries from the automotive sector have to compete with first-life batteries. This is a challenge because, although they can be purchased at lower prices, their lifetime will be rather short, and refurbishment and handling could be expensive. Furthermore, the potential users of second-life batteries also compete with the recycling sector. According to stakeholders from the energy sector, recycling could threaten the second-life approach if it is seen as a more profitable or at least cheaper alternative, thereby missing the opportunity for a more ecologically beneficial cascadic use. This consideration of remanufacturing or reuse – researchers conclude – only seems applicable for the battery source of EVs, where cooperation between second users and recyclers is possible. This is not a realistic option for other LIB applications such as portable devices, since the challenge of missing standardization applies here as well, but additionally, the cells are relatively small compared to EV batteries and therefore a recycling economy of scale is even more unlikely to be developed.

On 10 December 2020, the European Commission (EC, 2020c) proposed a new Battery Regulation which also includes proposals for requirements facilitating remanufacturing and reuse:

- As mentioned before, rechargeable industrial batteries and electric vehicle batteries shall contain a battery management system that stores the information and data needed to determine the state of health and expected lifetime of batteries. Access to the data on those parameters in the battery management system shall be provided at any time for evaluating the residual value of the battery, facilitating the reuse, repurposing or remanufacturing of the battery and for making the battery available to independent aggregators operating virtual power plants in electricity grids.
- Battery Passport: As of 2026, industrial batteries and electric-vehicle batteries shall have an electronic record for each individual battery they place on the market. The records shall be unique for each battery, to be identified through a unique identifier. The battery passport shall be linked to the information about the basic characteristics of each battery type and model stored in the data sources of an electronic exchange system to be established by the Commission.

Examples of circular business models in Europe

In the following, some examples of circular business models for lithium-ion batteries retrieved from literature review as well as reported either in the interviews or the survey conducted within this study are presented. The overview might not be exhaustive.

In France, Finland, Germany and further European countries, there are enterprises that came to agreements with large electric car manufacturers such as Renault, Hyundai, VW, BMW and Daimler and use these companies' still functioning batteries in a second-life application to build up larger residential battery packs to store solar energy. For example, they might be used as uninterruptable power supply replacing diesel generators; or as 'spare parts store' for corporate vehicle fleets (The Mobility House, 2018). This has an economic benefit, since batteries for reuse are cheaper than new batteries, and at the same time, this significantly reduces the environmental footprint, since the lifetime is thereby extended.

French companies are active in refurbishment of batteries, they have their own quality procedures, and certification by external organisations.

In some EU countries, take-back systems for industrial batteries were established on a voluntary basis by industry initiative. The distributors of energy storage devices, such as electrical trade businesses, are still obliged to accept the discarded models from their customers, i.e. private and commercial end users, free of charge, but the organisational and financial effort to have them returned individually to the respective manufacturers being responsible for disposal according to the law, is then eliminated for the distributors. The creation of take-back system ensures that all returned systems are collected from the distributor on behalf of the manufacturers' association and recycled properly. Reneos[3] is a European network of five national battery collection systems (Bebat, Belgium; GRS, Germany; Cobat, Italy; BatteriRetur, Norway; and Stibat, The Netherlands) providing legally compliant, cross-border take-back and recycling solutions or second-life concepts for LIBs.

Elretur[4] is a Danish organisation managing the collection, recycling and reuse of 80 % of the WEEE and battery waste from private and industrial use in the country. Beyond ensuring the circularity in this waste stream, Elretur conducts regular studies and feeds the resulting information to their corporate members and private user, raising awareness about the topic in the population. In Belgium, five organisations created a consortium in 2020 to address the disposal and recycling of LIBs from vehicles. Watt4Ever[5] collects these batteries, assesses and tries to remanufacture them into new battery packs when possible. The consortium further provides technical and organisational services to industry stakeholders with the aim of further improving the circularity of LIBs.

3.2.4 Policy gaps and market barriers for circular business models

- Implementation of innovative circular business models is slowed down because ecological benefits of recycled material are not yet priced.
- Secondary materials have to compete with primary material. The market for batteries and material demand is growing too fast to sustain it with recycled materials only.
- Measures to increase the demand for recycled material can be legally binding determinations of a fixed rate of recycling material input (closed loop) or they can use the emerging waste streams in other applications (open loop).
- Battery technologies and chemistries are still under development and changing which makes it difficult for new business models to make reliable assumptions regarding the future market development, demand and challenges to build on.

The EU Battery Directive[6] is currently under revision. The 2006 Directive classified energy storage systems used in connection with photovoltaic systems in private households as "industrial batteries". Depending on the country, recycling output which is not qualified for the direct use in the industry, still fulfils the recycling regulation’s requirements. This leads to the conclusion, that the recycling standards are too low and unambitious. This lack of good standardization is a problem in several life stages of a battery, from sourcing and production to dismantling and recycling. Manufacturers and distributors of industrial batteries must be registered and must take back waste batteries free of charge. However, in contrast to "portable batteries", for which the EU member states must meet minimum collection quotas, the 2006 Directive did not specify any concrete collection targets for industrial batteries. Accordingly, producers have no legal obligation to date to actively promote the collection of waste batteries.

There is a proposal for new battery regulation in the EU by the European Commission (see section 3.2.3), which includes, apart from other aspects like new collection targets, mandatory recycling efficiencies (65 % by 2025 and 70 % by 2030), recovery targets for critical materials (copper, cobalt, nickel and lithium, starting in 2026) and minimal recycled content for cobalt, nickel and lithium in

3 https://www.reneos.eu/
4 https://elretur.dk/
5 https://watt4ever.be/
6 Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC

newly produced or imported batteries. Furthermore, a battery passport has to be introduced, including a QR code and displaying data about the specific battery. Moreover, rules on Extended Producer Responsibility with clear specifications for extended producer responsibility obligations covering also industrial batteries are laid out in the proposal. However, this proposal still has to be ratified by the Parliament and the Council. Then, it will be active immediately without additional confirmation by the national governments.

Another problem in the 2006 EU Battery Directive was the missing stewardship of resources, since there was no clear differentiation between waste and resources. Policy makers are calling on stakeholders in the battery industry to contribute to solving the problem of emerging battery waste streams, for example by establishing or scaling up infrastructure and developing new business models. Despite that call for action, recyclers face a market where the ecological benefit of recycled material is not priced in and therefore secondary materials are economically disadvantaged in the competition. This market situation also hinders the development of new circular business models and innovations.

Another reason identified by recyclers with regard to the laggard implementation of innovative circular business models is, that the market for batteries is growing too fast (see section 3.2.1) to be able to completely sustain it with recycled materials and therefore, in the foreseeable future, secondary material will still have to compete with primary material. Furthermore, the battery chemistries are also changing. This could be an advantage regarding the critical cobalt supply, as less of it will be used in LIBs in the future, but also more nickel is needed. In such times of change, new business models can struggle to make reliable assumptions regarding the future market development, demand and challenges to build on.

Another economic barrier faced by recyclers is expensive insurance cost, since the recycling of batteries is always related to a higher safety issue than primary production. To increase the demand for recycled material and thereby support recyclers, a proposed measure is to legally determine a fixed rate of recycling material input for batteries. To realize these requirements on a large scale, harmonized standards in the EU or on a bigger scale are needed. In contrast to the suggestion of a recyclate input rate to promote a closed loop, further valorisation potentials to use the emerging waste streams in other applications are seen in open-loop applications instead. In advance of considering a closed-loop solution, the economically and ecologically best way of material use should be analysed. Lifecycle assessment (LCA) is one option to identify the ecologically preferable solution.

When the question comes to who will cover the cost for recycling or other EoL treatment, regardless of which technology is applied, researchers in the field conclude that single national examples show the strong impact of a “the polluter pays principle”. It incentivizes the polluter and therefore the entire value chain to reconsider their levers of change and to further develop their potentials for improvement. Some producers even react to it by developing their own EoL treatment.

3.2.5 Conclusions

As outlined in this chapter, there are several challenges with waste streams in the field of lithium-ion batteries for energy storage and electromobility. Not all relevant materials in the batteries that should be recycled are yet included in the existing processes. The logistics are difficult because of the risk of fire from spent batteries. The amount of battery waste grows, but the recycling capacities are not growing at the same pace. There are several approaches to tackle parts of those problems and a new regulation is on the way, but not all pending issues have been solved yet.

The strongly growing number of LIBs and production sites for LIBs in the EU is demanding a major action plan concerning the recycling and circularity of EoL batteries and of the waste created during their production. Economic efficiency is yet difficult to achieve. At the moment, the recycling market is waiting for the amount of batteries to grow. However, the amount of production scrap and the number of retracted batteries is supposed to grow faster than expected without a real solution for the resulting gap in recycling capacities.

Furthermore, the costs for logistics and recycling are often underestimated. Especially for cells without cobalt or nickel inside, the recovered materials will probably never cover the costs of the recycling process, as the transportation and recycling of LIBs pose a major risk to health and safety, as discussed in chapter 3.2.2. Therefore, stakeholders claim that the sector must move towards a consolidated way of working. The life chain must be well designed and transport, recycling and a second life option must be considered before the market entry of a new product. The European Commission's proposed new Battery Regulation could help define some of the ground rules to pave the way for a better waste management of LIBs.

Summarising the above, it can be said that the opportunities will only develop their full potential if they are developed and applied in an integrated approach by introducing the appropriate policies and through collaboration and close communication of all stakeholders in the industry. Especially the new proposal from the European Commission concerning batteries has several very positive policies, which, if implemented in this way, could lead to an improved battery waste management. However, it is unlikely to immediately solve all the challenges related to battery waste stream, also because practical implementation usually lags behind the legal requirements.

3.3 Emerging waste streams in the field of wind energy

3.3.1 Market developments and emerging waste streams

- In 2019, wind power made up 35 % of the total electricity generated from renewable sources in Europe, with more than 3 000 wind turbines (on- / off-shore) newly installed only in that year.
- Wind turbines are a highly relevant emerging waste stream because of their high demand of materials of about 400 000 t/GW wind power. In 2020, a total waste volume of about 2.5 million tonnes was expected, increasing to 3.3 million tonnes in 2025 and 4.7 million tonnes in 2030.
- Rare earth elements as a crucial part of magnets, according to forecasts, will add up to more than 500 tonnes in 2030.
- Around 14 000 wind turbine blades that could be decommissioned by 2023 are expected, equivalent to between 40 000 and 60 000 tonnes, difficult to recycle due to composite materials.
- The experience with EoL treatment is very limited because only few of the first installed wind turbines have reached their end-of-life stage by 2020.

To reach climate neutrality by 2050, to decarbonize the EU economy and to fade out fossil energy, the technology of wind power on- and offshore will play a key role. Statistical data confirm that in 2017 wind power made up 13.8 % of energy production in Europe, with a strongly increasing trend (EUROSTAT, 2019). Under the European Commission's long-term decarbonization strategy, this share is set to rise to 50 % by 2050. In 2019, in total 2 843 wind turbines (on-shore) with highest shares of France, Sweden, Germany and Greece, and 502 turbines (off-shore) with highest shares of the UK and Germany were newly installed in Europe (WindEurope, 2020). On the other hand, currently 34,000 turbines are 15 years or older, representing 36 GW of onshore wind capacity. Out of the 36 GW some 9 GW are 20-24 years old and around 1 GW are 25 years or older. Most of the ageing capacity is in Germany, followed by Spain, Italy, France and Portugal (WindEurope, 2020b).

The waste streams that come along with the sector's growth will emerge drastically in the decades ahead. In all their investigated scenarios for Europe regarding the power sector development until 2030, Tsiropoulos et al. (2020) conclude that wind and solar power will grow the fastest in the renewable energy sector. For wind energy, a growth factor between 1.5 and 2.7 is forecasted. In one of the scenarios in their outlook on energy supply technologies, Nijs et al. (2018) projected installed wind power capacity to increase from around 150 GWe in 2010 to 1 500 GWe in 2050, including 250 GWe of offshore wind.

Besides the aspect of rapid growth, the classification of wind turbines as a highly relevant emerging waste stream is based on the demand of materials for wind power, which is currently at about 400 000 tonnes per GW (see Table 3-7). Multiplied with the newly installed capacity of 9 295 MW in the EU-27 in 2010 (EWEA, 2011), i.e. the turbines that will be decommissioned in 2030, a waste stream of approximately 3.7 million tonnes per year is to be expected.

For the composite waste alone, the European Technology & Innovation Platform on Wind expects approximately 66 000 t of waste in 2025 to come from the wind sector (ETIP Wind, 2019). This is a range which corresponds to WindEurope's estimates with around 14 000 wind turbine blades that could be decommissioned by 2023, equivalent to between 40 000 and 60 000 tonnes (WindEurope, Cefic and EuCIA, 2020). According to WindEurope (2020b), starting at less than 9,000 tonnes annually, the on-shore blade waste is expected to reach about 25,000 tonnes per year by 2025 and up to 52,000 tonnes per year by 2030.

Most of the turbines will be first decommissioned in Germany and Spain, with some activity as well in Denmark. Toward the end of the decade Italy, France and Portugal will also decommission a large number of ageing wind turbines (WindEurope, 2020b).

Based on historic figures by IRENA combined with projections and material compositions by the JRC, the volume of the wind turbine waste streams has been estimated (see Table 3-7), based on a 20-year lifespan of the wind turbines. The total waste volume will reach almost 5 million tonnes in 2030. The most relevant materials in terms of volume are concrete and steel covering approx. 95 % of the total. Rare earth elements as a crucial part of magnets will add up to more than 500 tonnes in 2030.

