Naturgy Foundation

Wind, PV and batteries recycling in Europe:

an opportunity for the recovery of critical raw materials

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Co-funded by the European Union

Executive summary

The European renewable energy industry is set to expand by 50% in the next five years thanks to increasingly reliable decarbonising technologies, which will also bring wealth and create jobs.

Market traction and industry projections are ambitious when it comes to wind and solar PV, while batteries are key to the electrification of mobility and to the increase of renewables in the energy mix. However, the boost in deployment of renewable energy technologies brings an unresolved problem to the table: how to manage the enormous amount of waste generated when they reach the end of their useful life. The approach to this waste is a matter of concern; nobody wants to see wind turbine blades, photovoltaic plant panels, or batteries dumped on a landfill, particularly when they are sold as environmentally friendly.

There is, of course, more to the issue as this report makes clear. Effective end-of-life management in the renewable energy sector is essential to the energy transition as well as to Europe's energy independence. According to the EU Green Deal, securing access to resources is strategically necessary to reach ambitious 2050 objectives. To date, 60% of the global material demand is extracted in China while in Europe we remain dependent on foreign imports for more than 80% of our raw materials. This shows how heavily reliant Europe's economy is on imported supplies of many minerals and metals, which are often vulnerable or at risk of supply shortages. According to the European raw materials initiative, to determine which materials are critical

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we need to assess their geographic availability, economic value, quality of natural resources, and supply/demand imbalances. Despite several scientific models that attempt to predict the impact of material scarcity in Europe without overall consensus, experts do agree on the need for an improved system which fosters the introduction of a circular economy sector with more effective recycling and reuse of critical raw materials,implementing product models and solutions such as eco-design. In addition, technological developments should enable increased recovery rates of critical components, while Europe addresses the need for import diversification and formulates an expansion strategy for domestic mining. To better assess EU resilience to increasing demands for raw materials, additional studies are required, looking at the evolution of future material supplies and comparing them with the material demand results presented in this report.

At present, 20% of the world's silver is used by the PV industry when deploying +160 GW per year. This situation will become more critical in coming years as global manufacturing capacity ramps up to 500 GW per annum. As declared in the ambitious REPowerEU plan, the goal is to deploy 40 GW per year in Europe alone. While silver is only 0.5% of a PV module's mass, it represents 47% of the total economic value of the module. PV panels are made of materials which are valuable, expensive to produce, and toxic. A number of predictions conclude that there will be pressure placed on several other materials in this market, notably germanium, tellurium, indium, selenium and silicon. Although the recovery rate of PV panels seems high (around 80% of the weight), the recycling techniques most commonly used do not allow for the recovery of these critical materials, since a large majority implement mechanical treatments that limit the materials recovered to the heavier components of low economic value. In the future, however, treatment operators will be required not only to treat the bulk material, but more importantly, the materials integrating the systems. Being able to recover them is key to creating an incentive in the PV recycling market, both sustainably and economically. This will most likely entail additional processing going beyond mechanical treatments, fostering the implementation of the minimum treatment requirements and related technical specifications for depollution.

To size up the challenge for the wind energy sector: Europe aims to deploy close to 30 GW of new capacity per year, amounting to more than 1.5 million metric tonnes of materials, which may be partially offset by those recovered from decommissioned power plants. When it comes to wind turbines standard, non-specific materials account for more than 90% of the total weight, so technologies for the recovery of materials and business models are already in place. As for the rest, landfilling remains the most common

Wind industry is quite effective in reusing components and reincorporating such materials into the industry, particularly into the 750kW-2.5MW nameplate range.

solution at the moment. Among the remaining 10% we can find some rare earths and composite materials, which are of strategic importance and high intrinsic value and therefore attract special attention for research. Composite materials are inherently inert and nontoxic and therefore classified as non-risk. However, different processes are being studied due to the imminent visual impact and long deterioration time period. The main challenges in recycling rare earths are their difficulty to decompose, their low concentrations and the need for expensive processes compared to the value recovered. What's more, most of these materials are of less value than the turbine component itself, so it makes more sense to repair or refurbish.

By 2035 we will need to recover 30% of the cobalt and 20% of the lithium and nickel from used batteries if we want to be able to cope with the forecast demand.

As a consequence, the wind industry is quite effective in reusing components and reincorporating such materials into the industry, particularly into the 750kW-2.5MW nameplate range. Ideally, the circular use of recycled materials could supply one third of the materials required in Europe. However, the industry will still require most of the rare earths available, placing pressure on supplies.

In terms of storage solutions, this report focuses on the assessment on Li-ion batteries and their use in the automotive sector, which represents at least 80% of their usage. In 2021, global sales of electric cars hit over 6 million units, and although China is still the biggest actor in this market, Europe is winning the race in terms of market share. For this reason, recycling plays an even more critical role, as mining will not be able to provide all the raw materials needed for this industry. As of today, the number of batteries reaching the market remains negligible, but as from 2026-27 the amount of waste derived of it will reach significant proportions. When it comes to critical raw materials globally, by 2035 we will need to recover 30% of the cobalt and 20% of the lithium and nickel from used batteries if we want to be able to cope with the forecast demand. If we are not able to reach these objectives, we will be placing the green transition at risk.

Battery recycling today is a complex reality because there is an absence of standard practices among manufacturers. This is set to be simplified in future with the increase in volume, which will lead to economies of scale and the higher participation of automotive OEMs and cell manufacturers. This will bring more efficiency and homogenisation to EOL battery flows, as well as encourage eco-design. Another challenge is that of obtaining permits, a slow and problematic process at the moment.

In some cases, there is regulation in place, in others it is yet to come. In practice there is still a huge gap between producers and recyclers which must be overcome. In previous years, regulatory efforts have succeeded in making recycling mandatory in Europe. One good example is the recent announcement of a new EU battery regulation. The European Commission also aims to widen the eco-design directive in order to promote circularity in industrial processes, use digital technologies to track resources, and achieve an environmental EU certification mark. Still, the EU will need to rely on political leadership, guidance and adequate regulatory support, as well as public communication strategies. Up to now, there has been no official data made available on the amount of waste produced

Recycling plays a key role in fulfilling the green transition

or recycled, and material availability is not easy to predict, since material demands for PV, wind and batteries vary greatly given each technology's dependence on relative market share. In parallel, innovation and technological improvements have led the energy industry to notably reduce its use of materials.

This report also takes the business perspective into account in its intention to establish a reliable recycling scheme, from collection alternatives to second-use opportunities and recovery of materials. For PV the specific focus is on recovering high value materials and re-introducing them into the sector, for wind it is on the refurbishment of components that may extend the life of other assets, and for batteries the aim is to mitigate the shortage of materials beyond any additional financial consideration. An assessment of a generic working business model is introduced with the main objective to minimise waste, whereby some by-products are recovered in a way that enables their return to their original application, while others are sent on for use in other applications. The initial challenge is that a recycling business often requires funding early on, as the recycling process is usually more expensive than buying the virgin product directly or the recovered by-products are technically poor. One solution is the creation of legal bodies known as producer responsibility organisations (PROs) which fund the business with an eco-tax that the final clients pay when buying the new product. In those cases where recycling is profitable then it is left to the market to manage the business structure; by-products are scarce as virgin materials, and this presents an opportunity to recuperate them to reenter them into the market. This encourages producers to want to remain actively involved in the flux of their end-of-life products.

All in all, the objective of this report is to show how recycling plays a key role in fulfilling the green transition, setting a sustainable path for managing residues and offsetting the dangers of a shortfall of raw materials. The situation calls for an appropriate framework to mitigate this risk. Industries and R&I partners in Europe are working towards addressing the key challenges to set up the right business models to tackle recyclability and the carbon footprint of these technologies. This will not only reduce the huge CO_2 footprint derived from their waste, but enable Europe to recover critical materials and develop local supply chains.

Acronyms

AEDIVE: Asociación Empresarial para el desarrollo e impulso del Vehículo Eléctrico
BMS: Battery Management System
BNEF: Bloomberg New Energy Finance
CAPEX: Capital Expenditure
CFRC: Carbon Fiber Reinforced Composite
CIEMAT: Center for Energy, Environmental and Technological Research
c-Si: crystalline Silicon
DD: Direct Drive
FIG: Double Feed Induction Generator
DUH: Environmental Action Germany (Deutsche Umwelthilfe)
EBA: European Battery Alliance
EESG: European Battery Alliance
E-mobility: Electronic mobility
ENTSO-E: European Network of Transmission System Operators for Electricity
EOL: End of Life
EU: Europe
EV: Electric Vehicle
GB: Gear Box
GFRC: Glass Fiber Reinforced Composite
GW: gigawatt
ICT: Internet and Communication Technologies
IEA PVPS: International Energy Agency's Photovoltaic Power Systems Programme
IEA: International Energy Agency
IPP: Independent Power Producers
ISP: Independent Service Provider
kW: kilowatt
LCA: Life Cycle Assessment
LCI: Life Cycle Inventories
LCO: Lithium oxide and Cobalt
LFP: Lithium and iron phosphate
Li-ion: Lithium ion
LMO: Lithium and Manganese oxide
MW: megawatt
NECP: National Energy Climate Plan
NIMBY: Not in my backyard
NMC: Nickel, Manganese, Cobalt
OEM: Original Equipment Manufacturer

PHEV: Plug-in Hybrid Electric Vehicle
PMSG: Permanent Magnet Synchronous Generator
PPA: Power Purchase Agreement
PRO: Producer Responsibility Organisation
PV: Photovoltaic
Q3: Quarter 3
R&D: Research and Development
R3: Reuse, Repair, Recycle
SEC: Spanish Expert Committee
Si: Silicon
UNEF: Spanish Solar Association (Unión Española Fotovoltaica)
WEEE: Waste Electrical and Electronic Equipment Directive

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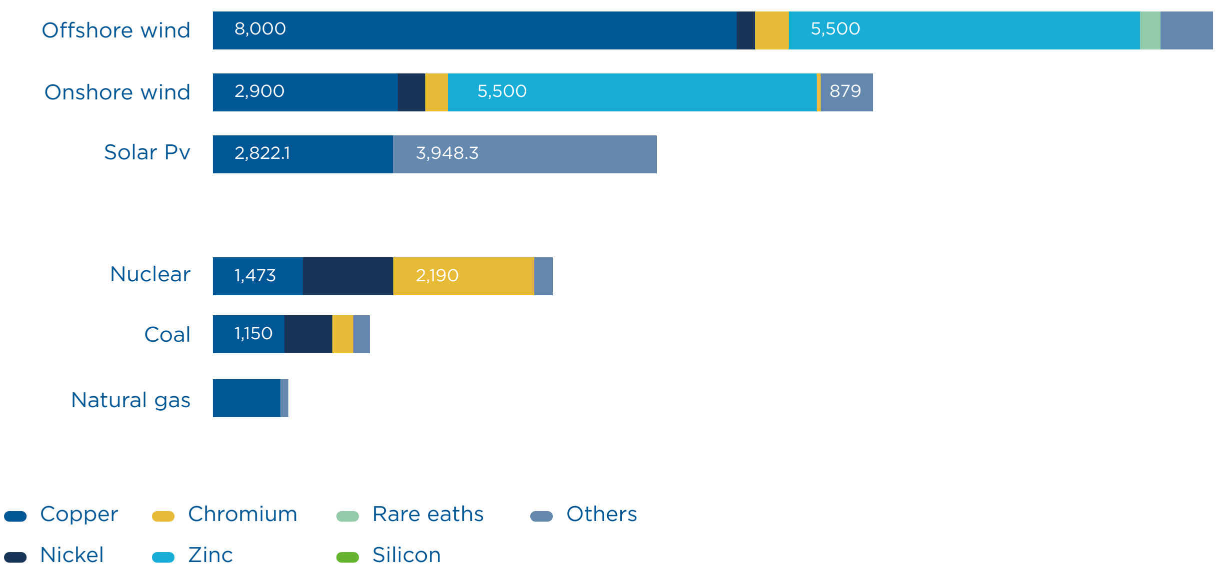
Context and introduction to the study

According to the International Energy Agency (IEA), the power generation capacity from renewable sources will grow by 50% in the next five years owing to the installation of photovoltaic solar panels, which will absorb 60% of growth compared to the 25% derived from wind systems.

The path towards the Fit for 55 (2030) and net zero goal (2050) will have to rely on these mature technologies able to deliver large quantities of energy at a competitive price and with a proven reliability. The European industry is a global leader in this, so the benefits exceed those related to decarbonisation, adding an important factor in terms of wealth and job creation. This deployment increase, of undeniable benefits, nevertheless, leaves a footprint that is beginning to cause concern; the manufacture, transport and minimal recycling of raw materials coming from renewable energy technologies leaves a polluting trail in its wake.

Furthermore, the rapid transition to renewable energy sources faces an even greater dependence on raw materials for Europe. As we can see in the graph below, clean technologies have several mineral requirements, which is why in this study we will show how developing resilient value chains to build a stable circular economy, based on resource efficiency, recycling, reuse, repair, substitution, and the use of secondary sources, will play an ever more important role in the near future.