Table 3-7: Expected mass of contained metals with high impact in windmill waste stream

	2020	2025	2030
Total (t)	**2 459 913**	**3 357 422**	**4 754 347**
Zinc	25 592	35 002	50 122
Copper	11 388	15 574	22 287
Aluminium	5 560	7 570	10 577
Manganese	3 669	5 018	7 189
Chrome	2 404	3 291	4 728
Nickel	1 843	2 511	3 528
Molybdenum	500	685	983
Rare Earth Elements total	215	307	537

Source: own calculations based on Carrara et al., 2020; IRENA, 2020.

3.3.2 End-of-life challenges and opportunities

- Critical raw materials in magnets (neodymium, praseodymium, boron, dysprosium and niobium) could be valuable enough to make recycling of permanent magnet generators of wind turbines profitable, depending on the future price and their concentration in the waste stream.
- For turbine blades, being made of lightweight like carbon fibre (CF), glass fibre (GF), and composite material, the recycling infrastructure is still under development and research is either ongoing or further research and implementation are needed.
- Downcycling of carbon fibres as plastic moulded Euro pallets and polymer concrete as well as other construction applications such as noise proof barriers or thermal insulation materials is applied.
- Huge size of blades would make transportation costs prohibitive for long-distance hauls to recycling facilities located far away.

High impact materials and supply chain

A key factor that influences the properties of waste is material selection and composition. Wind power plants consist of different parts such as the tower, the fundament and cables which are made of materials that have a well-established waste treatment, such as steel, aluminium, copper, cast iron and concrete, which is why about 85 to 90 % of a wind turbines total mass can be recycled.

The parts that put a greater challenge on recyclers are generators, which contain rare earths and critical materials, as well as the turbine blades, which are made of lightweight like carbon fibre (CF) and glass fibre (GF), and composite material, for which recycling infrastructure and technology are still under development. A waste stream from wind turbines which is better handled regarding recycling, is resin (polymers).

Opportunities for value recovery in the wind energy sector are seen in materials of value which are used in wind power plants (see Table 3-8). The deployment of permanent magnet generators is common practice for direct-drive turbines. The materials of high value contained in a magnet on average are about 28.5 % neodymium, 4.4 % dysprosium, 1 % boron and 66 % iron and weighs up to four tonnes (Carrara et al., 2020).

Table 3-8: Material usage estimates in t/GW for different wind turbine types

Material	Range [t/GW]
Concrete	243 500 - 413 000
Steel	107 000 - 132 000
Iron (cast) (Fe)	18 000 - 20 800
Glass/carbon composites	7 700 - 8 400
Copper (Cu)	950 - 5 000
Zinc (Zn)	5 500
Polymers	4 600
Aluminium (Al)	500 - 1 600
Manganese (Mn)	780 - 800
Chromium (Cr)	470 - 580
Nickel (Ni)	240 - 440
Neodymium (Nd)	12 - 180
Molybdenum (Mo)	99 - 119
Praseodymium (Pr)	0 - 35
Dysprosium (Dy)	2 - 17
Terbium (Tb)	0 - 7
Boron (B)	0 - 6

Source Carrara et al., 2020.

The opportunities of materials also involve some challenges. The criticality of a material is based on the high supply risk and its high economic importance. In wind turbines, the materials identified as critical are neodymium, praseodymium, boron, dysprosium and niobium (Pavel and Blagoeva, 2017).

The potential of the recycling of magnet material (see section 'recycling infrastructure' below) is not yet established in Europe but is part of several research projects[7]. The critical raw materials applied could be valuable enough to make magnet recycling under certain circumstances profitable, if it was conducted at large scale, but this depends very strongly on the future price for these resources and their concentration in the waste stream. A benefit that comes along with resource conservation and economic benefits is that the recycling of material reduces GHG emissions of turbines and therefore reduces their environmental impact.

Logistics and safety in waste handling

To improve the performance of recovering valuable material, reuse and recycling, the impact of appropriate logistics and dealing with hazards that are related to the waste stream must be taken into account as well. Regulations such as the Restriction of Hazardous Substances Directive (RoHS) and the WEEE directive, applicable for the electrical and electronic parts of a wind turbine, are examples of important regulations which the EU implemented in order to prevent products to become hazardous waste at the end of their life, to protect people and the environment from harmful substances and to improve material stewardship.

Although wind park utilities are responsible for the decommissioning of wind turbines at their end of life and there is no common take-back scheme at European level for decommissioned wind turbines, manufacturers state that the original equipment manufacturers (OEMs), mostly based in Europe, take their producer responsibility for the EoL management.

A wind power specific problem is the size of the blades, which can reach 20 metres for older, 80 metres for today's and up to 150 metres for future turbines (Veolia, 2018). This could present a challenge in the decommissioning and disassembly phase, making transportation costs prohibitive for long-distance hauls to treatment facilities, but for experienced service providers this is usual business.

Public authorities that have financed several research projects on the recycling of turbine blades confirm that the size is an immanent challenge for processing and transport, although recent development of processing facilities in harbours is helping to address this challenge.

Recycling infrastructure

In connection with the emerging trend towards more lightweight blades, an increasing demand of carbon and glass fibre can be expected (Carrara et al., 2020). Other light materials such as aluminium or steel would cause a much higher GHG intensity of manufacturing, have higher weight or might be less durable which is why turbine producers do not see any real possibility of replacing the critical composite materials in the design phase. This points out the demand for further research in the recycling technologies, since it seems to be very difficult to find material alternatives.

7 E.g. the European Union (EU)-funded SUSMAGPRO project, see https://www.susmagpro.eu/

Since the wind energy technology is relatively young and the operating times of turbines still vary between 20 to 30 years according to Carrara et al. (2020), by 2020 only few of the first installed wind turbines have reached their end-of-life stage and therefore, the experience with EoL treatment is very limited. Today, the majority of discarded blades seem to be either still reused or disposed of in landfills, however, without data on the respective shares.

The recycling (or waste treatment in case of carbon fibre reinforced plastics) of several components is not yet implemented (on industrial scale) (Oliveux et al., 2015). Carbon fibre-reinforced plastics cannot be burned in a municipal solid waste incinerator, because that would release asbestos-like toxic materials, for which the treatment site's gas cleaning facilities are not equipped to filter them out. Some blades are burned in kilns that create cement or in power plants. However, research shows that the conditions in municipal and hazardous waste incinerators are not sufficient for the destruction of carbon fibres. The majority of the carbon fibres are discharged unchanged via the slag. In addition, the carbon fibres are even discharged from the furnace with the flue gas flow (Stockschläder et al., 2019).

There are only very few and yet immature technologies under development for the recycling of turbine blade materials.

Today, a technology for recycling composite waste is through cement co-processing being commercially available for processing large volumes of waste. However, only one plant in northern Germany treats decommissioned blades with this technology. In this process, the mineral components are reused in the cement. However, the glass fibre shape is not maintained during the process. Composite waste recycling through the development of alternative recycling technologies which produce higher value recyclates and enable production of new composites still need to be expanded and improved (WindEurope, Cefic and EuCIA, 2020; WindEurope, 2020b).

A collection of recycling technologies for composite material under development (technology readiness level[8], (TRL) from 5 to 9) published by ETIP wind involves the approaches of gasification, solvolysis, high voltage pulse fragmentation, pyrolysis, mechanical grinding and co-processing (ETIP Wind, 2019). According to WindEurope (2020b), mechanical grinding and pyrolysis are the most mature technologies to recycle wind turbine blades. But more work and industrial upscaling is needed for pyrolysis to become more competitive and reach the required matureness to be widely deployed. And there needs to be a market for the granulates/powder (output of mechanical grinding process), recycled fibres and oils from the pyrolysis process. Other recycling technologies such as high voltage pulse fragmentation, microwave pyrolysis and solvolysis in earlier development phases still need to be demonstrated at industrial scale and on environmental aspects (WindEurope, 2020b).

In this context, for example, the research project *DecomBlades* started in early 2021, focussing on the development of sustainable techniques to recycle the composite material in wind turbine blades. The project is primarily concerned with three specific processes: the shredding of wind turbine blades such that the material can be reused in different products and processes; the use of shredded blade material in cement production; and, finally, a method to separate the composite material under high temperatures, also known as pyrolysis.

[8] Technology readiness levels indicate the development stage of an innovation. The lowest level 1 stands for basic technology research, level 5 for technology development and demonstration. The highest level 9 indicates an innovations readiness through system tests, launch an operation. The levels cannot always be clearly separated and blend into each other.

Public authorities share the scientists' conclusion that there are as yet no technical solutions enabling the reuse of carbon fibre from end-of-life turbines for the same purpose, but they are more optimistic than producers regarding opportunities for the application of recycling material. They see a useful application in products that need to be capable of absorbing weight pressure, such as plastic moulded Euro pallets and polymer concrete as well as other construction applications such as noise proof barriers or thermal insulation materials for which some recycling companies are specialised. Wind park operators even propose to consider that the recycling of glass fibre by breaking it down to its main component sand in some cases might be economically and environmentally more useful than remanufacturing.

Since the suggested applications for recycling material have significantly lower standards and demands regarding the fibre length and quality properties, these applications could be described as downcycling. However, based on the research findings by Stockschläder et al. (2019) that carbon fibres are not sufficiently destructed in incinerators, it could be that the recycled materials still contain carbon fibres, thus just shifting the EoL challenges to another sector.

Furthermore, chemical companies are investing into the development of new polymer technologies which can be recycled or broken down, but the development and qualifying times are very long.

In any case, in view of the sharply increasing waste streams that will have to be treated in the coming years, it is not possible to wait for the moment of profitable recycling. The infrastructure and recycling techniques must therefore be developed immediately.

3.3.3 Identified approaches how to increase circularity

- Waste prevention regarding production waste of wind turbines does not seem to be relevant.
- EoL waste prevention is tackled by extending the overall lifetime of wind turbines, e.g. through digital solutions facilitating preventive maintenance and repair or modular / upgradeable design with more easily accessible components for replacement of broken parts.
- Current research efforts with regard to circularity seem to be predominantly focused on finding recycling solutions for the existing wind turbines to be decommissioned rather than on exploring material improvement or ecodesign approaches that facilitate future dismantling, remanufacturing or recycling of wind turbines.
- Gear boxes and generators can be upgraded for reuse.
- Reusing turbine blades, e.g. as replacements for blades on similar (usually older) models of turbines seems to be a business model although being challenging due to their diversity in size and shape, which makes it harder to find the right types. A common way to trade these is by using e-platforms. Lifetime monitoring or fatigue testing of the blade might be necessary to ensure the safety of re-using the blade.
- A significant portion of decommissioned wind turbines are exported for reuse, e.g. to Eastern Europe or beyond Europe, e.g. to Latin America.

In the following sections, possible options along circularity principles such as waste prevention, ecodesign and design for recycling, remanufacturing and reuse approaches are analysed for wind turbines, and examples of circular business models are presented.

Waste prevention

One solution for waste prevention and to improve the life cycle performance of a wind turbine is to increase its durability by eliminating common errors such as the failure of switchgear and thereby decrease the environmental burden of the production and EoL phase. The current lifetime of a wind turbine is somewhere between 20 and 30 years, which producers are eager to extend by a more resilient design to keep turbines longer in operation and thereby out of the categorization as waste.

The greatest efforts were made already during the design phase, aiming at detecting potential hot-spots and finding solutions that require as little maintenance as possible. Another option would be a modular design with more easily accessible components and replacement of broken parts (Karavida and Nommik, 2015). Waste prevention could also be facilitated by design for an easy upgrade of existing blades to new versions, e.g. segmented or modular blades. However, these are not standard design yet. Future research might also look into the development of "smart" materials such as embedded sensors in turbine blades which enable material health monitoring and health forecasting capabilities (WindEurope, Cefic and EuCIA, 2020). Today, modern wind turbines include digital, cloud-based solutions facilitating preventive maintenance and repair.

In terms of waste prevention at the manufacturing stage, wind park operators and manufacturers suggest that the original equipment manufacturers (OEMs) already aim to optimise waste prevention during the manufacturing of blades for economic reasons and therefore do not see any real potential for major improvement.

Ecodesign and design for recycling

For wind turbines, lightweight design and design for durability are principles already implemented with the turbine blades made of carbon and glass fibres and composites to keep their weight low and the strength, i.e. durability high. On the other hand, these material designs compete with the design for recycling approach which did not seem to be well-balanced in the past as this part of the waste materials cannot be recycled yet.

Therefore, research for alternative blade materials with similar durability but better recyclability properties could be a future option. However, the results of the literature review and interviews within this study suggest that current research efforts are predominantly put on finding recycling solutions for the existing wind turbines to be decommissioned rather than on exploring ecodesign approaches that facilitate future dismantling, remanufacturing or recycling of wind turbines including research on new high-performance materials with enhanced circularity.

Active areas in material research for wind turbine blades targeting increased lifetime and improved recyclability include for example developing 3R-resins, a new family of enhanced thermoset resins and composites with better re-processability, repairability and recyclability properties (WindEurope, Cefic and EuCIA, 2020).

Further, German-based RDRWind e.V. worked with industry stakeholders and DIN SPEC to create a new standard for the sustainable dismantling, disassembly, recycling and recovery of wind turbines. The standard DIN SPEC 4866, published in 2018, has been updated in 2020. It considers cost, environmental and safety aspects and defines instructions and qualification requirements for the dismantling work of wind turbine components that have reached the end of their useful life.[9]

9 DIN SPEC 4866:2020-08 online: https://www.beuth.de/de/technische-regel/din-spec-4866/326469199

According to WindEurope (2020b), today the mechanical properties of recycled composites do not allow reuse into blades as the main properties cannot be maintained. In the longer term however, the industry aims to integrate recycled blade composites into the production of new blades (if this becomes technologically possible).

Remanufacturing and reuse

Producers confirm that pure waste streams are already monetized and/or bear a potential for reuse. By doing so, they claim for themselves 75 % savings in materials and emissions. Gear boxes and generators are examples for parts of a wind turbine that can still function when a turbine is decommissioned and can therefore be upgraded for reuse. A recent project in Denmark is aiming to increase the life span of wind turbines through the replacement and repair of used parts, particularly the nacelles in older wind turbines, with priority given to using lightly used parts as replacements. The project is partially supported by the Danish Energy Agency.

To consider reusing turbine blades that could have an extended lifetime, wind park operators point out the hindering circumstance that wind turbines are very diverse in size and shape, which makes it harder to find a “standard” type ensuring the right size and quality. Furthermore, this type should have the desired additional lifetime. However, wind park operators indicate that in some cases it may be possible to extend the lifetime of blades by reusing those that are in good condition when turbines are decommissioned, as replacements for blades on similar (usually older) models of turbines.

Lifetime monitoring or fatigue testing of the blade might be necessary to ensure the safety of reusing the blade. Reusing of in-service blades is currently taking place, and a common way to trade these is by using the e-platforms (Skelton, 2017).

On the other hand, a significant portion of decommissioned wind turbines seem to be exported for reuse outside of Europe or the original jurisdiction, although clear statistics are not available. Biggest second-hand turbine providers are Germany, Denmark, the Netherlands, the UK and Italy. The turbines are sold both to other European countries and abroad, the majority going to Eastern Europe or Latin America. The advantage of buying second-hand turbines relies mostly on its lower price; in addition, the waiting time for new turbines can be around two years, making it faster to purchase a reused turbine (Karavida and Nommik, 2015).

Whereas lifetime extension through reuse is in general a desirable approach, the potential export to countries with no stringent enforcement of environmental regulations could quite bear a risk of (potentially illegal) externalizing disposal costs to outside Europe (see section 4).

The assurance company DNV-GL has developed a standard for lifetime extension of wind turbines (DNVGL-ST-0262), and the International Electrotechnical Commission (IEC) is currently developing a standard for the through-life management and life extension of wind power assets (IEC TS 61400-28) (WindEurope, Cefic and EuCIA, 2020).

Examples of circular business models in Europe

In the following, some examples of circular business models for wind turbines retrieved from literature review as well as reported either in the interviews or the survey conducted within this study are presented. The overview might not be exhaustive.

As pioneers in the field, some producers such as Vestas are willing to set themselves targets for waste prevention. Their approach to track and improve their performance and identify their potentials for improvement, is the application of the LCA method. To increase the durability and lifetime of their wind power plants, they offer regular maintenance and repair of wind turbines in operation.

To upgrade single parts such as gear boxes and generators from end-of-life turbines to reuse them in new turbines can be a part of the producers' business model. Thereby, they save costs for waste treatment of these parts and improve their performance regarding their products' environmental footprints.

The initiative of wind park operators and other stakeholders to pursue an EU-wide dialogue to consider a ban on landfilling turbine blades may act as a catalyst for the consideration of other, more circular approaches. Furthermore, to achieve full recyclability in the future, the wind industry calls for establishing a European cross-sectorial platform (including all composite waste producing sectors) and sharing good practice (WindEurope, 2020b).

In 2020, Enel Green in Spain launched a call for start-ups to conceive solutions for the life extension, recyclability and remanufacturing of wind turbine components. For this, they created the 'Open Innovability' platform, aimed at attracting such start-ups through the commitment to involve expert partners in the relevant fields.

3.3.4 Policy gaps and market barriers for circular business models

- Limited legislation regulating treatment of composite or blade waste both at EU and national levels. European authorities use different regulatory instruments to incentivise recycling. Lack of regulation is one aspect why the disposal in landfills continues in many European countries.
- Industry stakeholders pursuing EU-wide dialogue to consider a ban on landfilling turbine blades. At the same time, some actors suggest considering landfilling at sea as option to find a solution for the shrinking space in limited landfills which might, however, pose challenges as well.
- Cost of recycling composite waste is considered too high compared to the levels of landfill taxes for wind turbine blade waste, to trigger substantial changes towards more recycling.
- No relevant market demand for recycled materials yet; value of recycled materials from composite materials still too low. Insufficient number of recycling facilities for proper handling of emerging volumes of composite waste stream expected in the coming years.
- Legally determined recycling targets, as introduced in France, or quotas of recycled content in some countries could stimulate recycling and the market for secondary materials.
- Extended producer responsibility for EoL management is not applied in the wind sector, but many European based OEMs state initiating voluntary approaches for improving sustainability.
- Composite waste arising from the wind turbine blades is often classified as plastic waste from construction and demolition, i.e. it may therefore become mixed with other types of plastics. Differing waste classification may limit efficient separate collection and sorting.
- On the other hand, so far, low volumes of composite wind blade waste make it challenging to build a recycling business based only on this waste stream. Cooperation of all composite-using sectors facilitates finding cost-effective solutions and value chains for the combined volumes.
- Lack of information and standardization in the composition of the different components hampers the development of a specified treatment process. Sector-specific guidelines could spread the application of design for recycling in the industry.
- Financial support for R&D would be beneficial to encourage industry, private companies, academia and others to share their knowledge and work together on future circular solutions

There is limited legislation regulating treatment of composite or blade waste both at EU and national levels. In the WEEE Directive, wind turbines are excluded because they are considered 'Large Scale Fixed Installations'. Generally, national European authorities use different regulatory instruments to incentivise recycling. These include legally binding targets, landfill bans and/or taxes and requirements for Extended Producer Responsibility (EPR) (however, the latter particularly in other sectors, i.e. not applied for wind turbines so far). National associations in Germany, Denmark and Belgium indicated in the online survey of this study that they need further EPR requirements, in particular for wind turbine blades, whereas OEMs state already being rather active at initiating voluntary approaches for improving sustainability.

Moreover, the existing national legislation is not necessarily aligned at international level. For example, at national level, Germany, Austria, Finland, France and the Netherlands forbid composites from being landfilled or incinerated. However, in the Netherlands wind farm operators can benefit from an "exemption" if the cost of alternative treatment is higher than a certain limit, which is often the case, meaning that landfilling is still practised, however with no data on the practiced shares (WindEurope, Cefic and EuCIA, 2020).

In Denmark, although the Danish government provides guidance on the classification of materials from wind turbines, there is no specific regulation for wind turbines, and it is up to municipalities to enforce regulations and determine if the waste from wind turbines should be landfilled or incinerated. According to a European public authority's impression, this represents the situation prevailing in most European member states. This lack of regulation is one aspect why the disposal in landfills continues, which is not a good solution regarding material stewardship in the long term. It also contributes to reducing the capacity of landfills, although wind park operators postulate that landfilling of the glass fibre material does not cause environmental protection issues, since the material is inert.

Strategies to increase the knowledge of wind turbine waste streams and their related opportunities and challenges, for example by putting the topic on the agenda of their waste management plans are good signals by countries to express their awareness of the development and to pave the way for more specific measures. Denmark, for example, will include wind turbines in its new waste management plan starting in 2021 to improve the management of the waste stream. Anyhow, stronger statements and bolder steps are needed from both the state and the industry to improve the governance of the emerging waste stream of EoL wind turbines in the near future.

Furthermore, the wind industry calls for a Europe-wide landfill ban on decommissioned wind turbine blades by 2025 which means that the industry commits to re-use, recycle or recover 100% of decommissioned blades. The ban should also apply to other large composite components that can be found in the nacelle. The wind industry also commits not to send decommissioned blades to other countries for landfilling (WindEurope, 2020b). At the same time, some wind park operators suggest considering landfilling at sea as an option to find a solution for the shrinking space in limited landfills. According to their view, repurposed, disposed turbine blades could support protection against erosion on offshore turbine fundaments and become an element for new habitats for fish between them. On the other hand, it should be carefully analysed if there might also be EoL challenges with landfilling at sea.

Since the waste hierarchy clearly puts disposal as the least favoured position of waste treatment, the next step is to make recycling more economic, since the secondary material cannot yet compete with cheap primary material.

When comparing the cost of recycling composite waste with the levels of landfill taxes for wind turbine blade waste, the tax level in some countries is considered too low to trigger substantial changes towards more recycling (WindEurope, Cefic and EuCIA, 2020). Also, there is no relevant market demand for recycled materials from composite waste of wind turbines yet as composites cannot compete with the price of virgin materials. According to producers, legally determined quotas of recycled content in some products provide an opportunity to stimulate the market for secondary materials. This could catalyse further research and innovations in this area, which could reduce the costs for recycling in the future. Furthermore, for example, standards and certification to classify the recycled material performance could support companies which are seeking to incorporate recycled materials into their products (WindEurope, 2020b).

France introduced recycling targets for wind turbines in its regulatory framework ICPE for Wind Assets in France to be applied from July 2020 onwards. The wind farms owners will be obliged to recycle at least 95 % of the total weight of the turbine including foundations, from 2024 onwards, and 55 % of the rotor blades, from 2025 onwards. Furthermore, to ensure recycling, a financial warranty has been introduced: A provision of 50 k€ for wind turbines with a capacity below 2 MW and a complement of 10 k€/MW for wind turbines with a capacity above 2 MW must be provisioned. This amount must be also indexed every 5 years according to a specific formula indicated in the decree (Greensolver, 2020).

Another barrier is that composite waste arising from the wind turbine blades is often classified as plastic waste from construction and demolition. It may therefore become mixed with other types of plastics. National authorities need to ensure that the correct and suitable code is applied to blade waste. Differing waste classifications may also limit efficient separate collection and sorting, identifying suitably authorised waste treatment options and the potential for a pan-European market for recycled composites. The industry plans to investigate whether a single waste code for blade waste would help improve monitoring or whether existing tools such as the serial number are enough (WindEurope, Cefic and EuCIA, 2020; WindEurope, 2020b).

According to WindEurope, Cefic and EuCIA (2020), composite recycling is seen as a cross-sector challenge and not solely a challenge for the wind industry. Actually, the (low) volumes of composite wind blade waste make it challenging to build a recycling business mainly based on this waste stream. All the composite-using sectors must work together to find cost-effective solutions and value chains for the combined volume of composite waste.

Public authorities funding research projects such as the Danish EPA see potential for future business models in the application of recycled carbon fibre in other fields of application, such as construction elements, too. To incentivize universities to go deeper into research on the technical barriers might be a first step in the right direction. Wind park operators suggest that financial support for R&D, whether from the EU or national bodies, would be beneficial to encourage industry, private companies, academia and others to share their knowledge and work together on future circular solutions. It is also important to encourage research in the less profitable area of material research, which tends to be neglected, but provides the opportunity for improving the recycling technology. It could also help to encourage collaboration with other major users of glass fibre, such as the construction, automotive, and vessel industries, which share the same material EoL issues.

Further, some very relevant challenges with EoL wind turbines are related to the single parts' composition, where a lack of information and standardization hampers the development of a specified treatment process. This was further highlighted by respondents of the online survey in Spain and Germany in particular.

Industry also mentioned an insufficient number of recycling facilities for proper handling the emerging volumes of composite waste streams expected in the coming years.

The understanding of the waste problem and customized solutions would benefit, if disaggregated data on waste from the sector were available, as well as information and labelling obligations regarding the material composition of rotor blades, with format and storage location (manufacturer, operator, authority) as well as competition relevance of the data collected.

To spread the application of design for recycling approaches in the industry, producers see a possible use for sector-specific guidelines, which build on the general guideline of ISO 140001:2015 for environmental management systems. The wind industry is currently working on a proposal for an international guideline for the dismantling and decommissioning of wind turbines. Also, the option of an update of the Environmental Impact Assessment Directive in order to provide it with information requirements on circularity, reuse and end-of-life management was proposed.

An approach to encourage the reuse of functioning parts of EoL wind turbines is to impose the obligation for EoL management on the producers, which will prompt them to minimize the cost intensive waste disposal. A barrier that hampers the effect of this legal measure is the “gap” in practice, where the entities that collect the waste are not the ones that brought them onto the market. In addition, the long service lives of rotor blades are an obstacle to an individual product responsibility.

3.3.5 Conclusions

As laid out in this chapter, there are several challenges with the waste streams in the field of wind energy. While on the one hand there are relevant as well as critical resources in wind turbines (e.g. rare earths, copper), on the other hand there are materials that are not easy to recycle (e.g. carbon fibre reinforced plastics). As the waste stream emerges, the need for recycling grows to recover especially the critical resources. However, without a proper treatment method it is hard to recycle the wind turbine as a whole. The size of the blades and the difficult logistics are challenges encountered during deconstruction and recycling.

Since producers only see limited options in terms of design for recycling, the need for a proper recycling technology is even more important. Reuse is already done for certain parts and may be an option for the blades, but not in large scale for the current generation, as regulations would be needed to make it possible (e.g. standards for certain parts of the blade to make it fit into other windmills). The process of increasing durability and thus the lifetime is a business model that already exists. The replacement of parts of the windmill is part of this process (e.g. gearboxes). Regulation is still largely missing as the wind energy is not as closely monitored as the batteries sector. This may be blamed on the longer lifetime, but still is a problem for the waste stream. Although further regulation for good management of the waste streams might be helpful, the main barriers with which producers are confronted are of an economic (in terms of secondary materials from recycling being financially viable) and technological nature (in terms of developing appropriate recycling processes). In addition, wind park operators stressed that insights into potential levels of demand are not yet available from relevant industries for the secondary materials arising from blades, whereas some producers emphasized that the current low level of demand is insufficient to warrant the pursuit of greater quantities of recycled material. Therefore, policy options could be to eradicate unwanted developments e.g. by banning landfilling or other disposal methods and extending producer responsibility. Additionally, complementary pull strategies are needed like setting targets for collection and recycling of certain materials, supporting R&D in this field or incentivizing circular approaches.