Figure 1.
Comparison of minerals used in different energy technologies (kg/MW). Source IEA.



Excludes operational mineral requirements for nuclear, coal and natural gas.

These minerals are some of the essential requirements of raw material supply on which climate neutrality targets depend. In fact, the EU Green Deal communication, released in 2019, already recognised access to resources as a strategic security question necessary to fulfil its ambition towards 2050 objectives, and increase climate targets for 2030. Raw materials are not only essential for the production of a broad range of goods and services used in everyday life, but also for the development of emerging innovations which are significant contributors to more eco-efficient technologies and globally competitive products. For the EU, the importance of raw materials is not only focused on clean technologies that count on certain raw materials considered irreplaceable in solar panels, wind turbines, electric vehicles, and energy efficient lighting, but also on industrial value chains for non-energy materials and other general strategies towards technological and economic progress. Many of these materials are currently extracted in only a few countries, which increases the risk of supply shortages and supply vulnerability along the value chain.

Raw materials are not only essential for the production of a broad range of goods and services used in everyday life, but also for the development of emerging innovations which are significant contributors to more eco-efficient technologies and globally competitive products

One example is lithium, a key material for sectors like energy storage or electric vehicles, aside from its many other electronic applications. For many years now, many countries worldwide have raced to secure their lithium resources by reaching agreements with those other exporting countries where the lithium mines are located, such as Australia, Argentina, Brazil, Chile, or China. While these countries are exploiting their lithium resources and selling them to Europe, Russia or the United States, there are other reserves which are not yet being used, as has occurred in Bolivia, a country which holds one of the biggest lithium deposits of approximately one fourth of global resources, or, on a smaller scale, in Ukraine. Historically, competition for control over a mineral resource has led to geopolitical rivalries. Now, this is more relevant than ever, given that the already exponential global need of lithium is expected to grow further in the coming years, with the demand for energy storage particularly evident from the electric mobility market.

But, how do we determine which raw materials are critical? The term 'critical' commonly draws on factors such as geographical availability, economical value, quality of the natural resources, supply-demand imbalances, and/or extraction efforts. Therefore, it is also common that most critical materials are either minerals or metals. Materials such as glass, plastic and aluminium are therefore not considered critical materials because the resource is in place and widely distributed. Other characteristics of critical materials could be their toxicity or their difficulty to degrade or be recycled.

Lithium, a key material for sectors like energy storage or electric vehicles, aside from its many other electronic applications

By 2008, the European Commission had already launched the **European Raw Materials Initiative,** an integrated strategy that established targeted measures to secure and improve access to most critical raw materials for the EU. It was based on:

- **A fair and sustainable supply of raw materials from international markets.**
- **Fostering a sustainable supply within the EU.**
- **Boosting resource efficiency and promoting recycling.**

To achieve this, there was a need to know the key critical raw materials for the European economy, understand their stocks and flows and their market, and to identify supply bottlenecks.

The table below represents the main global suppliers of an EU list of selected critical raw materials. We can see that almost 60% of the materials assessed are extracted in China. Other dominant suppliers are South Africa and the USA.

Table 1.
Major global supplier countries of critical raw materials – individual.

	Material	Stage	Main global supplier	Share		Material	Stage	Main global supplier	Share
1	Anthony	E	China	74%	23	Magnesium	P	China	89%
2	Baryte	E	China	38%	24	Natural graphite	E	China	69%
3	Bauxite	E	Australia	28%	25	Natural rubber	E	Thailand	33%
4	Beryllium	E	USA	88%	26	Neodymium	E	China	86%
5	Beismuth	P	China	80%	27	Niobium	P	Brazil	92%
6	Borate	E	Turkey	42%	28	Palladium	P	Russia	40%
7	Cerium	E	China	86%	29	Phosphate rock	E	China	48%
8	Cobalt	E	Congo, DR	59%	30	Phosphorus	P	China	74%
9	Coking coal	E	China	55%	31	Platinum	P	S. Africa	71%
10	Dysprosium	E	China	86%	32	Praseodymium	E	China	86%
11	Erbium	E	China	86%	33	Rhodium	P	S. Africa	80%
12	Europium	E	China	86%	34	Ruthenium	P	S. Africa	93%
13	Fluorspar	E	China	65%	35	Samarium	E	China	86%
14	Gadolinium	E	China	86%	36	Scandium	P	China	66%
15	Gallium	P	China	80%	37	Silicon metal	P	China	66%
16	Germanium	P	China	80%	38	Tantalum	E	Congo, DR	33%
17	Hafnium	P	France	49%	39	Terbium	E	China	86%
18	Ho, Tm, Lu, Yb	E	China	86%	40	Titanium	P	China	45%
19	Indium	P	China	48%	41	Tungsten	P	China	69%
20	Iridium	P	S. Africa	92%	42	Vanadium	E	China	39%
21	Lanthanum	E	China	86%	43	Yttrium	E	China	86%
22	Lithium	P	Chile	44%	44	Strontium	E	Spain	31%

Legend

Stage	E = Extraction stage P = Processing stage
HREEs	Dysprosium, erbium, europium, gadolinium, holmium, lutetium, terbium, thulium, ytterbium, yttrium
LREEs	Cerium, lanthanum, neodymium, praseodymium and samarium
PGMs	Iridium, palladium, platinum, rhodium, ruthenium

Access to these critical raw materials does not only depend on the geographical availability but also on the feasibility and willingness to extract them. In 2020, Europe represented just 5% of global mining activities and we are the only region in the world with a declining mining industry. To date we remain dependent on foreign imports for more than 80% of all the raw materials needed for our industry and economy. This dependence on imports makes us vulnerable to economic and geopolitical shocks and rivalries. The only few raw materials for which an EU member state is the main global producer are hafnium (France), strontium (Spain), natural cork (Portugal) and perlite (Greece).

This is one of the triggering factors for this study; the clean energy transition and energy independence of Europe are conditional on the availability of materials and technology development and require end-of-life management so that it remains clean in the future. As the cornerstone of the European Green Deal, the EU has adopted ambitious goals of climate neutrality by 2050, as well as the already mentioned net 55% reduction of emissions by 2030 compared to 1990. At this point in time, the case for a rapid clean energy transition has never been stronger and more clear cut, without forgetting the environmental aspects which are the key trigger of the cause.

5%

Europe´s mining activities regarding global in 2020

As part of the EU's strategy to reduce the growth of critical raw materials' demand, the member states are focusing their efforts on introducing a circular economy with much more recycling and reuse of critical raw materials, diversifying our imports and expanding domestic mining in Europe. Regarding this last point, there is a relevant conflict of interests and strategic objectives, where the right balance shall be found between local nature and environmental protection, and effective and sustainable global climate change mitigation. Both objectives are of relevant importance and shall coexist in order to achieve a greater objective. Even considering the low acceptance to mining activities in Europe, the silver lining is that this will enhance even more the need of a correct end-of-life management to recover the critical materials.

For the mentioned strategic objectives to be effectively implemented, the EU will need to rely on sound political leadership, guidance and adequate regulatory support, as well as public communication strategies. In this study, we will focus on introducing the existing reality of the end-of-life treatment options in the solar, wind and battery industries, as well as the forecast trends, bearing in mind that we are currently living through clear evolution in this sector in Europe. To date, there is no official data on the amount of waste produced or recycled from any of the three industries, but as it will be explained in the coming pages, there is a clear vision on the increase of installed capacity of clean technologies in the coming years. So, avoiding the disposal on landfills is strategic for a dual purpose: to reduce environmental impact, and to recover valuable materials. For this reason, Europe has a busy agenda for the next 10 years if it wishes to develop a market able to meet the requirements of a recycling industry.

Bearing in mind that we are entering an era where large quantities of renewable waste will need to be managed, considering the lifetime of the first wind turbines and PV modules installed in Europe, we should make sure the correct end-of-life management of these components is implemented. This is the only way to ensure renewable energies are clean not only in terms of emissions but also of physical waste. Actually, the waste itself is not necessarily the problem, rather the nature of that waste. Moreover, some of the materials may cause a severe bottleneck that could benefit from a proper strategy on the Reuse, Repairability and Recyclability of most of the components. This strategy, best known as R3, should be implemented not just in existing power generation capacity, but, starting at the design phase, planned for future installations as well. This is one of the motivators for European countries and private companies to generate interest in recycling solutions; from decision makers to the general public, there is a clear demand for renewable technologies to comply with the maximum environmental and circular economy standards.

Quantifying the environmental impact of these technologies is usually done by a life cycle assessment (LCA), a method to quantify the environmental profile of goods and services that analyses all the processes in the manufacturing of a product. Depending on the component and the value of the materials that can be recovered, routes for an R3 strategy may vary significantly. There is no one solution that fits all. In some cases, there will be potential stand-alone market solutions, in others, regulation and support mechanisms will play a fundamental role. In that sense an analysis across the value chain will be provided to explore other sources of waste or recyclable materials.

In this study, the implementation of an effective end-of-life management in the renewable energy sector is presented as a necessity for the energy transition, as well as for Europe's energy independence. Along the coming chapters, the principle of circular economy will be assessed in the areas of photovoltaic solar energy, wind anergy and batteries, aligned with their relevant geostrategic value.

For each technology, our analysis will begin with a study of the projected demand for materials. For that purpose, we will use the market outlook, both for Europe and Spain. That outlook will need to be translated into materials / components demand, and retirements to assess impact.

Some areas of concern are rare earths and composite materials, as all other materials (concrete, steel, copper, aluminum, ...) are considered R3 proof, with several companies providing services. For the most critical ones, we will examine the main technical solutions that are in development.

Regulation is a fundamental cornerstone in this quest for a comprehensive circular economy related to the renewable energy sector. In some cases, regulation is already in place, in others, it is yet to come. Moreover, the industry for certain specific materials is one step ahead of regulation, with the aim of finding solutions that improve social acceptance and the LCA footprint of their products.

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Finally, as anticipated, the costs of any R3 approach must be incorporated into analysis. Hopefully, in the majority of cases there will be a business case approach that brings about a natural solution. In certain other cases, however, a support mechanism will need to be designed and implemented.

1

Solar PV

1.1 Introduction to the End of Life Management of the Solar energy market

As we will see in this section, due to the rapid increase in PV deployment in the coming years, the solar energy market will need to face the challenge of end-of-life management of their products. The PV industry's carbon footprint is derived from: extraction and production of components, emissions generated in transport, and end-of-life management of the modules. Although the ultimate goal is to minimise all direct and indirect pollution sources, in this study we will focus on assessing the end-of-life alternatives of PV in Europe and in Spain.

The R3 rule (reduce, reuse, recycle) should also be implemented in the PV sector. However, given that PV panels are made of materials that are valuable, expensive to produce, and toxic, before looking for recycling solutions, there are other alternatives to consider which might allow for the reduction of use of materials, substituting them for other less critical ones or extending the life of the modules, for example:

- **Reducing**

  With the advancement of PV technology proven in previous decades, and the relevant role of R&D development, the efficiency of panels has increased notably, with the raw material input in their composition already significantly reduced. Nowadays, although the composition is still very similar, modern panels are much more energy efficient using less material, which means reduced environmental impact and reduced production of waste in the future. Production techniques have also been improved, and experts are focused on reducing the use of critical materials. For example, just a few months ago, an Australian start up, SunDrive,

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reached an efficiency record of 26% in a solar cell which replaces the expensive silver used in conventional solar PV cells with cheaper and more abundant copper. This is a key milestone in this relevant action line towards improving the environmental and economic impact of the PV industry.

- **Reusing**

The key to reusing PV modules is ensuring a remaining level of performance and lifespan in compliance with a minimum of quality and security standards. The problem today is that such standards are not in place, which makes it very difficult to identify if the modules in question are a good fit for reuse, or if they must be managed as waste. There are existing initiatives that aim to set these standards in order to avoid corrupted situations in which official PV collectors send away big volumes of PV modules to developing countries claiming these will be reused, when in reality it is just waste which should have been managed and recycled locally. When establishing standards at European level, it will be necessary to design an industry level testing line to proof the above-mentioned technical requirements for reuse.

- **Recycling**

Although to date Europe has launched initiatives to recover some toxic components such as cadmium, this is not enough; there is a lack of recovery of components like silver, copper, silicon, and lead, thus losing most of their potential value and worsening the environmental impact of the module. In fact, PV panel recycling is a very feasible and not particularly technically-challenging operation, with very high recovery rates. An ability to reuse these elements would mean both significant energy and economic savings.

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1.1.1 Materials and composition of PV panels

The 3 main PV technologies on the market are: thin film, monocrystalline silicon and multicrystalline silicon (Si), although two-thirds of the globally manufactured panels are crystalline silicon. Most actors in the sector today refer to Irena's report from 2016 on End-of-Life management of PV panels, about the general composition of a typical silicon PV module. This information is reflected in the table below. Despite not having more recent scientific publications to define these generic values, we shall keep in mind there has been an overall recent value increase of raw materials prices in the past 2 years, which might affect the numbers shown in Table 2.

Table 2.
Composition of a c-Si PV panel. Relative weight and value of each material. Source IRENA.

	Part of the module	Rel. material weight	Material	Rel. material value
Non-hazardous waste	Encapsulation	75%	Glass	8%
	Structure	10%	Polymer	-
	Frame	8%	Aluminium	26%
Hazardous waste	Transmittance	5%	Silicon	11%
	Wiring	1%	Copper	8%
	Semiconductor metals	1%	Silver	47%
			Lead	-
			Indium	-
			Tin	-

While the frame and glass together represent almost 80% of the weight of the panel, the relative material value is very differently distributed. For example, while silver is only 0.5% of the mass, it represents 47% of the total economic value. Today, 20% of the silver worldwide is used for the PV industry. Several scenarios have been proposed, and other metals have been studied to substitute silver, but none of them has matched its efficiency. Production of silver has been very stable for the past 20 years, but it could very well become a problem for the industry; if we increase the capacity of PV modules production without lowering the use of silver per cell, it will lead to a shortage in the silver market. And let's also bear in mind that in Europe we are dependent on imported silver. Therefore, silver is considered one of the critical materials in the PV industry.

20%

of the silver worldwide is used for the PV industry. It is only 0.5% of the mass and it represents 47% of the total economic value

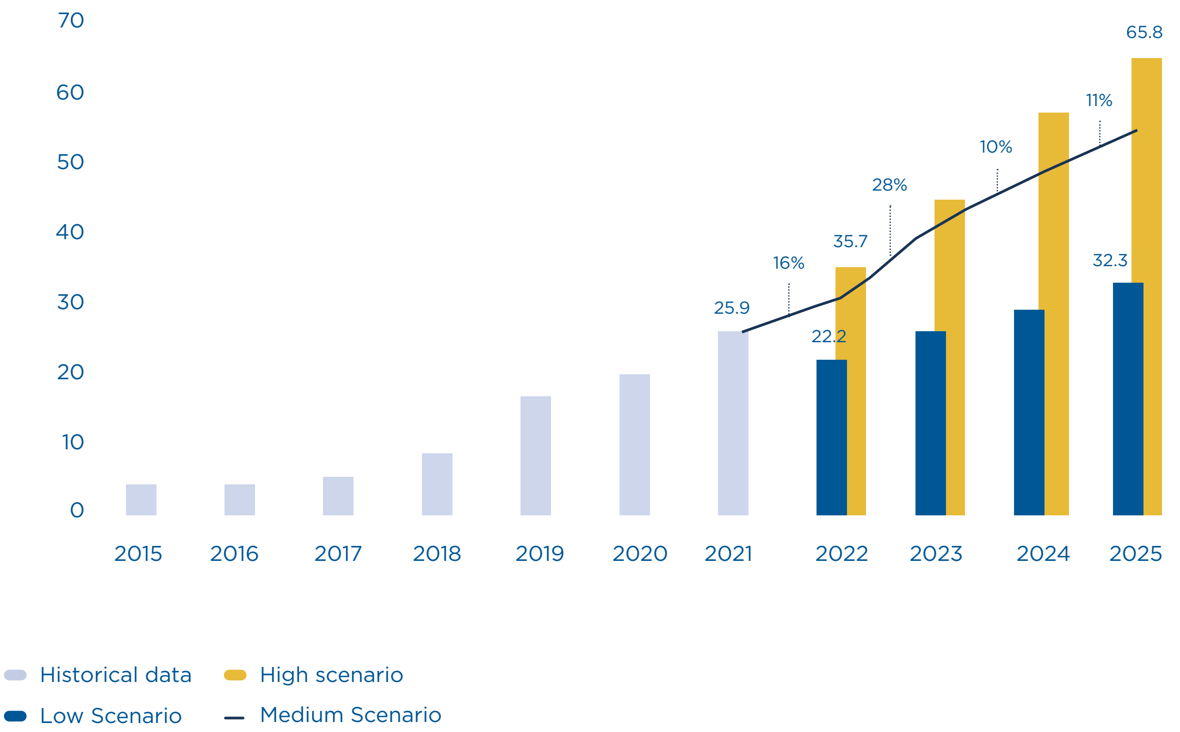
Another case is silicon, which also comprises a very small part of the weight, but has a very relevant economic value if recycled at a high-quality grade, offsetting its production that represents 80% of the total greenhouse gas emissions of the panel. Silicon comes from quartz, obtained after melting it and treating it chemically. Generally, the outcome purity of the silicon after this process is around 99%, which still needs to increase by up to 8 more decimals to reach the PV rate. This process is extremely expensive and energy consuming.

Thin-film panels, on the other hand, only contain around 2% of hazardous materials (copper, zinc, and other semiconductors). Such materials are typically subject to rigorous treatment requirements with specific classifications depending on the jurisdiction.

1.1.2 Analysis of the expected deployment of Solar PV

Solar photovoltaic technologies have become the world's fastest-growing energy technology and play an important role in securing a sufficient supply of decarbonised electricity. In 2021, despite the shortage on material supply, logistic issues and consequent price hikes suffered by all member states, there were 25.9 GW of newly installed PV in the European Union. This shows an increase of 34% over the 19.3 GW installed the year before, and a new record since 2011, adding up to a current total installed capacity of 165 GW.

Figure 2.
EU27 annual solar PV market scenarios 2022-2025 (SolarPower Europe 2021).



According to Solar Power Europe's EU market outlook, the aim of the National Energy Climate Plan (NECP) was to reach a target of 335 GW by 2030, starting with 30 GW installation set for 2022. This is the official goal, although the experts believe such deployment is likely to be exceeded much earlier, with a more realistic scenario of 328 GW of installed solar capacity by 2025. In line with this, in its impact assessment, the European Commission predicts that by 2030, from the 40% renewables share, 479 GW will come from solar energy. As shown in Figures 2 and 3, different scenarios have been proposed. Nevertheless, the industry claims the European Commission and the member states to be more ambitious with the targets in order to deal with climate change and be able to meet the Paris climate goals. In line with this, the recently published REPowerEU Plan, by the European Commission, triggered by the recent geopolitical situation, has set new more ambitious objectives in order to increase the resilience of the energy system of the entire European Union.

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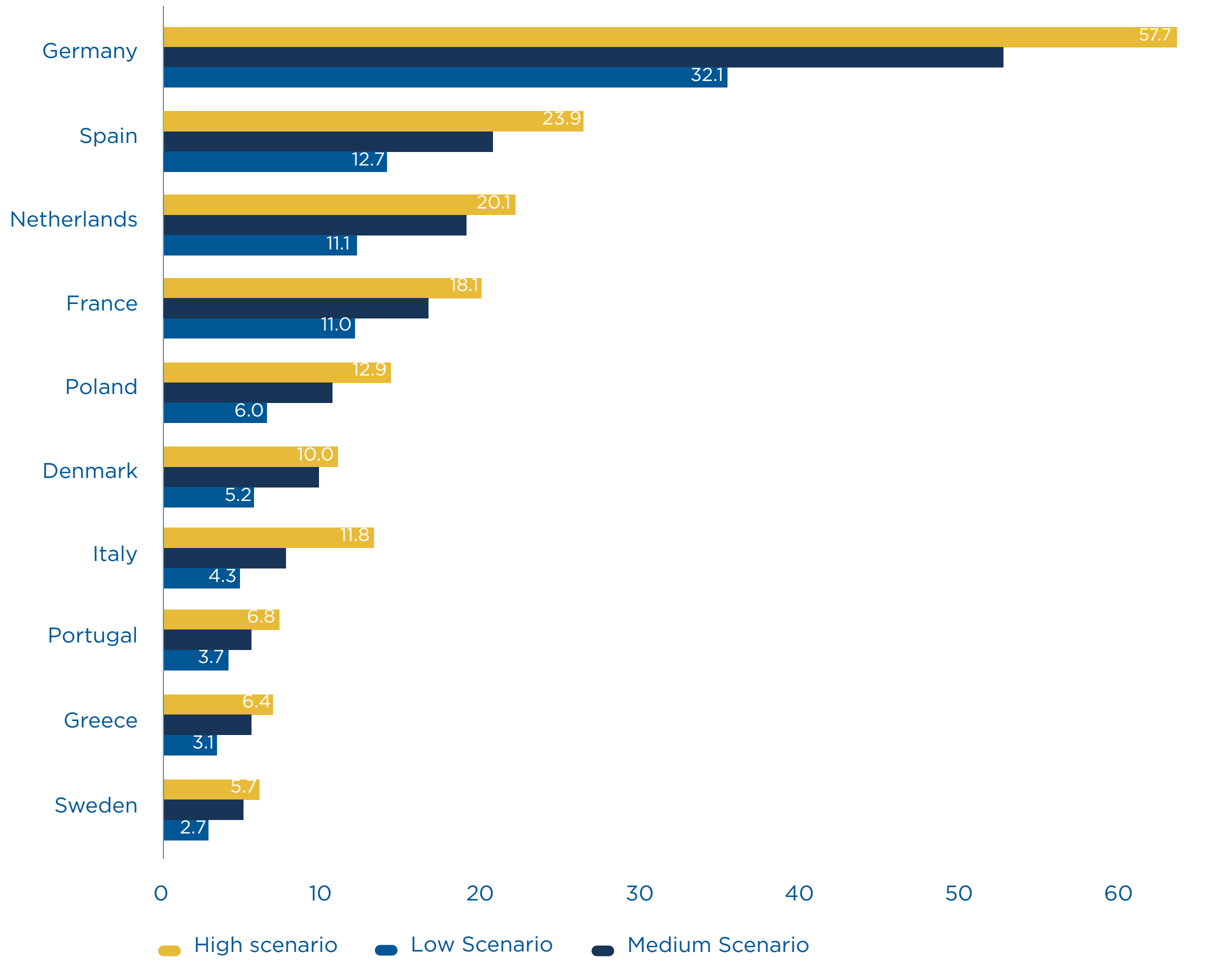
As shown in Figure 3, Spain has retained its second place in Europe, with an estimated capacity of 3.8 GW in 2021, slightly higher than that of the previous year. Out of these, 3 GW actually originated from systems based on PPAs, which represent one of the world's largest markets for unsubsidised solar power. In the years to come, a key emerging segment for PV in Spain will be self-consumption rooftops, which will help reach the upcoming target of 18.9 GW installation by 2025. The Spanish Energy Ministry created the Energy Expert Committee in 2018 to analyse the options on defining a strategy that allows Spain to comply with EU environmental objectives, while also pursuing the maximisation of the welfare of its citizens. In its recently published report, scenarios on the evolution of the low carbon economy national energy sector suggested that the national PV installed capacity could reach up to 90 GW in 2050.

Figure 3.
EU27 top 10 solar PV market additions 2022-2025 (SolarPower Europe 2021)



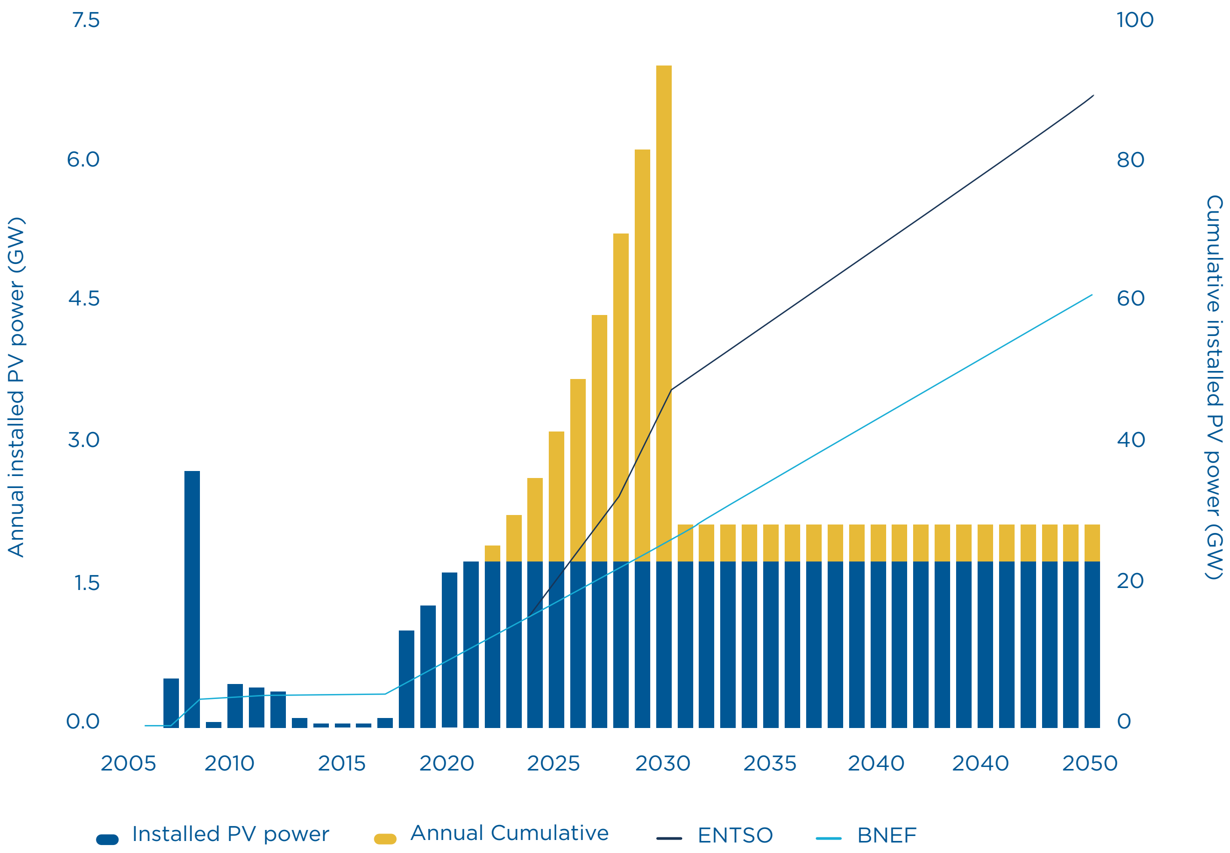
More concretely, in Spain, CIEMAT has developed one of the most thorough studies to predict the national PV deployment and consequent waste created. Figure 4 below, summarises the evolution of Spanish PV capacity considered by the following two projections presented in the study:

- **Projection ENTSO:** combines the distributed generation scenario proposed by the European Network of Transmission System Operators for Electricity (ENTSO-E), with the base scenario proposed by the Spanish Expert Committee (SEC). This ENTSO scenario assumes a PV capacity of 47 GW in Spain in 2030, boosted by a noticeable increase of small-scale generation and PV self-consumption, in good agreement with some of the new national energy policies. The SEC scenario uses an optimisation model that determines the cheapest technology mix that covers the expected national energy demand, leading to 90 GW in 2050. In this ENTSO projection an exponential growth of the cumulative PV capacity is assumed in the period 2020-2030, followed by a linear growth in the period 2030-2050.
- **Projection BNEF:** based on a different approach of the Spanish Expert Committee taking into account the forecast of Bloomberg New Energy Finance (BNEF) for the period 2020-2030. This BNEF projection considers that the high demand of new PV installations could lead to problems in the supply chain, limiting the development of the cumulative PV capacity in Spain to 26 GW in 2030. This forecast is in good agreement with the scenario produced by the European Commission in 2014 to achieve the climate and energy targets. In this BNEF projection, a linear growth is assumed in the period 2020-2050, leading to a PV capacity of 61 GW in 2050.

61

GW in 2050. A linear growth is assumed in the period 2020-2050, leading to a PV capacity of 61 GW in 2050 (Projection BNEF).

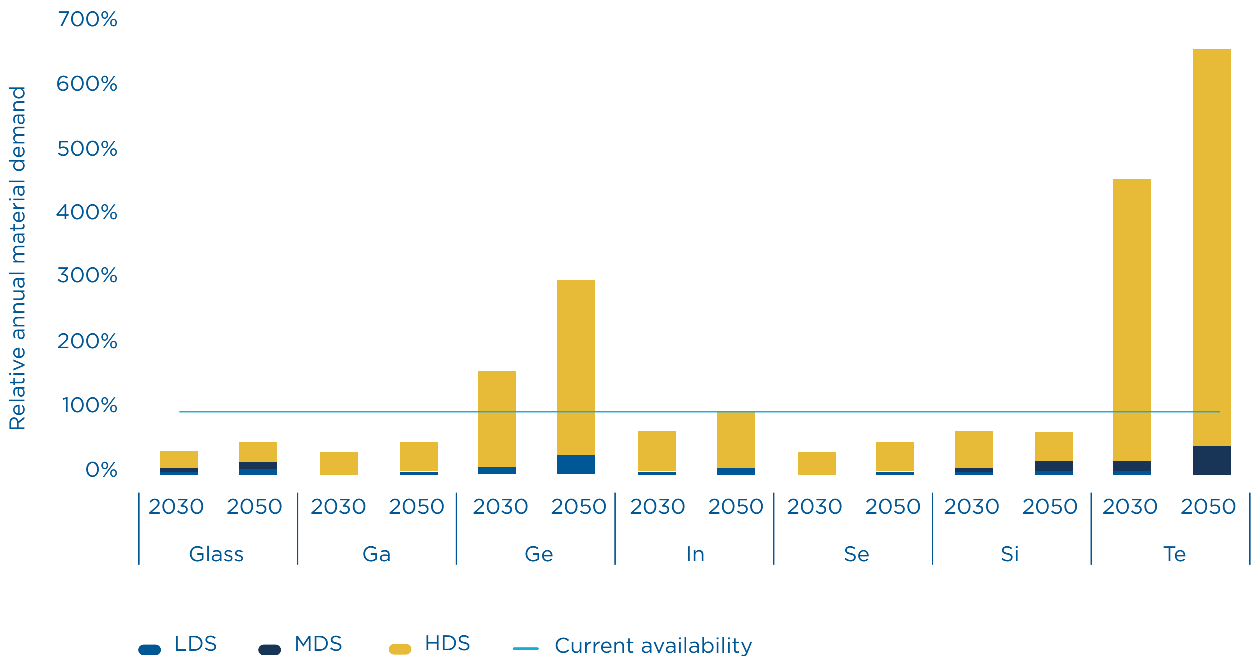
Figure 4.
Evolution of annual and cumulative installed PV capacity for the two chosen scenarios of the expert committee. Annual installed PV power from 2018 is initially approximated by the annual increase of the cumulative PV capacity, without considering repowering needs.



From this analysis we can conclude that PV demand will increase notably in the coming decades. Will the availability of raw materials needed for this sector limit this necessary growth? Well, this is not easy to predict yet, since material demands for solar PV vary greatly as they are dependent on the relative market share of each technology. By now, although no major supply issues are foreseen, some scenarios at global level predict additional pressure on several materials, in particular germanium, tellurium, indium, selenium and silicon.

By now, although no major supply issues are foreseen, some scenarios at global level predict additional pressure on several materials, in particular germanium, tellurium, indium, selenium and silicon

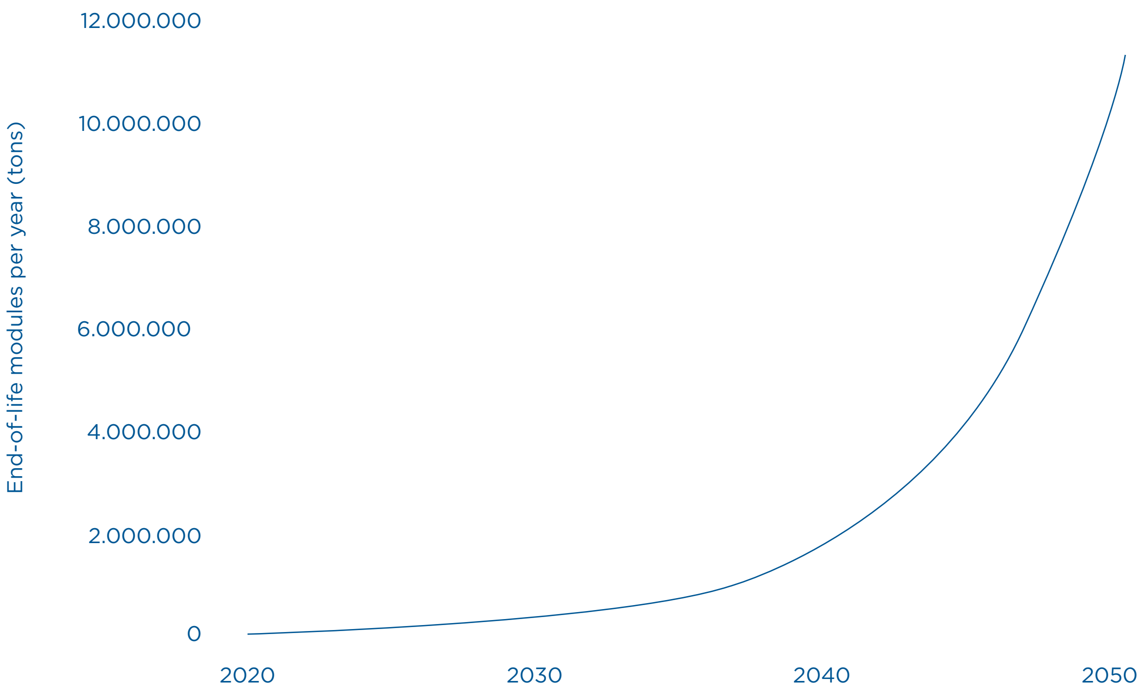
Figure 5.
Global PV material demand-to-global supply ratio in 2030 and 2050 – levels of demand close to current availability.



1.1.3 Prediction of PV waste generation

No matter which expert scenario we focus on, the reality is that the PV industry is still in a ramp up phase. With these large quantities of photovoltaic modules installed every year, one key question arises: what happens to solar panels when they reach the end of their lifespan? This is an aspect we must not forget; modules will eventually have to be replaced or disposed of. In order to achieve the maximum contribution to climate protection and conservation of resources, reuse and recycling play a key role in closing cycles.

Figure 6.
Annual waste PV module expected per year in Europe.

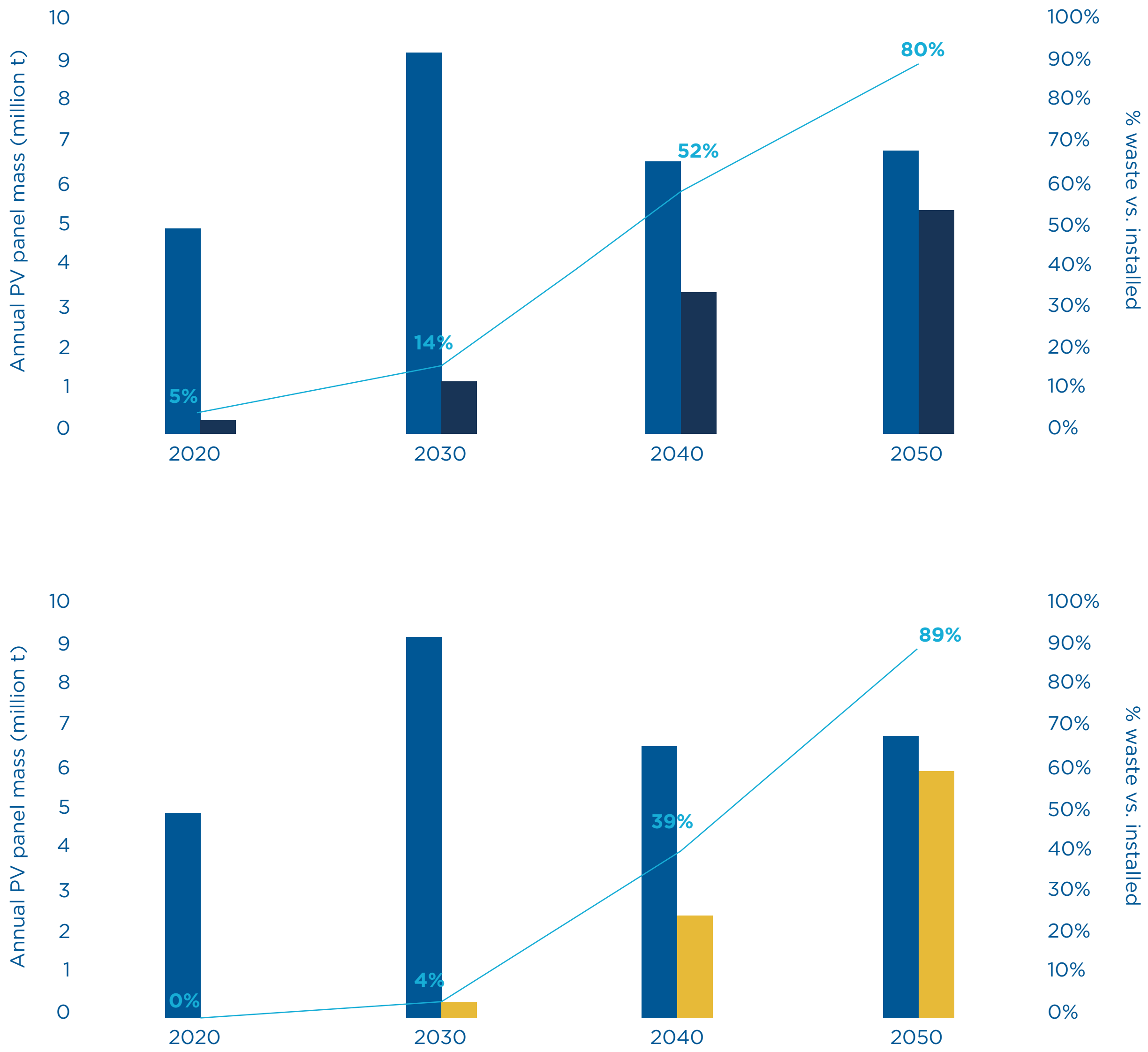


Given installation targets, and considering their lifespan of 20-25 years, in addition to the extra replacements of defective panels and repowering initiatives due to improved efficiency, in the coming years we can expect an exponential growth in PV systems reaching the end of their physical and, in some cases, economic end of life. Some forecasts predict a quantity of up to 1 million tonnes of old modules for 2030; it is therefore urgent that we build the right scenario today to make collection and disposal structures fit for the future, so that the greenhouse gas emissions related to PV energy can be tackled.