4 Potential side effects related to the emerging waste streams of energy transition technologies

Emerging waste streams may provide both challenges and opportunities as analysed above for the fields of photovoltaics, batteries for energy storage and electromobility as well as wind turbines. While opportunities are mostly tied to the fact that some of these waste streams represent a potential source of (partly critical) secondary raw materials and subsequently jobs and business opportunities in recycling and attached value chains, challenges might arise in collection and transport logistics, as well as in waste handling due to safety risks and an inappropriate recycling infrastructure. In case of an unsound management of (hazardous waste) components, this could result in potentially negative impacts on the environment or human health.

Unfortunately, such unsound management cannot be ruled out for many waste streams. Amongst others, collection rates for many relevant waste streams such as waste electrical and electronic equipment, waste batteries and end-of-life vehicles are unsatisfactory, which means that substantial amounts of these wastes are not managed as foreseen. Various studies on the whereabouts of such waste types report about mismanagement in the EU which is also linked to export practices and recycling/disposal outside the EU.

Within the EU, problems are mostly associated with consumer products not collected separately, e.g. disposed together with other municipal solid waste. For equipment shipped to other world regions such as West Africa, Asia, Eastern Europe or the Middle East, challenges lie in the fact that end-of-life management is often being carried out in quite a crude manner non-compliant with European standards.

In general, there are various drivers for exports of used goods and installations, mainly:

- High demand for second-hand machinery and equipment outside EU (pull factor)
- Evasion of treatment and disposal cost in the EU through illegal export (push factor)

While the exportation of functioning equipment for reuse is widely legal (presupposing it is done in line with the applicable technical guidelines under the Basel Convention[10]), the second driver is clearly illegal and increasingly targeted by customs and environmental authorities inside and outside the EU.

The export of used equipment is also gaining importance for emerging product groups relevant for the energy transition. This is particularly stimulated by efforts supporting the electrification of rural households in developing countries – and especially Africa: For example, various initiatives supported by development organizations and related donors support off-grid solutions in Sub-Sahara Africa and consider the use of second-hand batteries from industrialized countries. While such funded initiatives are very careful regarding safety and quality aspects of equipment and batteries, these trends are likely to be taken up also by other players, and may even sooner or later follow the logic of the free market where a locally high demand for affordable equipment is saturated by used equipment from other world regions. These trends can already be anticipated for lithium-ion batteries; however, it is possible that they might also affect other segments such as photovoltaics or wind turbines.

10 http://www.basel.int/Portals/4/download.aspx?d=UNEP-CHW.14-7-Add.6-Rev.1.English.pdf

Figure 4-1: Projects supporting energy-access in developing countries increasingly consider the use of high-quality second-hand equipment

Source: Oeko-Institut e.V.

An export facilitating the reuse of used equipment is not necessarily a negative development with a view to circularity principles, however, it will occur only in those cases where end-of-life issues and a sound recycling of (critical) raw materials and/or hazardous substances are still relatively underdeveloped.

A business case (push factor) for the export of used equipment outside Europe might arise in those cases where the end-of-life management of the waste streams in Europe is substantial and exceeds shipment costs for used equipment to non-EU countries with no stringent enforcement of environmental regulations, i.e. this would be a (potentially illegal) externalization of disposal costs. This shall be exemplified in the following for the waste stream of lithium-ion batteries from electric vehicles or energy storage systems.

On the on hand, there are push factors providing incentives for exporting used electric vehicles and/or energy storage systems containing LIBs before their end of life to non-EU countries to avoid costs for battery recycling and disposal in the EU:

- For electric vehicles, the exchange of an ageing LIB after about 10 years would be costly, in some cases, the costs might even exceed the residual value of the car.
- Currently, the net scrap value of non-electric cars at their end of life is positive (about € 300); for electric vehicles, however, the cost factor will probably become negative at the end of life, i.e. recyclers will charge recycling fees from the suppliers to cover the costs for recycling and disposal of the lithium-ion battery including the necessary safety measures like special transport boxes with inbuilt safety measures to avoid thermal runaways (see section 3.2.2).
- Furthermore, the recycling of lithium-ion batteries is currently not profitable when solely considering the recovery of embedded raw materials, i.e. this is no business case: the share of cobalt (which might make the recycling profitable) is decreasing in new batteries; LFP-containing cells, used in buses and stationary storage systems are even less valuable, i.e. their recovered value will not cover recycling and additional costs for disposal. Waste managers might aim at reducing operating costs by undermining best-practice approaches for hazardous waste treatment in Europe through exports of still functioning LIBs for reuse in non-European countries.

On the other hand, there are increasingly pull factors from non-EU countries reinforcing the need to increase imports of used electric vehicles and energy storage systems from Europe:

- In many developing countries rural electrification still takes place, enabling households to gain access to electricity. This also includes solar home systems (SHS) in combination with battery storage systems, for example. Solar home systems, if subsidized e.g. by World Bank and KfW, are usually well-designed units that follow certain quality standards for all components. Over the last years, declining purchasing prices for solar panels together with the consumer demand for charging mobile phones and using electric lighting and possibly also TV, created strong incentives to purchase own SHS, even without government support. In contrast to subsidized SHS, these consumer SHS are mostly very rudimentary in terms of quality as they often lack suitable charge controllers and quality standards for PV panels and batteries. Regarding battery technologies in combination with SHS, lead-acid batteries are still the most commonly used type. Lithium-ion batteries are often still too expensive for the consumer markets in developing countries and are therefore only used in some of the subsidized systems financed by the World Bank because of their superior lifetime compared to lead-acid batteries. However, due to the trend of steadily declining purchasing prices for Li-ion cells, Li-ion batteries are increasingly attractive for the SHS consumer market in developing countries which might also include used, still functioning battery systems imported from Europe.
- Many urban city centres in developing countries are struggling with severe air quality problems related to vehicle emissions as one of the most important sources of air pollution; at the same time, most countries have signed and ratified the Paris Agreement and have to communicate their nationally determined contributions (NDCs), i.e. actions they are required to take to reduce their greenhouse gas emissions in order to reach the goals of the Paris Agreement. In several countries, electromobility and renewable energy systems are amongst these actions (UNEP, 2018).
- Some non-EU countries have been providing incentives for the import of used hybrid electric and electric vehicles and this furthered a switch to cleaner fleets. Some countries which had banned the import of all used vehicles are now permitting used hybrid electric vehicles or all-electric vehicles (UNEP, 2020). For example, Barbados levies an environmental tax on the arrival of used vehicles, however, hybrid and electric vehicles being incentivized by reducing duties on their import; furthermore, there is growing campaigning for further duty reductions on electric vehicles with an amendment tariff issued in 2017. In Egypt, all electric used vehicles are exempt from tax. Lebanon approved the reduction of road-usage and excise taxes to zero per cent for electric vehicles in its 2018 budget. Costa Rica incentivizes the import of electric and hybrid vehicles. Also, the Jordan government has waived import duties on electric vehicles and on parts used for charging electric vehicles (UNEP, 2018; UNEP, 2020).

A huge market for the cross-border trade of used vehicles has already been established within and outside the EU. The major destinations for used vehicles from the EU are West and North Africa. In Africa, more than 60 % of vehicles added to their fleet annually are imported used vehicles (UNEP, 2020). Due to stricter import standards of non-EU countries for cleaner vehicles[11] and financial incentives for the import of used hybrid electric and electric vehicles, as well as because of the high level of costs for the recycling and disposal of battery-driven electric vehicles in the EU, the cross-border trade of used vehicles outside the EU will sooner or later also include the trade of used electric vehicles. In 2018, exports of electric vehicles from the EU were targeted to Ukraine, Moldova,

[11] For example, fifteen countries in West Africa (ECOWAS, Economic Commission of West African States) have jointly decided on new standards for clean fuels and vehicles. Since January 2021, all imported and newly registered vehicles would need to meet Euro 4/IV vehicles emission standards, and the age limit for importing vehicles is five years for light-duty vehicles and ten years for heavy-duty vehicles. Similar initiatives are under development in East Africa and Southern Africa. (NL ILT, 2020)

Jordan, New Zealand, Belarus, the Russian Federation, Egypt, Serbia, Albania, and Comoros (UNEP, 2020).

Whereas the EU usually has best-practice approaches for hazardous waste treatment, the export of used lithium-ion batteries, either in electric vehicles and/or as energy storage systems, to non-OECD countries with no stringent enforcement of environmental regulations may have severe environ mental impacts in those countries:

- Whereas specific safety requirements are foreseen for the transport of lithium-ion batteries, this might not be necessary if the export goods to non-OECD countries were classified as electric vehicles or energy storage systems; however, this might still imply transport risks (thermal run-away) of the LIBs.
- In contrast to lead acid batteries that are providing a net value for recyclers, i.e. being collected and recycled, the waste management of lithium-ion batteries is only of limited value, high costs being involved. This bears the risk that lithium-ion batteries will not be collected and recycled at the end of their life at all but will rather be disposed of with municipal waste or will be landfilled.
- Although lithium-ion batteries have a lower toxicity compared to lead acid batteries, all hazardous substances (e.g. harmful, corrosive hydrofluoric acid) will end up in the environment if the whole LIB will be improperly disposed of.
- Further, if LIBs are improperly disposed of, there is also the risk of thermal run-aways during transport, storage, and in landfills.

The distinction between end-of-life vehicles from used vehicles for export can be difficult and is important for identifying illegal exports of ELVs to non-OECD countries. In contrast to the export of ELVs, the export of used vehicles from EU is not prohibited. Currently, the European Commission is revising the Directive 2000/53/EC on End-of-Life Vehicles and assessing options to review the regulation (EC) No 1013/2006 on shipments of waste (Waste Shipment Regulation - WSR). There is a need for a clear definition of the criteria under which a used vehicle can be distinguished from waste. The current Correspondents' Guidelines No 9 to the Waste Shipment Regulation (to distinguish ELVs and used vehicles when being exported)[12] are not legally binding.

The (potentially illegal) export of used battery electric vehicles to non-OECD countries for externalizing high costs for the recycling and disposal of lithium-ion batteries in Europe, is not currently the focus of these legislations. Additional requirements would be needed for the export of used lithium-ion batteries in electric vehicles such as quality standards ("at least as good as new" regarding quality, i.e. residual capacity or lifetime), appropriate packaging and/or safety measures for transports, labelling of hazardous substances etc. In some countries, lithium-ion is already classified as hazardous waste, and transport must be notified when crossing borders.

At the same time, policy instruments, R&D and funding to facilitate environmentally sound battery collection and recycling and additional circularity approaches of lithium-ion batteries waste streams emerging from electric vehicles in Europe are necessary and should be encouraged to avoid those side effects of externalising environmental impacts as outlined above.

[12] https://ec.europa.eu/environment/waste/shipments/pdf/correspondents_guidelines9_en.pdf

5 Conclusions and recommendations

This chapter presents a series of policy options that could be implemented in the future to move towards the proper management and increased circularity of emerging waste streams arising from the renewable energy technologies discussed in this report, namely photovoltaics, wind energy and lithium-ion batteries for energy storage and electromobility.

5.1 Guiding principles for policy implementation

This section highlights several **guiding principles** that should be applied to enable the sound implementation of any of the policy options described in the next section.

Firstly, it is important to **address existing data gaps**, to provide both a solid foundation for good policymaking, and a firm baseline against which to assess the policies' impact in the future. For example, data is currently limited, e.g. on the quantities of the emerging waste streams produced, how the waste is currently handled, and the amount and type of hazardous substances contained in the waste streams, the volumes and shares of reuse inside and outside of Europe. One way to fill these data gaps would be to introduce requirements for manufacturers and/or technology operators to report the specific types of data sought. This could be done in various ways, for example through legislation (most likely at the EU level to ensure coherence of reporting), through extended producer responsibility schemes (if these are introduced for any of the emerging waste streams) or by encouraging industry to report on a voluntary basis.

Secondly, the policies implemented should **respect the order of the waste hierarchy**, as defined in the EU's Waste Framework Directive (2008/98/EC). This is important as the hierarchy places priority on the use of waste management approaches that make the strongest contribution to circularity (prevention, then preparing for reuse, then recycling, with recovery and disposal as the least-preferred options). Following this priority order of waste management should therefore ensure that the greatest possible level of circularity is achieved by the management of the emerging waste streams of today's applied or installed technologies on the one hand, and by applying design principles to increase circularity of those technologies entering the market in future on the other hand.

Thirdly, an **ex-ante assessment** should be carried out on each policy prior to implementation. This would allow for the identification of likely environmental benefits, any potential unintended harmful environmental impacts, financial viability, cost implications, infrastructure/logistical needs and administrative capacity required for implementation, thus ensuring that the potential impacts of the policy are known, which should lead to the most appropriate policy design.

Finally, policies should be introduced that ensure – besides proper management of hazardous substances in the waste streams – the **capture of the most appropriate materials**, for example scarce or rare materials, or those with a high value that are difficult to recover and/or not captured by existing waste management practices. This would have the benefit of ensuring both that the best use is made of resources, and also that the monetary value of those resources is not lost to waste disposal.