In 2016, IRENA presented a report with the first ever projections made on PV waste. It predicted that Europe was to experience the second largest PV waste market in the world, after Asia, with projected waste of up to 3million tonnes by 2030. Germany was at that time forecast to a mass between 400,000 and 1 million tonnes of PV panel waste by 2030, an amount which has notably increased based on the higher actual deployment compared to the projections made in 2016. Furthermore, Italy and France were also predicted to produce significant volumes of PV waste.

From more recent predictions by Solar Power Europe, the calculation of the annual PV waste produced in Europe versus the capacity installed will reach between 4 and 14% ratio in 2030, depending on the scenario, with around 1 million tonnes of waste and 9 million tonnes of new capacity. And, what is more relevant and worth keeping an eye on are the 2050 figures, where it is expected to reach an 80% ratio, with only 1 million tonnes less waste than new installed capacity.

Figure 7.
Annually installed and end of life PV panels (2020-2050) Early loss and regular loss scenarios.



In terms of Spain there are also specific predictions, as more recently published in the Journal of Cleaner Production in 2018, where the PV waste mass is assessed on the basis of cumulative PV capacity projections of a 100% renewable Spanish scenario in 2050. This study predicts a cumulative PV waste mass ranging from 70 000 to 300 000 tonnes by 2030 deriving from PV modules installed in 2007–2008 and the order of 1 000 000 to 2 000 000 tonnes by 2050, with values dependent on the PV capacity projection; a clear call for action for the PV recycling sector in Spain, expected to be one of the leading countries in PV waste generation in the EU.

1.1.4 Some initiatives addressing the problem

Although to date the end-of-life of PV modules is insufficiently managed, there are many actors and initiatives in Europe and worldwide aiming to address the problem. One example is the International Energy Agency's Photovoltaic Power Systems Programme (IEA PVPS), which has joined over 30 international members in the sector to undertake a variety of joint research projects in PV power systems application, designating distinct 'tasks,' that may be research projects or activity areas. Within the scope, Task 12 focuses on PV sustainability, and covers relevant studies on environmental profile quantification (LCA), end-of-life management options and environmental health and safety issues that are important for market growth. Based on this study, despite the economical motivation to dismantle panels earlier than their lifetime (because of performance losses and higher efficiencies of new modules), a common technique known as early re-powering/revamping, it is better for the environment to keep a panel in use for its 30-year lifetime instead.

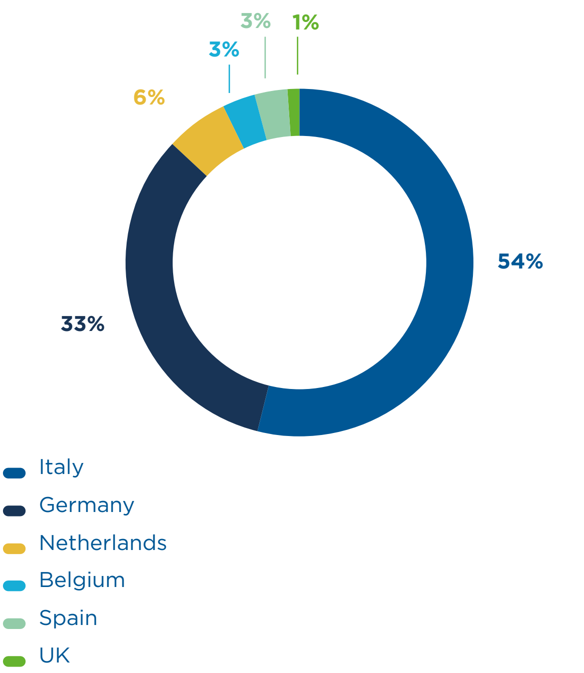
The same initiative conducted a study where they collected information from different collecting and recycling plants of PV waste around Europe, concluding with the following statements on the actual status of the market:

- Recycling rates are quite high (74-95% of the weight).
- A large majority implemented mechanical treatments that limited the recovery materials to the aluminium of the frame and glass, but did not allow for recovery of critical materials of highest value.
- A minority implemented more innovative techniques based on thermal treatments, which allowed for the elimination of the encapsulant and could recover critical materials, thus increasing the profitability of the recycling process.

Since to date the number of panels reaching their end of life in Europe is still limited, at the moment they are being processed in bigger plants with other electronic waste. However, in 2018 the first PV recycling plant was created in France. The plant, managed by Veolia, processed in its first year 1800 tonnes of waste, with a capacity of reaching up to 4000 tonnes annually. The recovered materials from this plant were: glass, aluminium, electronic components, and cables.

According to the PV CYCLE Association, also involved in several R&D projects such as CIRCUSOL where the circular economy meets solar energy, in the past few years there has been stability in the collection rate, mainly due to the Italian market, which has continued to rise despite the COVID-crisis. With 5801 tonnes including 1492 tonnes of batteries processed for the year 2020, Italy has increased its operations by almost 21%.

Figure 8.
Cumulative collected volumes of PV waste by country.

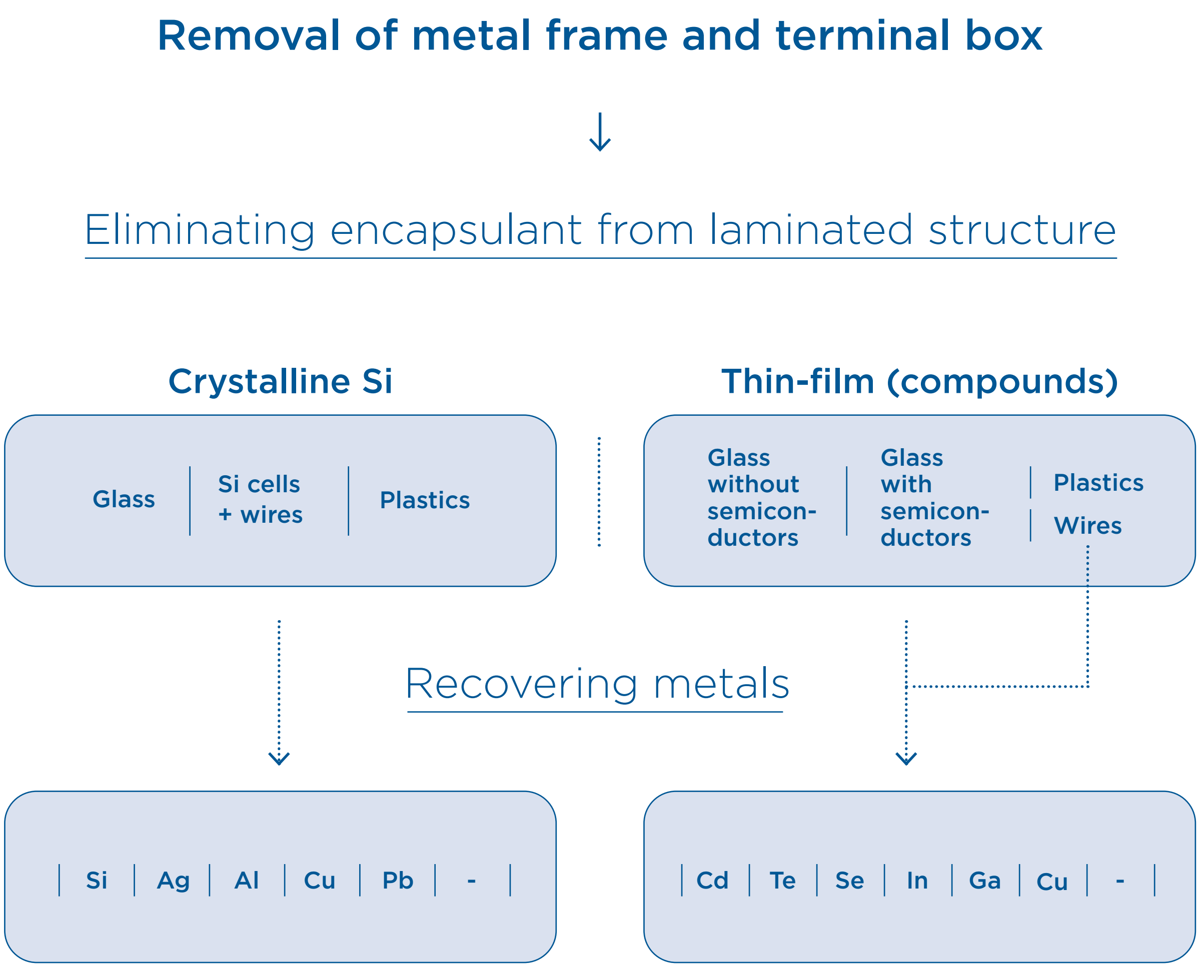


As we can see, although the recovery rate of the PV panels seems high, the recycling techniques most commonly used are limited to the recovery of the heavier components of low economic value. Being able to recover the critical materials of high value, such as silicon, silver, copper, and aluminium is key to creating an incentive in the PV recycling market, both sustainably and economically.

1.2 Technologies for Solar PV recycling

Figure 9 below indicates the basic steps of a PV module treatment process, differentiating c-Si from thin-film structures. As we will explain in this section, there are different techniques for the recovery of materials. Nevertheless, in every case the most important and most difficult process is eliminating the encapsulant from the laminated structures.

Figure 9.
Separation process for PV module recycling.



1. **Removal of the metal frame and terminal box** ⟶ this first step is purely mechanical, although it is very important to do it effectively without damaging the glass in order to be able to reuse/ sell it. For this step, specific machinery is usually used, such as a cylinder actuator which uses air to remove the aluminium frame, or a milling machine for the backsheet.

2. **Eliminating the encapsulant** ⟶ separating glass, polymers, Si cells and other metals, and recovering PV cells without breakage. Different approaches to this are:

   a. Thermal

   Consisting of a combustion/burning or a cracking process: PV modules are heated in a furnace at 500-600°C at which temperature the polymer components will melt, and the remaining materials, such as Si cells, glass and metals can be separated. The separated materials are later recycled.

   b. Mechanical

   The mechanical approach for PV module processing usually includes crushing, scraping glass or layers, and cutting the encapsulation layer. These methods break up the laminated structures, with subsequent additional step(s) for separating glass, metals including Si cells, and polymers combined. As previously explained, nowadays it is very common to use crushing. However, this practice jeopardises the capability to recuperate metals from the cell, since once the glass is mixed with the metals, it is no longer feasible to recover them. There are other mechanical techniques which stop contamination of the glass by the encapsulation layer, such as:

   - Mechanical scraping.
   - Mix of mechanical scrapping and chemical treatment.
   - Use of a heated cutter.
   - Use of roller mill and vibrating knife equipment.
   - Use of grinding technology under refrigerated conditions.