5.2 Policy options for the emerging waste streams in the fields of photovoltaics, batteries and wind energy

There are many different policy approaches that can be taken to move towards the proper management and increased circularity of the emerging waste streams discussed in this report. These range from hard legislative measures to softer voluntary measures. Table 5-1 provides a general overview of available policy options or approaches.

Table 5-1: General overview of available policy options and approaches

Policy options and approaches	Further details
Mandatory targets	Set targets for specific products, components, materials or types of waste. Targets could relate to various aspects, including material composition, recycling or collection. Targets may be set by legislation (as is the case in the EU WEEE and ELV Directives), through EPR (with each EPR scheme setting specific targets) or on a voluntary basis (with industry making its own commitments).
Ban on certain waste operations	Place a formal ban on the use of specific waste operations for specific products, components, materials or types of waste. This should be done through legislation to enable a coherent approach and a level playing field. The initial focus could be on banning landfilling or other types of disposal, to drive management of emerging waste streams higher up the waste hierarchy towards greater circularity.
End-of-waste and waste treatment criteria	Specify end-of-waste criteria and requirements for the treatment of emerging waste streams. This would facilitate recycling and the supply of secondary resources, thereby increasing circularity. This could most effectively be done at EU level.
Ecodesign criteria	Introduce ecodesign criteria for specific products or components. This could be done effectively via the development of product-specific regulations, for example in the context of the EU Ecodesign Directive or other regulatory framework, to ensure common criteria and a level playing field.
Formal design standards or industry-led design guidelines	Develop design standards for specific products or components to encourage design that maximises the potential for circularity. This could include elements related to materials used, reducing hazardous content, repairability, ease of disassembly etc. Standards could either be formalised, e.g. through national or international standards organisations (ISO, EN etc.) or developed by industry in the form of recommended guidelines to be followed by manufacturers.
Extended producer responsibility (EPR)	Introduce EPR for specific products, components or materials. This could be led by new or amended EU level legislation (which would help to ensure some coherence and a more level playing field), or industry could be encouraged to develop EPR on a voluntary basis. EPR would help to finance the costs of proper waste management.

Policy options and approaches	Further details
Voluntary industry commitments or initiatives	Develop voluntary industry commitments or initiatives. Achievements should be monitored and reported. Examples include the pledges in the context of the European Strategy for Plastics in the Circular Economy[13] or Operation Clean Sweep which aims to achieve zero loss of plastic pellets[14].
Fiscal incentives	Provide fiscal incentives for measures that lead to greater circularity. Examples could include product or material taxes, tax cuts for recyclable or repairable products, reduced VAT for repair services etc.
Financial support	Provide financial support for measures that lead to greater circularity. Examples could include grants or loans for transport, storage and treatment infrastructure.
Support for research & development (R&D)	Provide financial support such as loans or grants for R&D on measures that would lead to greater circularity, such as product design (including design innovation), repair options, recycling technologies, infrastructure, development of markets for recycled materials etc. This would also facilitate future planning for waste, since many technologies have lifespans of many years and waste has not always been considered during their design.
Collaborative approaches	Undertake collaborative work on circularity measures, for example collaboration between actors along the length of material or product value chains, between different industry sectors, or between industry and academia.
Training	Technical training could be provided to individuals involved with the relevant technologies, to teach them how to work towards greater circularity. This could include training on repair, maintenance and disassembly of the technologies, health and safety etc.

The following Table 5-2 gives examples of the policy options and approaches where these have been identified, being of specific relevance to the emerging waste streams analysed in this study.

13 https://circulareconomy.europa.eu/platform/en/commitments/pledges
14 https://www.opcleansweep.org/

Table 5-2: Policy options and their relevance to the analysed emerging waste streams

Policy options	Photovoltaics	Batteries / energy storage	Wind energy
Recycling targets	WEEE is applicable but without material-specific recycling targets for PV waste streams. Material-specific recycling targets would help to recycle more than glass and aluminium.	The proposal for a new EU Battery Regulation (December 2020) includes proposals for battery recycling targets and recycled content quota.	Legally determined recycling targets (so far only in France), recycling targets for specific metals / critical raw materials, or quotas for recycled content could stimulate recycling and secondary material markets.
Ban on certain waste operations	The thermal treatment, leading to a loss of materials, is an issue which could be tackled with recycling targets or a ban.	The current EU Battery Directive and the proposal for a new EU Battery Regulation (December 2020) include recycling targets, i.e. also ban of certain waste operations.	A European ban on landfilling of turbine blades is currently under consideration as voluntary initiative by industry and might be supported by a legal ban. Further discussed options of landfilling at sea should be carefully assessed regarding potential environ-mental impacts and legally banned if necessary.
End-of-waste and waste treatment criteria	End-of-waste criteria would help to facilitate recycling as metal containing filter cakes could be classified as products (like metal ores) and therefore can be shipped to a refinery with much lower effort. Attention should be paid to the potential risk of externalising high recycling costs in Europe by exportation of aged photovoltaic panels to non-EU countries with no stringent enforcement of environmental regulations.	The proposal for a new EU Battery Regulation (December 2020) includes proposals regarding data availability (‘battery passport’) facilitating reuse, repurposing or remanufacturing, and recycling Attention should be paid to the potential risk of externalising high recycling costs in Europe by exportation of aged batteries in near end-of-life vehicles ELV to non-EU countries with no stringent enforcement of environmental regulations; the current revisions of the ELV Directive and the Waste Shipment Regulation could address the challenges of battery electric vehicles.	Composite waste from turbine blades is often classified as plastic waste from construction and demolition, which may limit efficient separate collection and sorting. Attention should be paid to the potential risk of externalising high recycling costs in Europe by exportation of aged wind turbines to non-EU countries with no stringent enforcement of environmental regulations.
Ecodesign criteria	Mandatory requirements (incl. durability, repairability and design for recycling) are currently under development through the EU Ecodesign regulatory framework.	The proposal for a new EU Battery Regulation (December 2020) includes proposals for the battery design (including requirements on durability, repairability, design for recycling).	Regulatory ecodesign requirements are not in place but could facilitate future disassembly, remanufacturing or recycling of wind turbines.

Policy options	Photovoltaics	Batteries / energy storage	Wind energy
Formal design standards or industry-led design guidelines	Standardised PV panel design would facilitate reuse and recycling. Hazardous substances (e.g. cadmium, arsenic, lead, antimony, polyvinyl fluoride and polyvinylidene fluoride) pose a challenge to recycling.	New or revised standards expected after new EU Battery Regulation has been adopted. As different cell types of different types of electric vehicles each need different types of costly safety boxes, standardisation could facilitate reducing costs for transport and storage logistics.	Recent standards / standardisation activities on sustainable dismantling, disassembly, recycling and recovery of wind turbines and lifetime extension of wind turbines. Standards on repairability and modular/upgradeable design with components being more easily accessible for repair/replacement would be beneficial. Current lack of information and standardization on component composition hampers the development of a specified treatment process. Diversity in size and shape of blades might hamper easy reuse.
Extended producer responsibility	Not currently applied in the PV sector.	EPR schemes are already mandatory in the EU for batteries.	Not currently applied in the wind energy sector; industry points to several voluntary initiatives for increasing circularity.
Voluntary industry commitments or initiatives	Voluntary take-back schemes by industry as well as mandatory collection targets coming from WEEE.	Collection and take-back schemes for batteries are implemented at national or cross-national, but not yet at EU level.	Voluntary take-back schemes by industry.
Financial incentives / Financial support / Support for R&D	A carbon tax could be considered. Delamination and separation of components is a particular issue. Mobile recycling systems could be investigated.	Besides technology innovations research, design for recycling approaches are increasingly included in R&D. Transport and storage infrastructure, as well as recycling technologies and recycling capacity are currently lacking and need a swift build-up for managing the huge waste stream expected in the coming years.	Various research projects on the potential to recycle turbine blades (carbon fibre, glass fibre and composite material) and alternative material design. Need for incentivising utilising the recycled composite materials. Incentives or financial support for a swift build-up of wind turbine recycling infrastructure for the huge waste stream expected in coming years.
Collaborative approaches	Stakeholder dialogues during preparatory study for EU Ecodesign and Energy labelling measures.	Several examples of collaborative approaches and stakeholder dialogues, e.g. European Battery Alliance, Global Battery Alliance, stakeholder dialogues during revision of EU battery directive, cross-sectoral research projects etc.	Collaboration with other significant suppliers / users of composites and / or glass fibre to find common, cost-effective solutions. E-platforms used to trade existing turbine blades for reuse.
Training	There is a lack of highly qualified, certified technicians to facilitate maintenance and repairs of PV modules.		

For photovoltaics, the collection and treatment of PV modules that are not falling under EPR should be tackled. Material-specific recycling targets should be put up to recover critical materials. The infrastructure for recycling still needs to be further built up and processes to recycle e.g. silicon need further development, so research should be funded. New regulations like for recycling targets or the ban of certain treatment methods as the thermal treatment would be useful to improve the chances of reuse and to increase recycling. The standardization of the panels may be an option to establish design for recycling, facilitate reuse and the recycling of the panels at the end of their life. A treatment standard, a harmonized classification of the waste as well as end-of-waste criteria could also help in recycling PV modules. Additionally, more information can be put on the panels (e.g. by a tag) to give recyclers more information, thus making recycling easier, because the different types of PV cells could be sorted before treatment. New financing models to recover the costs of collection, treatment, recovery, recycling and disposal seem to be necessary such as producer-financed or consumer-financed models (upfront or at end of life) or a carbon tax.

With regard to lithium-ion batteries for energy storage and electromobility, apart from the European Battery regulation, the most important policy options should be targeted at a swift setting up of the battery waste logistics and recycling infrastructure. The amount of batteries put on the market is rising, the new battery cell production in the EU is connected to large amounts of production waste and the retraction of faulty batteries leads to a major increase of battery related waste. If the EU is not able to build up recycling capacities fast enough, this waste has to be stored until capacities are sufficient, or otherwise might be shipped to Asia. Both possibilities are connected to safety risks and high storage and transportation costs, respectively. The latter also leads to a loss of valuable critical raw materials connected to the export of these battery cells necessary for the battery industry in the EU.

In the field of wind energy, most OEMs and recycling facilities are based in Europe. With regard to the emerging waste streams, however, there is no or only limited legislation regulating the take-back and treatment of composite or blade waste, neither at EU nor at national levels. Moreover, no extended producer responsibility scheme is applied. Industry has started own initiatives such as take-back schemes, research on recycling technologies for the composite materials, platforms for the trade of reused turbines, or initiating a voluntary initiative for a ban of landfilling waste blades. Legally determined recycling targets (so far only adopted in France), recycling targets for specific metals / critical raw materials, or quotas for recycled content could further stimulate recycling and secondary material markets. Besides further R&D activities in the field of recycling technologies for composite carbon fibre materials, especially incentives or financial support for a swift building up of the wind turbine recycling infrastructure would be necessary to manage the huge waste stream expected in the coming years.

Finally, for all three waste streams, attention should be paid to the potential risk of externalising the high costs for recycling in Europe by exportation of aged, near end-of-life batteries or electric vehicles, photovoltaic systems or wind turbines to non-EU countries with no stringent enforcement of environmental regulations; for batteries, the current revisions of the ELV Directive and the Waste Shipment Regulation could address the challenges of battery electric vehicles.

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Annex

Annex I. Long list – summary profiles of analysed technologies

The information for selected technologies is classified according to the following colour scheme:

- Time horizon for emerging waste streams: current | next 5 to 10 years | > 10 years or still unclear
- Relevance of waste stream (quantity/volume): low relevance | medium relevance | high relevance
- Waste related issues: low relevance | medium relevance | high relevance

The colour code offers at first glance a classification of the importance of different technologies with the aim to prioritize those technologies and identify key waste streams to be selected and analysed in further detail (“short list”, see section 3).

Technology fields	Main technologies (for illustration)	Time horizon for waste streams emerging	Relevance (quantity / volume) of the waste stream	Waste related issues		Literature sources
Relevance Ranking: Green: Low - to be excluded from short list Yellow: medium - to be discussed; **Red**: high - recommended for short list		Relevance sorted by the following colour code: current | next 5 to 10 years | > 10 years or still unclear	Relevance sorted by the following colour code: low relevance | medium relevance | high relevance	**Chances** (mainly valuable raw materials) Relevance sorted by the following colour code:: low relevance | medium relevance | high relevance	**Challenges** (e.g. hazardous substances, missing infrastructure; difficult waste transport logistics, no (economic) recycling procedures in place, missing mechanisms for separate collection, treatment capacity and facilities,recycling technologies, waste recycling targets, ...) Relevance sorted by the following colour code:: low relevance | medium relevance | high relevance	
Bioenergy	•Biochemical conversion: Anaerobic fermentation to ethanol / biogas •Thermochemical conversion: combustion gasification and hydrothermal processes •Physicochemical conversion: physical preparation, catalytic conversion	remained relatively low, there was a particularly rapid expansion in the output of biogas, liquid biofuels , which accounted respectively for a 7.4 % and 6.7 % share of the EU-28 renewable energy produced in 2017. (EUROSTAT 2019) The overall potential for increased biogas production from waste and residues remains high and, if fully exploited, could lead to biogas and biomethane production levels in 2030 of 2.7–3.7% of the EU's energy consumption in 2030. (EC 2020; CE Delft 2017). In the EU-28 wood and other solid biofuels accounted, as the most important source, for 42% of the renewable energy production in 2017 (EUROSTAT 2019)	There were more than 17 000 biogas installations and around 450 biomethane installations in the EU in 2015, accounting for more than 8 GW of electricity production. (EC 2018) This is of low relevance regarding the total mass stream, compared to demolition waste.	amounts or newly critical substances Further Details on Biogas Plant Material (Hartmann 2006, Chapter 2.6.4) ´- Reactor: Fermenters of concrete or steel. Stirring and heating units are situated inside. ´- Management and technology building: concrete, bricks, and corrugated sheet metal ´- Weighbridge: reinforced concrete and steel. ´- Storage vessel & reactor vessel: steel and concrete, two stirrers. ´- Heat exchanger: Several designs are possible, here	Low relevance	´- CE Delft 2017, Eclareon, Wageningen Research, Optimal use of biogas from waste streams. An assessment of the potential of biogas from digestion in the EU beyond 2020; ´- EC 2020: Powering a climate-neutral economy: An EU Strategy for Energy System Integration ´- EC 2018: "A Clean Planet for allA European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy" https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf ´- K. Hartmann 2006 Dissertation "Life-cycle-assessment of industrial scale biogas plants" https://ediss.uni-goettingen.de/bitstream/handle/11858/00-1735-0000-0006-AEBF-9/hartmann.pdf?sequence=1
Photovoltaics	•Solar cells and modules –Crystalline silicon (c-Si) (mono-c, multi-c, thin c-Si solar) and modules –Stacking cells on c-Si and modules Technology development –Thin-film modules made of CuIn(Ga)Se (CIGS), CdTe; c-Si, GaAs –Multiple concentrator solar cells & modules –Organic solar cells and modules •PV manufacturing and systems engineering and production equipment •Systems engineering –PV inverter technology –Network connection and network management •Related technologies –Building-integrated photovoltaics	Although their levels of production remained relatively low, there was a particularly rapid expansion in the output of solar energy, which accounted for a 6.4 % share of the EU-28 renewable energy produced in 2017. (EUROSTAT 2019) Outlook: Depending on the scenario, PV will grow from around 100GWe in 2010 to almost 2000GWe 2050 (JRC 2018)	High relevance 8.1 million tons of PV modules are currently installed in Europe (source: PV Cycle). The BIFA Environment Institute assumes approx. 10,000 tons of end-of-life (EoL) modules in 2017. In 2022-2023, 100,000 t/a are expected with the tendency further increasing. (Fraunhofer)	Aluminum frames (10-15 % of the weight) and the cover glass (70-75% of the weight) are easily recycled. Per ton of PV module scrap there is (Source Fraunhofer) * Silver 0,5-1 kg * Copper 5-10 kg * Tin 0,5-1 kg * Silicon 25-50 kg * Aluminium (Frame) 100-150 kg * Glass 700-750 kg * Plastic Remainder	It is possible to disassemble and delaminate modules systematically, but very time- and cost-intensive and thus hardly suited for an industrial process. From frame and glass separated remaining portion of silicon, silver contacts, tin, and heavy metal containing solder (lead) is usually burned together with the plastic foil. (Fraunhofer ISE) Hazardous substances in PVs are cadmium, arsenic, lead, antimony, polyvinyl fluoride and polyvinylidene fluoride etc. (Fraunhofer 2017) Further infrastructure needs to be built to handle the emerging waste stream.	´- EUROSTAT (2019): "Energy, transport and environment statistics - 2019 edition" ´- Fraunhofer ISE https://www.ise.fraunhofer.de/en/research-projects/eol.html ´- JRC 2018: Deployment Scenarios for Low Carbon Energy Technologies - Deliverable D4.7 for the Low Carbon Energy Observatory(LCEO)

Technology fields	Main technologies (for illustration)	Time horizon for waste streams emerging	Relevance (quantity / volume) of the waste stream	Waste related issues		Literature sources
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Solar Heating and Cooling	•Solar thermal heating •Solar thermal cooling •Photovoltaic-Thermal (PVT) collector (solar heat + solar electricity)	Data for Europe (EU 28, Albania, Northern Macedonia, Norway, Russia, Switzerland, Turkey) (SHC 2019): ´- From the early 1980s up to 2016, the large-scale (>350 kWth, 500 m²) plant market was almost exclusively concentrated in Europe. Then the concentration of newly installed systems has shifted outside of Europe. ´- Market for glazed water collectors decreased steadily since 2008 down to 2.9 GWth (2018). ´- The market for PVT collectors had a growth rate of +14% (2017-2019) 25 years lifetime (Greening 2014)	Following Data by SHC for Europe (EU 28, Albania, Northern Macedonia, Norway, Russia, Switzerland, Turkey): ´- Europe has a collector area of ~2.5 mio. m² (excl. concentrating solar thermal systems and PVT), of which 3% are Unglazed water collectors, 97% glazed water collectors (81% flat plate collectors and 15% evacuated tube collectors with 54,867 MWth capacity ´- 675,427 m² of PVT installed (2019) Waste amounts: see "chances" for material per m²	Materials kg per m² gross area: (Greening 2014) Aluminium: 3.93 kg (90% recycled; 10% landfilled) Copper: 2.82 kg (41% recycled; 59% landfilled) Steel: 36kg (61.7% recycled; 38.3% landfilled Plastics: 100% landfilled Propylene glycol: 100% to wastewater treatment	Over 80% in domestic use. (SHC 2019) No centralized collection. Problem: see "Photovoltaics" above	´- Greening 2014: B. Greening & A. Azapagic "Domestic solar thermal water heating" in "Renewable Energy" 63 (2014) 23-36 ´- SHC: International Energy Agency; Solar Heating & Cooling Programme. "Solar Heat Worldwide 2020" https://www.iea-shc.org/solar-heat-worldwide
Solar Thermal Power Plants	•Parabolic trough or tower, Molten Salt as heat transfer and storage medium •Hybrid biomass cogeneration plants for fuel saving, parabolic trough with thermal oil or direct evaporation	Low relevance: Since 2008 declining trend in newly installed Capacity in EU-28. 2015 newly installed capacity of 1.9 GWth (approximately 2.7 million m²) is a decrease in newly installed capacity of -6,6% in comparison with 2014 and a increase of 4.4% on the total installed capacity by the end of the previous year. Plant lifetime of 25 years expected (ESMAP 2011)	Total installed of 33.3 GWth (47.5 mio m²) in operation. (ESTIF 2016) Installed Capacity equals 666 plants of 50 MW. Materials see below (calculated) In a parabolic trough plant 50 MW, 7h storage (total 666 Plants) Materials needed: (ESMAP 2011) Steel 10,000–15,000 tons (6,6 Mio. t), Glass 6,000 tons (4 Mio. t), Storage Medium (Salt) 25,000–30,000 tons (20 Mio. t), Concrete 10,000 tons (6,6 Mio. t), Insulation Material 1000 tons (0,6 Mio. t), Copper 300 tons, 650 tonnes thermal oil	´- Parabolic trough systems consist of trough solar collector arrays and a conventional power block with steam turbine and generator, heat transfer fluid synthetic thermo oil ´- Low relevance: materials as concrete, steel, and glass means the possibility of their recycling which is common practice (Bosnjakovic 2019) ´- Copper in mirrors is of high interest (expensive). 300 tonnes in a 50 MW plant ´- silver layer on mirrors	For occuring wastes, treatment facilities are in place (Bosnjakovic 2019) ´- non-hazardous solid wastes: oily rags, empty containers, metal and machine parts, waste electrical materials ´- Hazardous waste includes waste HTF and solvents, waste oil and oil filters, cleaning rags etc. Toxic materials as organic compounds (biphenyls and biphenyl ether) are being replaced with water or molten salts. main materials used: steel, glass, and concrete (> 95% recycling rate) and inert material (road building /land-filled)	´- ESTIF (2016): "Solar Thermal Markets in Europe -Trends and Market Statistics 2015" (European Solar Thermal Industry Federation) ´- Mladen BOŠNJAKOVIĆ, Vlado TADIJANOVIĆ (2019): "Environment impact of a concentrated solar power plant" ´- ESMAP 2011: Report "Middle East and North Africa Region Assessment of the Local Manufacturing Potential for Concentrated Solar Power (CSP) Projects" - Chapter 1
Wind Energy (land / marine)	•Synchronous generators •Asynchronous generators •Direct drive •Reluctance generators •HTS generators •Rotor blades •Wiring •Wind mill base	as the second most important source, for 13.8% of the renewable energy production in 2017, with a strongly increasing trend from 6.057.900 toe (2005) to 31.161.800 toe (2017). (EUROSTAT 2019) Outlook: Depending on the scenario, wind installed power increases from	power is currently at about 500 000 t/GW. (JRC 2020b) Combined with the installed capacity in Europe in 2010 (9 918 MW; EWEA 2011), that means the turbines that will be decomissioned in 2030, a waste stream of about 5 million tons is generated, which is highly relevant	There are several (highly) relevant metals in wind tubines like rare earths (Dy, Nd, Pr, Tb), nickel, copper or chromium (JRC 2020b)	turbines is complex, but usual business. The recycling (or waste treatment in case of carbon fibre reinforced plastics) of several components is not realized (on industrial scale), yet (Oliveux 2015). Carbon fibre reinforced plastics cannot be burned, because asbestos	environment statistics - 2019 edition" ´- JRC 2018: Deployment Scenarios for Low Carbon Energy Technologies - Deliverable D4.7 for the Low Carbon Energy Observatory(LCEO) ´- JRC 2020: Towards net-zero emissions in the EU energy system by 2050 https://publications.jrc.ec.europa.eu/repository

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Environmental Heat	•Near-surface geothermal energy and development of air-technology •electric heat pumps and chillers with components refrigerant circuit •compressor technology •gas sorption heat pump technology •Thermoelectric energy conversion •Urban waste heat sources (sewerage, transport systems) •ORC Organic Rankine Cycle	accounted to 5% of the renewable energy production in 2017 (EUROSTAT 2019) The HP sales development shows a consistent growth of 12-13% per year since 2014 (stats.ehpa, European Heat Pump Association). 2030 expected 10-35% replacement of oil and gasboilers in buildings mainly by heat pumps and district heating (JRC 2020) The Lifetime of a HP is assumed to be about 20 years (Greening 2012) In the EU-28 geothermal energy and accounted to 3% of the renewable energy production in 2017, with an increasing trend from 5.309.200 toe (2005) to 6.812.300 toe (2017) (EUROSTAT 2019) Estimates of the future potential of	The sales of HPs in the EU developed from about 800k units (2008) to 1.3 Mio. units in 2018. (stats.ehpa, European Heat Pump Association) Compared to WEEE this is not a relevant amount.	The compressor and housing of heat pumps are made from reinforced steel and the evaporator and condenser from low-alloyed steel. The pipework, electrical cables and expansion valve are all made from copper, with the pipework insulated with a polymer (elastomere) and the cables insulated with PVC (poly-vinylchloride). The heating system structure comprise material input of aluminium, Polystyrene, LDPE, cement and sand and a refrigerant. At the EoL metal components are recycled;	The refrigerant is reused, assuming 20% losses during extraction. Many organisations use heat pump systems containing HFC refrigerants such as R410A, R134a or R407C which are also known as "F gases". F gases are GHGs which will damage the environment if they leak. Low relevance: treatment of refridgerants in place	´- EUROSTAT (2019): "Energy, transport and environment statistics - 2019 edition" ´- Greening (2012): "Domestic heat pumps: Life cycle environmental impacts and potential implications for the UK) ´- JRC 2020: Towards net-zero emissions in the EU energy system by 2050 https://publications.jrc.ec.europa.eu/repository/bitstream/JRC118592/towards_net-zero_emissions_in_the_eu_energy_system_-_insights_from_scenarios_in_line_with_2030_and_2050_ambitions_of_the_european_green_deal_on.pdf
Decentralised power plants (electrolyzers and fuel cells)	•PEM fuel cell •Solid oxide fuel cell •Alkaline water electrolysis •Polymer electrolyte membrane (PEM) electrolysis	Fuel cells are not matured enough, being too expensive at the moment to be scaled up. As they are supposed to last over several years, there is no waste stream to be expected in the next few years. Today, there are only a few electrolyseurs (300) in the EU, mostly in pilot plant scale. Although the market is supposed to grow strongly over the next few years, they will not create a waste stream relevant for 2030. (Hydrogen Strategy EU)	low relevance "the share of hydrogen in Europe's energy mix is projected to grow from the current less than 2% to 13-14% by 2050" (hydrogen strategy EU)	(s. time horizon)	(s. time horizon)	https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf
Electricity transmission and distribution	•Power lines •Transformer stations	Power lines and transformator stations have been there for a long time. Even the increasing grid extension is not extending the waste rapidly, as they power lines are built for 20 to 120 years (depending on many parameters) and, therefore, they are not relevant for this study. (IBEGA 2012)	low relevance	(s. time horizon)	(s. time horizon)	IBEGA 2012: Freileitungen oder Erdkabelleitungen? Eine Metastudie über die Kriterien und Ergebnisse von Untersuchungen zum Netzausbau https://www.db-thueringen.de/servlets/MCRFileNodeServlet/dbt_derivate_00025591/ilm1-2012100129.pdf