   c. Chemical

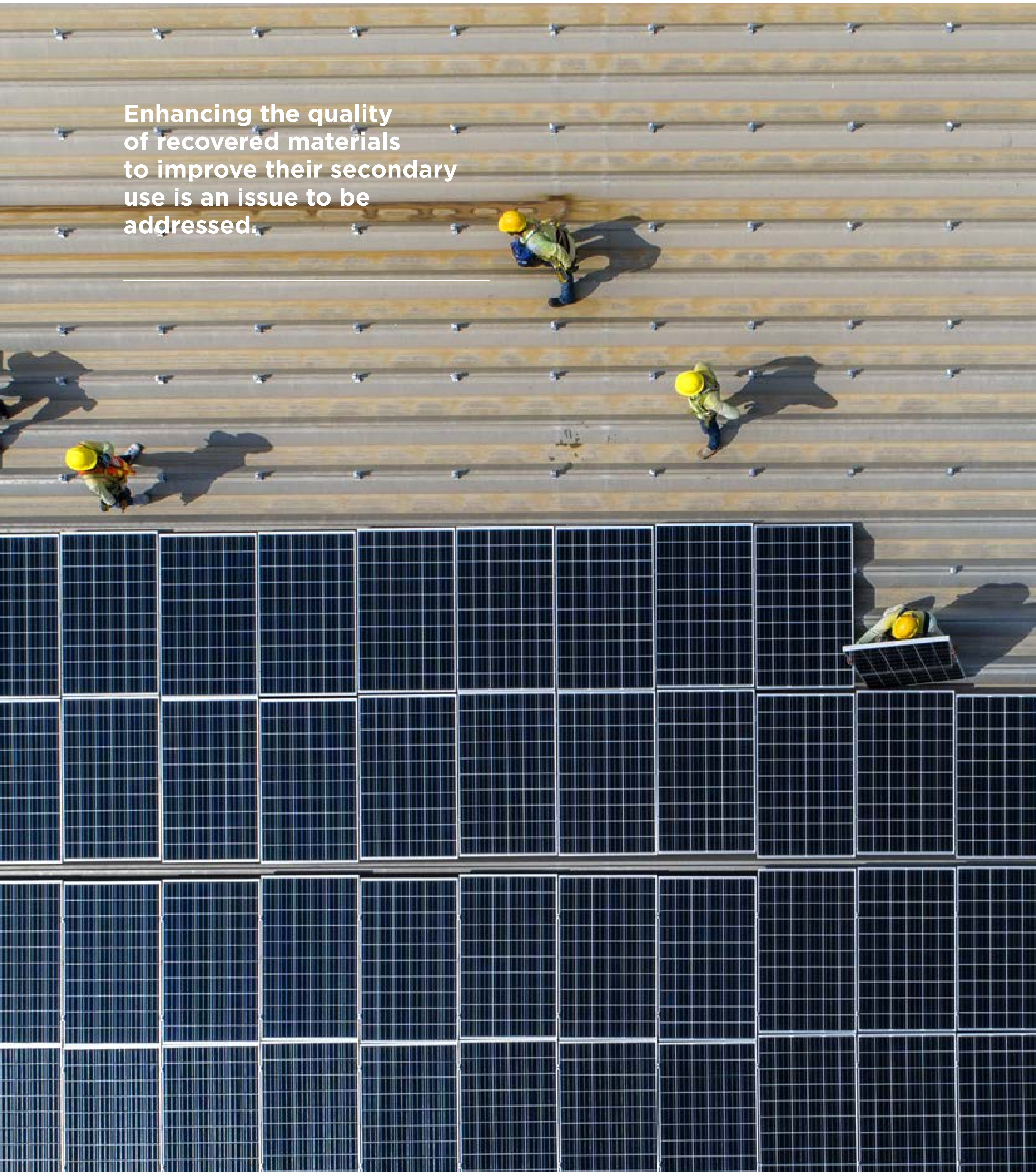
   A chemical approach consists of separating the components by using solvents, which dissolve the encapsulation layer, allowing for the separation of the glass, the Si cell, and the metals. It tends to require more time, but these techniques show good Si recovery rates. A relevant countereffect here, is the disposal of chemical solvents after treatment. For this reason, the use of organic solvents has been tested in the field. Nevertheless, these were only shown to be effective before thermal treatment.

   d. Optical

   This method basically consists of cutting the encapsulant with a laser.

1. **Recovering metals** ⟶ After theremoval of the encapsulation layer, recovery of the metals from Si cells can be achieved by chemical approaches such as etching with acid or alkali hydroxide, thus requiring proper treatment for chemical waste. In some cases it is directly treated by a metal refinery company. On average, around 85-95% of the metals could be recovered, although this depends on the recycling technology selected. Finally, if the process is efficient enough and the quality of the recycled materials meets the PV industry's requirements, they can be reprocessed from wafers into cells again.

This last step, the recovery of the low weight valuable materials, is the new focus of the sector moving forward. Also, enhancing the quality of recovered materials to improve their secondary use is an issue to be addressed. In the box below, we give an example of a French company that has developed a solution for this. ROSI Solar is a good example of how the technologies of the future can aim higher in the PV recycling business.



Enhancing the quality of recovered materials to improve their secondary use is an issue to be addressed.

Interview with ROSI Solar, French PV recycling company

To better understand the recycling process at firsthand, we took the opportunity to **meet one of its experts, ROSI solar.** This French technology start-up has developed a process that enables deep separation of the materials inside PV panels, to reduce financial losses and ultimately cut down greenhouse gas emissions triggered by the production of raw materials for the industry. Their desired participation in the operation and recycling site is included in their business model, to which end, they partner with other recyclers to cover the whole recycling chain.

As they explained, when a module comes in, the first step is to remove the cables from the junction box, the frame and the glass. The frame and cables are in good condition and easy to reuse. The glass is removed by one of their partners with a hot knife, which allows it to be kept intact. The glass is very heavy, transparent, and of very high quality, a good deal for an already existing secondhand market of industries with such requirements, such as the bottle and glass wool industries. A good practical example for this is a German company called Reiling, a glass producer that also recycles glass from PV modules. Sometimes, the panels arrive with the glass broken. In this case, it can be reused as an inert material, which is commonly used in roads as a stabilising layer. In such cases, it is not really recycled, since there is an important loss of a quality material.

The next step consists of detaching the polymer from the metals inside the module. In medium and large-scale modules, ROSI does this through pyrolysis, evaporating the polymer, which allows for the recovery of metals in a very good condition. Then, they separate the metals: copper from the ribbons, the silicon cell, and the very thin but valuable silver fingers which are on top of the cells.

As previously mentioned, the base material used in PV modules is silicon (PV-Si). To produce silicon wafers, a silicon ingot is cut into very thin slices. During this process more than 40% of the

ultra-pure silicon is lost as part of the sludge known as “kerf”. ROSI has developed a solution to salvage this kerf by fully separating the fine silicon from the sawing liquid. This way, the liquid can be reused in the process, and the silicon particles can be recovered and reconditioned and re-entered upstream.

When it comes to recycling the silicon from PV modules at end of life, the challenge is to maintain the purity rate. This requires working with very high efficiencies and extremely precise separation techniques; if the silicon is mixed with the glass, it becomes very difficult to separate them, as they have the same density. So when, in some recycling plants, they crush before separating, the value (environmental and economic) of the silicon is entirely lost.

ROSI Solar’s technologies can recover the ultra-pure silicon from the cell, but also the silver fingers used to collect the electric current generated by each. Moreover, they do not use aggressive chemical reactions; their processes are based on physical, thermal, and soft chemistry mechanisms. In parallel, they also collaborate with other companies in Europe to test new solutions to detach the polymers and the glass from the cells.

Regarding the silver, in PV modules it comes as silver-plated conductors. Worldwide, there are just a few companies able to print this specific combination of silver alloy with a good enough quality to conduct the current. For this, they require silver of significant purity (99.99%), which is later treated and mixed with lead and tin for the final composition, which is sold to PV producers. In order to recycle it, it needs to be separated from the mix and purified again.

Apart from ROSI, there are other proven technological solutions for PV module recycling. This growing trend worldwide is key to the energy transition, and it goes hand in hand with regulatory, business and other incentivising initiatives on the market. Last year, for example, based on literature, interviews, and surveys collected from the main parties in the value chain, the DUH developed and published a white paper with improvement options for the reuse/recycling sector. Other collaborators in the solar and waste disposal industry included in this study were First Solar, ROSI Solar, Take-e-way and Veolia.

Thin-film modules

Thin-film modules are processed and recycled using a combination of mechanical and chemical treatments. As a reference, these are the steps of the process implemented by the company First Solar, with a mass recovery rate of nearly 90% for glass and approximately 95% for semiconductor materials:

1. **Breaking** the lamination bonds by shredding and crushing in a hammer mill into particles of about 5 mm. In parallel, aspiration of the dust with a particulate air filter.
2. **Etching** a semiconductor layer with a chemical mixture.
3. **Separating** the glass and larger pieces on a vibrating screen, and then rinsing the glass with water and drying it on a belt filter unit.
4. **Extracting** filtration liquids with metals via precipitation.
5. **Purifying** cadmium and tellurium by third parties, if desired, for reuse in the solar industry.

New generation panels

Although most PV modules follow similar rules on the structure and cell size, there are already 50 000 different designs on the market. This means that the existing recycling sites, and the ones to be built, will need to be able to adapt their processes to this variety, since different designs may use different materials and have different thicknesses. Despite this, the new generation panels, such as heterojunction or tandem cells, are based on adding thin-film layers to the top of the panel, which means that new technologies will still be based on silicon. This will allow the existing processes to be able to handle most of the incoming PV waste.

1.3 Regulation on PV waste management

PV module recycling is the solution to both, reducing the environmental impact of the PV industry and assuring the supply of raw materials. This is a strategic action for the PV industry and for Europe. For this reason, a regulatory framework has been implemented to support the management and recycling of the waste of electrical, electronic equipment (WEEE), associated with the PV module at end of life. In this sense, existing EU directives have been an inspiration for other countries around the world, such as Australia or South Korea, aiding in the process of drafting recycling and other environmental protection regulations. The necessary policies and technologies for recycling PV systems are currently under rapid development. In Spain concretely, they have established the Royal Decree 110/2015 that determines minimum annual WEEE recycling targets.

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1.3.1 Introduction to the WEEE Directive

In Europe, PV modules have been subject to the Waste Electrical and Electronic Equipment Directive (WEEE 2012/19/EU) since its last adaptation in 2012. This means that the return and recycling of PV modules is, in fact, already mandatory in Europe. In practice, although it is slowly increasing, this is currently performed in small quantities. Another EU directive which is in some cases affecting PV waste is the RoHS 2011/65/EU – Restriction of other Hazardous Substances.

WEEE is transposed by each member state into national law; they must implement it by complying with the producer responsibility rule, which states that the end-of-life management of PV modules is the legal responsibility of producers. So, who are these producers? Any natural or legal person who manufactures and sells electrical and electronic equipment, places products manufactured by third parties on the market, or makes community acquisitions or imports from third countries. Applied to photovoltaic panels, this 'producer' can be any company present in the chain: the panel manufacturer, its distributor, the plant promoter, or even the self-consumption installation company. In the case of Europe, there are some small producers in countries such as Spain, France, or Italy, but generally recycling responsibility falls on the importers. According to the directive, the producers must manage the equivalent market share of modules they deploy in a year.

There is one exception on the market, which is the thin film manufacturer First Solar, which manages its own modules because they contain dangerous specific substances like Cadmium telluride, not usual in other PV technologies. For this reason, the company has developed their own collection system and recycling technologies, as detailed in the previous section, thus providing a full service until the end of life of their modules.

WEEE establishes collection rates targets based on the volumes put on the market. Even on paper, the objectives set are ambitious. The problem is that in Europe to date, end-of-life modules are still limited in quantity compared to the volumes placed on the market each year. This means that the waste generated by PV panels will remain limited for some years to come. In addition, there is a big difference in the number of panels installed by each European country.

1.3.2 Implementation of WEEE

Each country has developed their own system, although the most common way is through recycling schemes, also known as producer responsibility organisations (PRO); legal bodies that manage end-of-life actions. These nonprofit organisations take the legal burden of collection and recycling activity. Despite the name, these bodies are not composed by the producers themselves. What is more, to finance these operations, the PRO charges each producer a membership fee based on waste generated. But they do not work alone; in practice PROs are responsible for collecting the modules, but they still need to find the right technical partners to conduct the recycling. Sometimes PROs specialise in a type of electronic waste, other times they deal with several waste streams.

- In Spain, for example, there are at present few organisations collecting PV waste, and uncertainty regarding who is responsible for each role.

- In France, in comparison, there is one organisation monopolising collection of all PV waste, with collection rates of up to 5000 tonnes/year.

- Another example is Germany, which has set an open market with several actors and different legislations in charge, depending on the use (household or industrial) and the panel technology (newer versus older designs).

1.3.3 The challenge of tracking the PV waste

While there are different approaches by each European country to handling the collection and recycling market of PV waste, they all have one thing in common: there remains a serious lack of transparency on the monitoring of the modules at their end of life. Even though waste treatment is considered part of a module's life cycle, there are very few life cycle inventories (LCI) of energy and material flows available for industrial recycling processes. How can countries which were pioneers in PV in Europe, still record such low waste collection rates? This highlights another key legal problem in the sector, that related to un-tracked exporting.

In Europe there are a number of initiatives studying this situation in detail, interviewing all parties involved in the chain to understand why modules go missing at their end of life. Some reveal that they are exported to developing countries as secondhand material. The issue here is not that they create a secondhand market, but that many times they burden these countries with modules that are no longer functional or have a very short lifetime remaining. Since there is no regulatory framework currently available to track exported modules, this activity is commonly, and wrongly used to avoid the expenses related to the treatment of e-waste in Europe, or simply to make a profit. Nonetheless, the market is slowly changing, developing the right rules to control border transactions in Europe, enforcing an obligation to provide proof and waste identification references as part of a series of close checks by customs and port authorities.

Another aspect of the regulatory framework for PV recycling which seems likely to change in the near future, is the requirement of WEEE mandates for recovery fractions of the modules' mass. Currently, in order to comply with the law, recycling facilities designed to treat glass, metal or e-waste have simply increased their work capacity, but there are only a few specialised recycling processes for the minor constituents of the panels. The goal is to optimise collection and recycling structures and be able to close the material cycles so that they can be used for renewed module production. To this end, there are other emerging EU initiatives pushing for eco-design, energy labels and ecolabels with the aim of encouraging and promoting a more sustainable PV design.