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Energy storage (electrical and electrochemical)	•Lithium-based technologies (Li-Ion, Li/Air, Li/S) •Sodium-based technologies (NaS, NaNiCl) •Redox flow technologies (VRF, Fe/Cr, Br/S, V/Br)	research and not expected to be practical before 2030, therefore not relevant for the near future as waste stream (Dühnen 2020) Li/S is a promising technology, but far from being practically applied and is therefore not relevant as waste stream for the near future (Dühnen 2020) Sodium based battery technologies have been on the market since over 30 years, first for electromobility. As they have several challenges, especially the necessary high temperature >250°C, they nearly vanished from the mobility market and only play a minor role for stationary storage (exeption: Japan), which is not expected to increase over the next 10 years, they are not a relevant	The amount of stationary storage units sold so far lies in the range of 50,000-100,000 for Europe, mostly below 10 kWh of energy storage capability. (Fraunhofer 2015) Li-Ion batteries are the only battery technology relevant for this study used in larger scale for stationary electrochemical energy storage as home storage or grid stabilization.	Li-Ion: High amount of Co and Ni in NMC containing batteries are valuable enough to be able to make battery recycling profitable, when conducted at large scale. (Dühnen 2020) Many companies and start-ups have realized the problem and are working on solutions.(Dühnen 2020)	contain hazardous substances (electrolyte, incl. Salt and organic solvent, toxic metals). They are easily flammable, when wrongly handled, especially, when not discharged below 30% SOC. LFP containing cells are not valuable enough for recycling, additional costs for disposal necessary. Li is not yet valueable enough to make a large impact, as the amount/concentration in a battery cell is comparably small. Copper (and aluminum, often going to scrap) is not valuable enough to cover the costs. Infrastructure for recycling is still missing (only pilot plants available, e.g. in Belgium by Umicore with 7000 t per year, which is enough for today's market). Especially for transporting and	"Gigafactories für Lithium-Ionen-Zellen–Rohstoffbedarfe für die globale Elektromobilität bis 2050: Kurzstudie erstellt im Rahmen des BMBF-Verbundprojektes Fab4Lib-Erforschung von Maßnahmen zur Steigerung der Material-und Prozesseffizienz in der Lithium-Ionen-Batteriezellproduktion über die gesamte Wertschöpfungskette." (2019). Dühnen, Simon, et al. "Toward Green Battery Cells: Perspective on Materials and Technologies." Small Methods (2020): 2000039. Fraunhofer_Gesamt-Roadmap Lithium-Ionen-Batterien 2030 Bulach et al, LfU Bayern, 2020, Vergleichende Analyse von Stromspeichern - Anwendungsszenarien, ökonomische und ökologische Bewertung, Endbericht und Factsheets
Energy storage (thermal, thermochemical and mechanical)	•Thermal energy storage (TES) like water storage tanks (buffer storage tanks, large storage tanks for district heating), high temperature salt storage tanks, low temperature storage tanks (ice storage) •Central power storage (mechanical and thermal) like heat storage, adiabatic compressed air energy storage (ACAES), adiabatic liquid air energy storage (ALAES), pumped storage tanks, flywheel accumulators	Market development decreasing. See "Solar Thermal Power Plants"; Plant lifetime of 25 years expected (ESMAP 2011)	Materials needed: See "Solar Thermal Power Plants"	No scarce materials used Solar heat can be stored in concrete, molten salt, ceramics, or phase change material (PCM) as pure salts, salt eutectics (60% NaNO3 and 40% KNO3), metals, metal eutectics (Pb, Al, Al/Si). The state of the art storage material molten salts as the and synthetic oil as the heat transfer fluid for T< 400° C. Currently available HTFs are oils, water/steam and molten salts. (Liu et al 2012)	for occuring wastes treatment facilities are in place (Bosnjakovic 2019) Large volumes of storage materials required. Details see "Solar Thermal Power Plants" Hazardous wastes: HTF and solvents, waste oil and oil filters, cleaning rags, used or expired deadline of chemicals from the water treatment system, expired deadline of paints, etc.	´- Liu et al. (2012): "Review on storage materials and thermal performance enhancement techniques for high temperature phase change thermal storage systems" in Renewable and Sustainable Energy Reviews 16 (2012) 2118– 2132 ´- Mladen BOŠNJAKOVIĆ, Vlado TADIJANOVIĆ (2019): Environment impact of a concentrated solar power plant ´- ´- ESMAP 2011: Report "Middle East and North Africa Region Assessment of the Local Manufacturing Potential for Concentrated Solar Power (CSP) Projects" - Chapter 1

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Building systems engineering	•Building automation, •Heat accumulator, •Power storage; •Heating, ventilation and air-conditioning systems	Building automation is increasing, but the amount of new buildings is limited and their lifetime is long, therefore this wastestream is not increasing in the near future Heat accumulators are built into newer buildings and have a long lifetime, hence the wastestream is not increasing in the near future Power storage see Energy storage (electrical und electrochemical) Heating, ventilation and air-conditioning systems is constantly increasing by 6 % per year, but that is no meaningful increase, since it is in line with the increase of WEEE	low relevance over all technologies, because in comparison to e.g. WEEE building automation or HVAC are rather small streams, that are treated in similar facilities heat accumulators have higher volumes, but in comparison to the material in buildings themselves, they have a low relevance Power storage: see Energy storage (electrical und electrochemical)	low relevance since they are similar to WEEE and can be treated that way heat accumulators have no relevant materials Power storage: see Energy storage (electrical und electrochemical)	low relevance since they are similar to WEEE and can be treated that way heat accumulators are similar to buildings regarding materials Power storage: see Energy storage (electrical und electrochemical)	Market development building automation: https://www.marketsandmarkets.com/Market-Reports/building-automation-control-systems-market-408.html Market development HVAC: https://www.marketsandmarkets.com/Market-Reports/hvac-system-market-202111288.html
Electric mobility - Car/LNF / Hybrid Overhead Line Truck	•Batteries, •Vehicle to grid systems (including charging infrastructure)	PHEVS and HEVs incorporate a LIB. For BEVs, the LIBs are usually guaranteed to hold either 8 years or 160,000 km driven. A life time between 8 and 15 years can be expected of a car battery. Therefore this waste stream is currently emerging (https://www.carwow.de/ratgeber/elektroauto/elektroauto-akku-haltbarkeit-wie-lange-haelt-mein-e-auto) There are only a few models like the new Nissan Leaf or Peugot iIOn capable of being used as vehicle to grid storage system. There are several problems concerning this technology, like the battery not speciallized for being used as stationary storage module and the strong dependence of the life time of	Until 2020, about 550,000 BEVs, 550,000 PHEVs and over 2,4 million HEV were sold in the EU, although BEVs are the stronger growing number. (Fab4lib). As the sales rose strongly in the last few years, it will take several years for the waste stream to evolve, but it rises steadily. A battery from a BEV weighs between 150 and 650 kg. (Fab4lib) Therefore this waste stream is highly relevant.	Li-Ion: High amount of Co and Ni in NMC containing batteries are valuable enough to be able to make battery recycling profitable, when conducted at large scale. (Dühnen 2020) Many companies and start-ups have realized the problem and are working on solutions.(Dühnen 2020)	contain hazardous substances (electrolyte, incl. Salt and organic solvent, toxic metals). They are easily flammable, when wrongly handled, especcially, when not discharged below 30% SOC. LFP containing cells , used in buses,are not valuable enough for recycling and additional costs for disposal are expected in Europe (in China, Cu is enough). Li is not yet valuable enough to make a large impact, as the amount/concentration in a battery cell is comparably small. Copper (and aluminum, often going to scrap) is not valuable enough to cover the costs. Infrastructure for recycling is still missing (only pilot plants available, e.g. in Belgium by Umicore with 7000 t per year, which	"Gigafactories für Lithium-Ionen-Zellen–Rohstoffbedarfe für die globale Elektromobilität bis 2050: Kurzstudie erstellt im Rahmen des BMBF-Verbundprojektes Fab4Lib-Erforschung von Maßnahmen zur Steigerung der Material-und Prozesseffizienz in der Lithium-Ionen-Batteriezellproduktion über die gesamte Wertschöpfungskette." (2019). https://www.fleeteurope.com/en/new-energies/europe/analysis/vehicle-grid-pilot-schemes-gather-pace?a=JMA06&t%5B0%5D=V2G&t%5B1%5D=Nissan&t%5B2%5D=EDF&t%5B3%5D=CHAdeMO&t%5B4%5D=The%20Mobility%20House&curl=1 Dühnen, Simon, et al. "Toward Green Battery Cells: Perspective on Materials and Technologies." Small Methods (2020): 2000039.

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Information and communication technologies (ICT)	•Smart meters	Like many other electric devices mostly only two years guaranteed life time (FFE) The market is expected to grow with a compound Annual Growth Rate of 6.7% until 2025. The growth is attributed to the government mandated smart meter rollout plans. (M&M)	Roll-out in many countries for the general public up to 2020 (EUR 2015)	Similar to other electronic devices, could be processed with them (CIED) Smart Meters are composed of the following material; (Aleksic/Mujan 2016): 20% Plastic, 18% Copper, 17% Power transformer, 15% Current Transformer, 8% printed circuit board, PCB), 7% Steel, 1% LCD, 14% Other.	Not part of the WEEE directive (CIED) Could contain mercury in liquid crystal displays (CIED)	´- https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX:52014SC0189 ´- http://www.cied.ac.uk/wordpress/wp-content/uploads/2018/01/4049_policy_briefing_08_web.pdf https://www.ffe.de/attachments/article/851/FE_13549_Bericht_final_online.pdf ´- Aleksic/Mujan (2016): "Exergy-based Life Cycle Assessmentof Smart Meters" file:///C:/Users/C3CF3~1.HER/AppData/Local/Temp/ELEKTRO_2016_paper_Authors_Copy.pdf ´- M&M: Smart Meters Market Global Forecast to 2025; https://www.marketsandmarkets.com/Market-Reports/smart-meter-366.html
Fossil power plants	•Coal Power Plants	The rate of use of coal plants diminishes, due to lower competitiveness and aged equipment. Generation from solid fuels declines significantly throughout the projection period. Power plants with solid fuel type make up 24% of the electricity Generation in 2010, 22% in 2020 and 15% in 2030. Power	In recent years fossil fuel plants have already been decommissioned, dismantled and demolished.	Single parts can have remnant value and can be sold for reused. The primary materials used for constructing a power plant are concrete, steel, iron and aluminium. These materials can mainly be recycled. (NREL 1999)	Hazadous materials that can be found in fossil power plants mainly for insulation purpose include asbestos, refractory ceramic fibres, cristobalite and ozone-depleting substances. Building products containing asbestos are considered to have been extensively used in the construction of coal-fired and oil-fired	´- EC 2016: "EU Reference Scenario 2016 - Energy, transport and GHG emissions Trends to 2050" ´- Pei 2018: Power Engineering international, "Better asbestos management in coal plant decommissioning" (1.6.2018) https://www.powerengineeringint.com/coal-fired/equipment-coal-fired/better-asbestos-management-in-coal-plant-decommissioning/

Annex II. Interviews

Interview guide

Öko-Institut e.V. Institut für angewandte Ökologie Institute for Applied Ecology | Institute for European Environmental Policy | IDEA CONSULT thinking ahead | European Environment Agency

Emerging waste streams – Challenges and opportunities

The energy transition is geared to facilitate achieving the climate mitigation ambitions of the EU - but it should also be in line with other environmental objectives of the European Green Deal. In the coming years, Europe will increasingly have to deal with challenges and opportunities arising from emerging waste streams generated by the infrastructure, technologies and products of the energy transition, i.e. photovoltaic & battery storage systems, or wind turbines.

Identifying the key challenges for these emerging waste streams and suggesting solutions on how to move toward greater circularity is the aim of a study which the European Environment Agency (EEA) has commissioned to Oeko-Institut in cooperation with IDEA Consult and IEEP. This also includes specific needs for research, innovation opportunities, circular business models or policy response. The geographical scope of the study is the group of EEA member countries.

You have been identified as a relevant stakeholder in the field of either photovoltaic systems, battery storage systems, and/or wind turbines and related emerging waste streams. Dealing with these technologies, your practical challenges and good practice examples shall complement the results of the study. The main findings of the interviews will be fed anonymized into a draft report for the EEA which will be presented and discussed at a webinar on 25 January 2021 to the participating interviewees as well EEA countries. The project will end in February 2021.

Interview guide

A) Introductory questions:

1. To start, could you briefly describe your role within your organisation?
2. What materials does your organisation primarily work with?
3. Would you agree that we mention the name of your organisation and/or your name in the list of interview partners in the report?

B) Material waste:

4. Waste prevention options:
   a. Is waste prevention addressed during the design and/or material sourcing phase? If so, how?
   b. Are there any relevant waste streams that emerge from the manufacturing process (e.g. faulty products or modules)? If so, what share of total production? What methods are used to prevent or minimise this waste stream? Are they (internally) recycled within the same production cycle, or sold as a side product?
   c. Are there any relevant waste streams that emerge from the maintenance of infrastructure and equipment? If so, what are they? What methods are used to prevent or minimise this waste stream?
5. Remanufacturing:
   a. What methods for circularity relating to the end of life (EoL) products are already applied (e.g. remanufacturing, preparation for reuse or repurposing, or others)?
   b. Which processes already exist to treat products or parts of products in such a way that they can be reused? Are there difficulties in applying them?
   c. Are there any specialised organisations for remanufacturing your products on the market or is it done by your own company?