1.3.4 Existing regulation in Spain

A similar thing occurs in individual member states, such as Spain, where having a legal framework is the first step to achieving an increase in collection quantities and better utilisation of old PV modules. In Spain, the directive was transposed by the Royal Decree 110/2015, which initially included PV panels in the category of electronic devices, but since 2019 has classified them apart. The Royal Decree defines the minimum requirements for PV waste recycling facilities, as well as the technical procedure for managing them.

According to the RD 110/2015, Spanish producers must comply with the following:

- Official Register - in the National Registers of Producers of Electrical and Electronic Devices and Batteries and Accumulators managed by the Ministry of Industry.
- Products declaration - on a quarterly basis, regarding the quantities of products placed on the national market.
- End-of-life management - adopt the necessary measures and financing costs so that the panels are collected at the end of their useful life and receive proper environmental management.

There is still a challenge to overcome regarding this last point, which is that some PV production companies have not survived long enough in the market, or at least not longer than their PV installations. This means that by the time a PV plant reached its end-of-life, there was not a legal entity to take responsibility of the collection. Although this situation is still happening from time to time, nowadays the market is much more mature and structured, and the survival of the PV producers is no longer so challenging.

Regarding the collection practices, at present, the sector is working towards providing a user-friendly process and nationwide return options. This way, producers/importers would be obliged to join a take-back system or create similarly good return options with sufficient collection points. Furthermore, experts agree that the minimum recycling targets proposed in the Spanish Royal Decree on Wastes of Electric and Electronic Equipment (WEEE) should be revised to offer long-term direction.

Minimum recycling targets proposed in the Spanish Royal Decree on Wastes of Electric and Electronic Equipment (WEEE) should be revised to offer long-term direction

2

Wind Power

2.1 Introduction to the End of Life Management of the Wind energy market

Regarding the wind energy industry, as it happens with the PV industry, market traction and industry projections are ambitious. Already to the date, some wind farms are nearing their end of life and need to be assessed to make an informed decision as to whether life extension, or dismantling is appropriate. Several factors influence this decision.

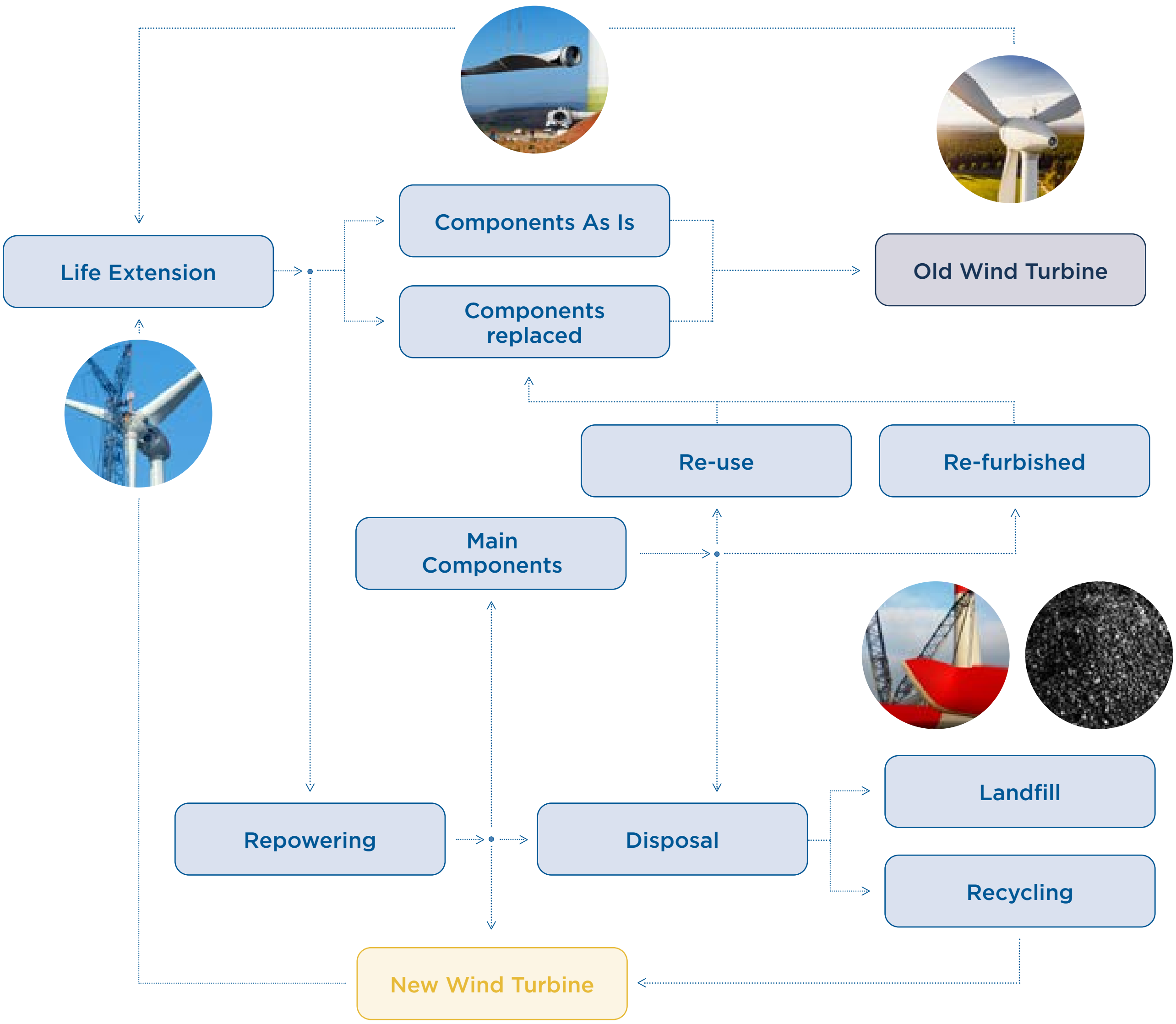
In most cases, life extension is the preferred option as it is the easiest way to maximise on return of investment. However, this approach requires that the owner assess the status of their asset in terms of possible lifespan. In addition, a reliable spare parts supply is required. This might prove difficult, as OEMs may not have information at hand as to the original design of certain wind turbines. Some models were designed and manufactured by companies that have since been acquired or disappeared some time ago.

Where this is unfeasible, a repowering approach is required, where wind turbines are dismantled and replaced by modern ones, in addition to potential small upgrades to the grid connection infrastructure. There are several elements that would affect the decision to pursue this solution: regulation, for example, or how much of the previous investment in the balance of the plant may be reused.

Finally, if neither of the above options are deemed appropriate for economic or regulatory reasons, the asset owner may decide to discontinue activity and completely dismantle the power plant. The decision-making process is detailed in Figure 10.

Regarding the wind energy industry, as it happens with the PV industry, market traction and industry projections are ambitious

Figure 10.
Wind turbines Life & Components Flowchart.



If dismantled assets are balanced against life-extended assets, we may have a quite stable and interesting opportunity for reuse and re-furbishment using main components. Of interest in such cases are reuse of gears, inverters, generators, blades, actuators, powertrains, and controls.

However, this balance will not work for wind turbine models that were not a mainstream solution in the past, as it is unlikely that sufficient volume of reused or refurbished components will be available to sustain their life-extension requirements.

2.1.1 Materials and composition of Wind turbines

Even though the materials used and wind turbine power ratings have evolved in recent decades, the average consumption of materials per MW has remained stable. This can help us define the quantities used or needed for use, and establish the requirements of managing such disposals now and in the future.

As shown in Table 4, below, most differences are derived from the introduction of permanent magnet synchronous generators (PMSG) and the intensity in use of rare earth materials.

Standard, non-specific materials account for more than 90% of the total weight of a wind turbine, including its foundation. This ratio is even greater if we consider offshore power plants. This is especially important when talking about recyclability and recovery of raw materials for which there are already technologies, business models or supporting mechanisms in place.

However, the other 10% come with challenges in terms of economic viability and the availability of technologies. This will be discussed further below.

Table 3.
Metric tons of material per GW (ref: Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system, JRC – European Commission, Carrara, S., Alves Dias, P., Plazzotta, B., Pavel, C., 2020)

Material	GB-DFIG	DD-EESG	GB-PMSG	DD-PMSG
Concrete	355.000	369.000	413.000	243.000
Steel	113.000	132.000	107.000	119.500
Iron (cast) (Fe)	18.000	20.100	20.800	20.100
GFC / CFC	7.700	8.100	8.400	8.100
Zinc (Zn)	5.500	5.500	5.500	5.500
Polymers	4.600	4.600	4.600	4.600
Copper (Cu)	1.400	5.000	950	3.000
Aluminum (Al)	1.400	700	1.600	500
Manganese (Mn)	780	790	800	790
Chromium (Cr)	470	525	580	525
Nickel (Ni)	430	340	440	240
Molybdenum (Mo)	99	109	119	109
Neodymium (Nd)	12	28	51	180
Dysprosium (Dy)	2	6	6	17
Praseodymium (Pr)	0	9	4	35
Terbium (Tb)	0	1	1	7
Boron (B)	0	0	1	6
Total (only WT)	**153.393**	**177.808**	**150.852**	**163.209**
Total (all)	**508.393**	**546.808**	**563.852**	**406.209**

(DD EESG = Direct Drive External Excitation Synchronous Generator, DD PMSG = Direct Drive Permanent Magnet Synchronous Generator, GB PMSG = GearBox Permanent Magnet Synchronous Generator and GB DFIG = GearBox Direct Feed Induction Generator)

In comparison with the PV market, in the wind energy industry most of the materials are of less value than the component itself so it does make more sense to repair and refurbish them to use it as spares for other turbines. Just when the life of the component cannot be extended, the material recovery will be an option. In such case the value of the materials may just cover the costs of the disposal processes. Only exception to consider are the rare earths with very high intrinsic value.

Table 4.
Materials requirements vs production capacity and prices (all referred to metric tons) for an annual retirement of 10 GW.

			Production		
Material	**Demand**	**vs. World**	**Global**	**Europe**	**Price $**
Concrete	10.350.000	0.10%	10.058.000.000	610.400.000	50
Steel	3.536.250	0.18%	1.911.900.000	11.500.000	736
Iron (cast) (Fe)	592.500	0.43%	139.000.000	9.100.000	1.481
Glass/carbon composites	242.250	3.79%	6.400.000	950.000	1.000
Zinc (Zn)	165.000	1.24%	13.300.000	88.926	3.639
Polymers	138.000	0.23%	59.000.000	6.726.000	N/A
Copper (Cu)	77.625	0.46%	16.890.000	135.321	9.919
Aluminum (Al)	31.500	0.05%	65.296.000	262.000	3.546
Manganese (Mn)	23.700	0.13%	18.000.000	0	4
Chromium (Cr)	15.750	0.04%	44.000.000	0	7.400
Nickel (Ni)	10.875	0.40%	2.700.000	285.000	2.4695
Molybdenum (Mo)	3.270	1.31%	250.000	100	12
Rare Earths (Nd, Dy, Pr, Tb)	2.693	1.12%	240.000	0	50.000
Boron (B)	53	0.00%	4.310.000	0	290

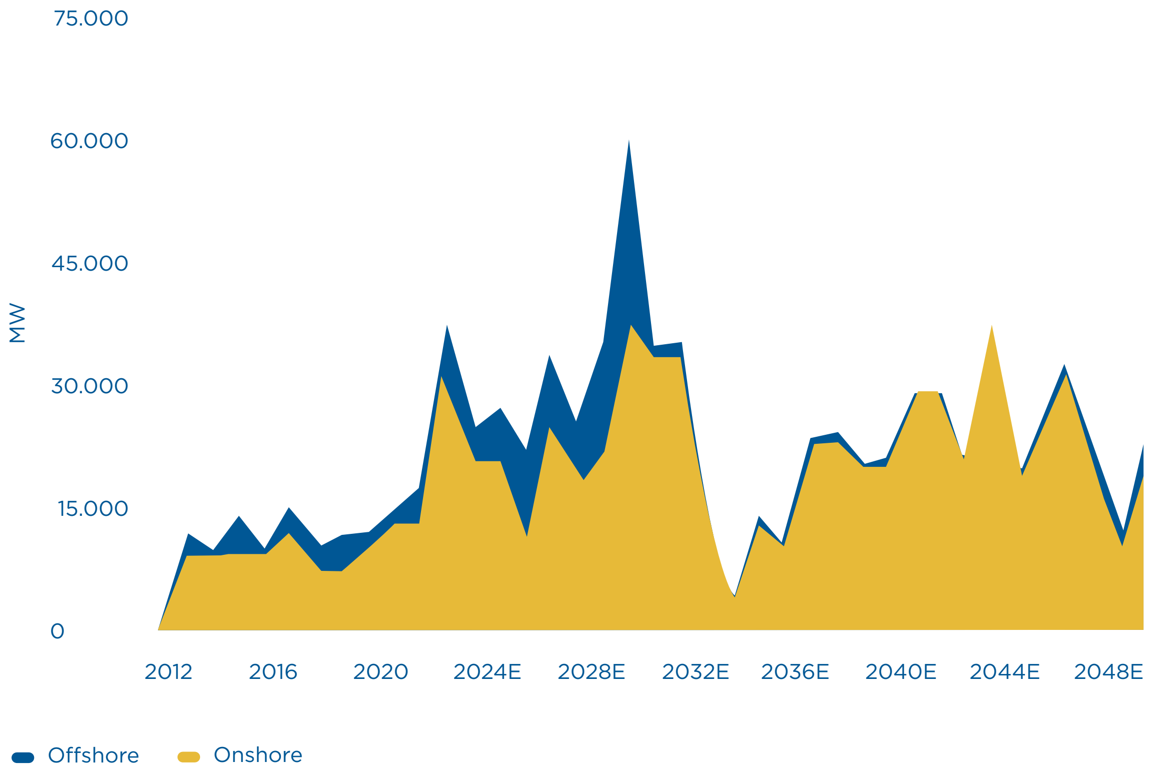
Besides that, a closer look into the production capacity for such materials, as well as the ease of access to them, can provide important input in terms of market traction in the recovery or non-recovery of materials.