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6. (Design for) Recycling:
   a. Are you aware of any challenges for recycling of the emerging EoL products (e.g. hazardous substances, lack of collection/treatment infrastructure, logistics)? If so, how do you deal with them (manufacturers e.g. design for recyclability)?
   b. Which processes exist for high quality recycling that enable material to be suitable to be used in the same applications (i.e. closed-loop recycling)?
   c. To what extent is high quality (e.g. composite or complex materials) an issue when recycling material?
7. Waste management infrastructure / its readiness for challenges these streams may pose:
   a. What infrastructure is already in place/missing to manage this waste stream, e.g. mechanisms for separate collection, transport logistics, treatment capacity and facilities, recycling technologies etc.?
   b. What challenges do the materials pose for the infrastructure they enter and are treated within?
   c. In your view, which solutions or best practices address these challenges already, or could address them in the future?

C) Further Business Opportunities / Circular Business Models

8. High value material loops identified:
   a. What potential for future circular business models (CBM) related to this waste stream do you see?
   b. Which (economic?) triggers facilitate or improve CBM, or, on the other hand, currently impede the implementation of innovative CBM?
   c. Are there other valorisation potentials to use the emerging waste streams in other applications?
   d. What benefits in terms of combined waste reduction and greenhouse gas (GHG) reduction do CBM offer in relation to the emerging waste streams? Have these been or could they be quantified?

D) Policy relevant to the waste stream

9. Relevance and potential:
   a. What regulations exist that are linked to this emerging waste stream?
   b. What other policy instruments are already in place relevant to the waste stream (e.g. financial/fiscal incentives, extended producer responsibility, waste management-related targets (for collection/recycling), eco-design rules, product standards, green public procurement requirements/guidance etc.)?
10. Policy gaps and barriers:
   a. Do existing regulations or policy instruments create barriers to the recyclability of the emerging waste stream?
   b. Is further regulation needed to enable good management of the waste stream?
   c. What additional (new) policy instruments could help to maximise circularity for this waste stream in future?

E) Any other input:

11. Which other technical, economic or policy barriers do you see for improving the circularity of these waste streams?
12. We have covered a range of topics. Are there any topics that we missed that you feel are important for us to consider when assessing the circularity of emerging waste streams?

Thank you very much for your input and support!

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List of interviewed organisations

- Belgium – SINTEF
- Belgium – Umicore
- Denmark – The Danish Environmental Protection Agency
- Denmark – Vestas
- Denmark - Ørsted
- EU – Circusol
- France – PVCycle
- France – Veolia
- Germany – RWE
- U.S.A. – First Solar

Annex III. Online survey

Online survey questions

Öko-Institut e.V. Institut für angewandte Ökologie Institute for Applied Ecology | Institute for European Environmental Policy | IDEA CONSULT thinking ahead | European Environment Agency

Emerging waste streams – Challenges and opportunities

The energy transition is geared to facilitate achieving the climate mitigation ambitions of the EU - but it should also be in line with other environmental objectives of the European Green Deal. In the coming years, Europe will increasingly have to deal with challenges and opportunities arising from new, or "emerging", waste streams generated by the infrastructure, technologies and products of the energy transition, i.e. photovoltaic & battery storage systems, or wind turbines.

Identifying the key challenges for these emerging waste streams and suggesting solutions on how to move toward greater circularity is the aim of a study which the European Environment Agency (EEA) has commissioned to Oeko-Institut in cooperation with IDEA Consult and IEEP. This also includes specific needs for research, innovation opportunities, circular business models or policy response. The geographical scope of the study is the group of EEA member countries.

Besides targeted interviews with stakeholders from manufacturing and recycling industries, the experiences, challenges and perspective of EEA's National Reference Centres on waste and renewable energies shall complement the results of the study. Therefore, we invite you to participate in an online survey on challenges and opportunities of emerging waste streams in the field of photovoltaic systems, battery storage systems, and/or wind turbines. The main findings of the survey will be fed anonymized into a draft report for the EEA which will be presented and discussed at a webinar on 25 January 2021 and finalised in February 2021.

We would appreciate your participation to the online survey – please provide your answers by 18 December 2020 latest.

Survey questions

A) Introductory questions:

1. Name of your organisation / your responsibility in the organisation
   a. ___________
   b. __________

   Would you agree that we mention the name of your organisation in the list of survey respondents in the report?

   c. Yes
   d. No
2. Your first and last name
   a. ___________

   Would you agree that we mention your name in the list of survey respondents in the report?

   b. Yes
   c. No
3. Your field of experience (multiple options possible):
   a. Wind
   b. PV
   c. Batteries
   d. Other: ________
4. Are you aware of the emerging waste streams in the field(s) of your experience?
   a. Yes (Grading 3 levels)
   b. No

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B) Waste management and its readiness to address challenges posed by these emerging waste streams

5. Infrastructure
   a. In your opinion, are the following infrastructure elements currently adequate for managing the emerging waste streams from wind turbines, battery storage systems, or photovoltaics systems in your country? Tick the waste stream(s) where this is the case.
      a. Mechanisms for separate collection:
         ❑ wind ❑ battery storage ❑ PV ❑ N/A, specify: _______
      b. Transport logistics:
         ❑ wind ❑ battery storage ❑ PV ❑ N/A, specify: _______
      c. Treatment capacity and facilities
         ❑ wind ❑ battery storage ❑ PV ❑ N/A, specify: _______
      d. Recycling technologies
         ❑ wind ❑ battery storage ❑ PV ❑ N/A, specify: _______
      e. Other (please specify): ___________
         ❑ wind ❑ battery storage ❑ PV ❑ N/A, specify: _______

   b. Which elements of the infrastructure need further improvement to manage the emerging waste streams in your country? Tick the waste stream(s) where this is the case.
      a. Mechanisms for separate collection:
         ❑ wind ❑ battery storage ❑ PV ❑ N/A, specify: _______
      b. Transport logistics:
         ❑ wind ❑ battery storage ❑ PV ❑ N/A, specify: _______
      c. Treatment capacity and facilities
         ❑ wind ❑ battery storage ❑ PV ❑ N/A, specify: _______
      d. Recycling technologies
         ❑ wind ❑ battery storage ❑ PV ❑ N/A, specify: _______
      e. Other (please specify): ___________
         ❑ wind ❑ battery storage ❑ PV ❑ N/A, specify: _______

   c. In your opinion, which policy or other instruments are necessary to address these infrastructure challenges?
      i. Waste streams: ❑ wind ❑ battery storage ❑ PV
      ii. Please specify: _________

6. Recycling:
   a. In your opinion, which of the following challenges are the most relevant for recycling of the emerging waste streams?
      a. Hazardous substances (please specify): _______
      b. Lack of collection/treatment infrastructure (please specify): ________
      c. Logistics (please specify): _________
      d. Complexity of the materials (please specify): __________
      e. Lack of information (please specify): ________
      f. Other (please specify): ________

Thank you very much for your input and support!

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b. In your opinion, which policy or other instruments are necessary to address these challenges for recycling?
   iii. Waste streams: ❑ wind ❑ battery storage ❑ PV
   iv. Please specify: ________
c. Do you know of any existing best practices that address the challenges you identified in the previous question? In which countries are they applied?
   a. Best practice 1:
      i. Country:
   b. Best Practice 2:
      i. Country
   c. Best Practice 3:
      i. Country:
   d. (Up to 5 best practices)

7. Remanufacturing / reuse:
   a. Are you aware of any existing remanufacturing / reuse strategies in your country (or beyond)? Tick the waste stream(s) where this is the case.
      i. Yes
      ❑ wind ❑ battery storage ❑ PV ❑ N/A, specify: ______
      ii. No
   b. Is there any policy in place in your country promoting remanufacturing / reuse strategies? Tick the waste stream(s) where this is the case.
      i. Yes
      ❑ wind ❑ battery storage ❑ PV ❑ N/A, specify: ______
      ii. No

C) Circularity options to reduce the waste streams

8. Waste prevention options:
   a. Are you aware of any waste prevention options to reduce the waste streams? Tick for which waste stream(s) this applies.
      a. Yes
      ❑ wind ❑ battery storage ❑ PV ❑ N/A, specify: _______
      i. No
   b. Is there any policy in place in your country promoting waste prevention strategies ? Tick for which waste stream(s) this applies.
      i. Yes
      ❑ wind ❑ battery storage ❑ PV ❑ N/A, specify: _______
      ii. No

9. Other policy instruments to increase circularity:
   a. What other policy instruments are already in place to increase the circularity of the waste stream(s)? Please tick for which waste stream(s) this applies.
      i. Financial or fiscal incentives
      ❑ wind ❑ battery storage ❑ PV ❑ N/A; Please give a brief description
      ii. Extended producer responsibility
      ❑ wind ❑ battery storage ❑ PV ❑ N/A; Please give a brief description

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iii. Waste management-related targets (for collection and recycling)
❑ wind ❑ battery storage ❑ PV ❑ N/A; Please give a brief description

iv. Eco-design rules or regulations
❑ wind ❑ battery storage ❑ PV ❑ N/A; Please give a brief description

v. Product standards
❑ wind ❑ battery storage ❑ PV ❑ N/A; Please give a brief description

vi. Green public procurement requirements/guidance
❑ wind ❑ battery storage ❑ PV ❑ N/A; Please give a brief description

vii. Circular Business Models
❑ wind ❑ battery storage ❑ PV ❑ N/A; Please give a brief description

viii. Funding research
❑ wind ❑ battery storage ❑ PV ❑ N/A; Please give a brief description

ix. Other (please specify): _________
❑ wind ❑ battery storage ❑ PV ❑ N/A; Please give a brief description

b. Is further regulation, or improvement of current policy instruments, needed to increase the circularity of wind turbines, photovoltaic and battery storage systems? Please indicate for which waste stream(s) this is this case.

i. Yes
❑ wind ❑ battery storage ❑ PV
Please specify how: _________

ii. No

D) Any other input:

10. Any further comments or information you think may be useful to the study team?

E) Interest in further information:

Would you like to participate in the online workshop on the study results (25 January 2021, 9:00-12:00)?

a. Yes

Please provide your email address for the workshop invitation:

____

b. No

If you would you like to suggest someone else, please provide the person's email address for the workshop invitation: __________

Thank you very much for your input and support!

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List of participating organisations agreed to be mentioned in the report

- Albania – Kosovo Environmental Protection Agency
- Albania – National Environment Agency
- Belgium – OVAM The Flemish Public Waste Agency
- Bulgaria – Executive Environment Agency (ExEA)
- Czech Republic – Ministry of the Environment
- Denmark – The Danish Environmental Protection Agency
- Estonia – Ministry of the Environment
- Germany – German Environment Agency
- Italy – Italian Institute for Environmental Protection and Research, ISPRA
- Spain – Ministry for Ecological Transition and Demographic Challenge/ General Subdirectorate of Circular Economy
- Turkey – Ministry of Environment and Urbanisation
- Turkey – Turkish Statistical Institute
- Turkey – Ministry of Energy and Natural Resources

Annex IV. Online workshop

Workshop invitation

Öko-Institut e.V. Institut für angewandte Ökologie Institute for Applied Ecology | Institute for European Environmental Policy | IDEA CONSULT thinking ahead | European Environment Agency

Emerging waste streams – Challenges and opportunities

Online workshop 25th January 2021, 9:00-12:00

The energy transition is geared to facilitate achieving the climate mitigation ambitions of the EU - but it should also be in line with other environmental objectives of the European Green Deal. In the coming years, Europe will increasingly have to deal with challenges and opportunities arising from emerging waste streams generated by the infrastructure, technologies and products of the energy transition, i.e. photovoltaic & battery storage systems, or wind turbines.

Identifying the key challenges for these emerging waste streams and suggesting solutions on how to move toward greater circularity is the aim of a study which the European Environment Agency (EEA) has commissioned to Oeko-Institut in cooperation with IDEA Consult and IEEP. This also includes specific needs for research, innovation opportunities, circular business models or policy response. The geographical scope of the study is the group of EEA member countries.

We invite to this online workshop to inform about the main results which are based on literature research, targeted stakeholder interviews and a stakeholder consultation via online survey.

Main topics of the workshop:

- Challenges and barriers for the end-of-life management for the waste streams of photovoltaic & battery storage systems, and wind turbines emerging in coming years
- Approaches, best practice examples and circular business models identified currently maximising circularity for these emerging waste streams
- Policy recommendations to maximising circularity for these waste streams in future

Please confirm your participation by 11 January 2021 by accepting the outlook invitation

Time	Agenda
09:00	Welcome Presentation of scope and objectives of the study Tour de Table of participants
09:30	Waste stream I: **Photovoltaic systems**: *Presentation of results | Q&A*
10:00	Waste stream II: **Battery storage systems**: *Presentation of results | Q&A*
10:30	Break
10:45	Waste stream III: **Wind turbines**: *Presentation of results | Q&A*
11:15	**Cross-cutting findings & policy recommendations**: *Presentation of results | Discussion on findings*
12:00	End of the workshop

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Participating organisations / representatives of EEA member countries (83 participants)

- EEA
- Oeko-Institut, Germany
- IDEA, Belgium
- IEEP, Belgium
- Accurec, Germany
- Deutsche Umwelthilfe, Germany
- First Solar, Germany
- Orsted, Denmark
- OVAM, Belgium
- PV Cycle, Belgium
- ROSI - Return of Silicon, France
- Sintef, Norway
- Take-e-way, Germany
- University of Muenster, Germany
- Veolia, France
- Vestas, Denmark
- VITO, Belgium
- Austria
- Belgium
- Bosnia and Herzegovina
- Bulgaria
- Croatia
- Cyprus
- Czech Republic
- Denmark
- Estonia
- Finland
- France
- Greece
- Hungary
- Iceland
- Ireland
- Latvia
- Lithuania
- Luxembourg
- Malta
- Norway
- Poland
- Portugal
- Slovakia
- Spain
- Sweden
- Switzerland