2.1.2 Analysis of the expected deployment of Wind Power

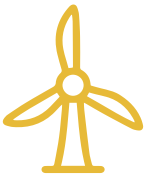
As one of the pillars of the European Union's decarbonisation strategy, the wind energy industry will not only deliver large supplies of energy for the coming years, but it will also benefit other aspects such as wealth and job creation. In order to provide an accurate idea of the European wind energy outlook in coming years, we must consider both the market capacity retirements as well as the annual capacity installation.

As seen in Figures 11 and 12, there is an expected annual average of 30 GW of new installations, while retirements are set to reach 10 GW per year. Ideally, and provided it is feasible from a technical and economic point of view, the circular use of recycled materials could supply one third of the materials required.

Figure 11.
Annual capacity additions.



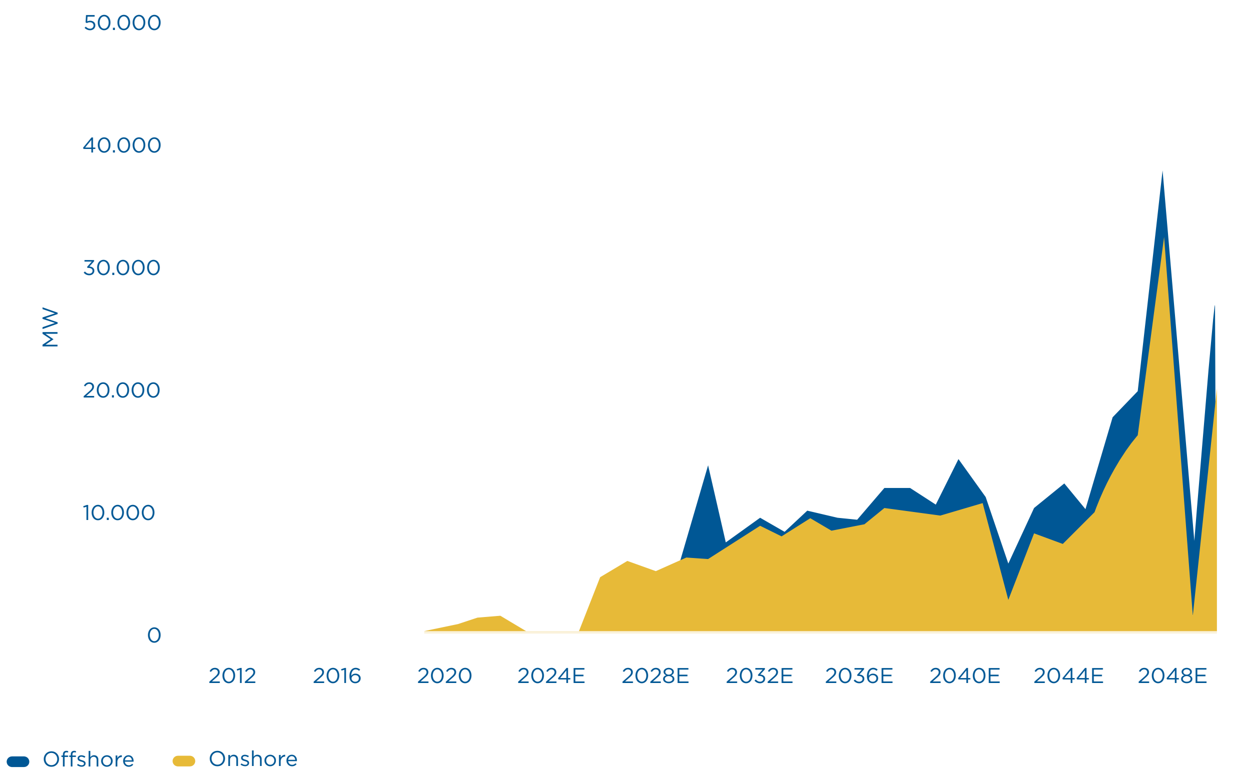
This decommissioning is expected to open new business opportunities as well as presenting some challenges.

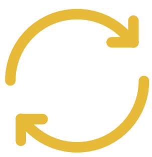


30

GW is the expected annual average of new installations while retirements are set to reach 10 GW per year

Figure 12.
Annual capacity retired.



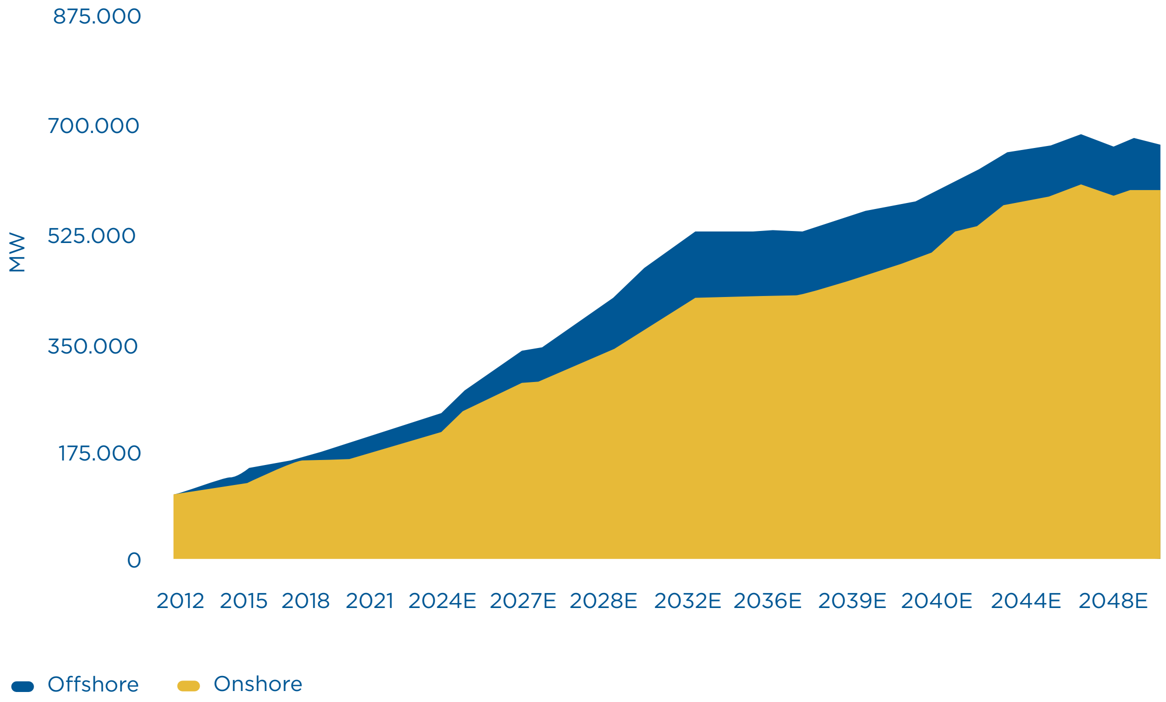


1/3

Ideally, and provided it is feasible from a technical and economic point of view, the circular use of recycled materials could supply one third of the materials required

As a result, considering an average power plant life of 25 years, Figure 13 below shows a conservative scenario of how the wind energy market is expected to evolve.

Figure 13.
European Market Outlook 2012-2050.



Before calculating the waste produced in the wind energy market, let's analyse the current situation in terms of increased future deployment versus materials availability. In this sense, as we will see in the coming pages, the wind industry is quite effective in reusing components, thus reentering these materials in the industry. Even so, **the deployment of wind turbines according to EU plans alone will require in 2050 most of the neodymium, praseodymium, dysprosium and terbium currently available.** As a consequence, a strong pressure on supplies is expected for the rare earths.

2.1.3 Expected waste from the Wind energy industry

Out of the 10 GW of decommissioned wind farms some of the components will be:

- Reused: Either directly used as a spare part (life extension at component level) or refurbished to be sold as a high-grade spare part (as is occurring in the automotive industry).
- Alternative applications for other markets.
- Recycled to recover raw materials (mining-like approach) to be reused in the wind energy sector (circular use) or through use in other sectors.

As a working hypothesis, it is considered that 65% of the components salvaged from a decommissioned power plant will be used again as spare parts for non-decommissioned power plants that are extending their operational life. This market, although limited in time, could be very attractive as most wind turbines / main components are no longer supported by OEMs thus making it very difficult to find high quality spare parts.

The other 35% will need to be scrapped. Technologies of a reasonable cost that can recover the materials of higher value will be sought. For those elements that could not be processed, ways to make them inert and low volume will be required as well as support mechanisms.

Technologies of a reasonable cost that can recover the materials of higher value will be sought

2.1.4 The role of re-using in the Wind energy industry

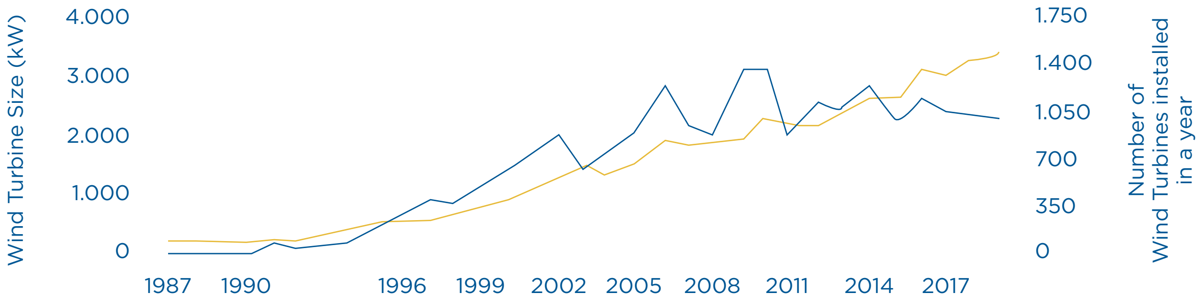
Today, 108 165 wind turbines remain operational in Europe. 8 325 could not be identified. The remaining 99 840 are from 103 different OEMs, out of which less than 10 remained operational in 2020. Most of OEMs have disappeared, either through acquisition processes or dissolution.

Table 5.
European turbines installed and operating (2021).

OEM	Quota	# units
SGRE	29.26%	31.649
Vestas	27.89%	30.167
Enercon	18.09%	19.567
Non classified	7.70%	8.325
Nordex	7.05%	7.626
GE Energy	6.19%	6.695
Various – Closed	2.60%	2.812
Various - Active	1.22%	1.320

Table 5 provides an overview of wind turbines installed in Europe that remain operational as per 2021 data. As seen, 5 main OEMS (SGRE, VESTAS, ENERCON, NORDEX and GE ENERGY) cover close to 90% of installed units. Caution when assessing this data is required, given that the acquisition of companies sometimes leads to legacy wind turbines receiving insufficient operational and engineering supervision by their new owners. Nevertheless, it can be concluded that there is volume enough for making a sustainable reuse and re-furbishment market business model possible in the 750 kW to 2.5 MW nameplate range (Figure 14 shows the VESTAS evolution of wind turbine size over the last 25 years).

Figure 14.
VESTAS evolution in units installed and nameplate evolution.



This offers an opportunity for first tier suppliers of the main OEMs. Their knowledge in the manufacturing of key components may position them very well to diversify their current business model to include services or spare part supply. Depending on the end customer (wind power plan owner, IPPs or OEMs) this may require specific quality, service supply definition or commercial distribution channels.

Another issue is the collection of components. This collection may be different if we are considering a power plant to be dismantled, or replacement of a faulty component. Logistics tied to the size of some components will be a relevant factor.

This offers an opportunity for first tier suppliers of the main OEMs. Their knowledge in the manufacturing of key components may position them very well to diversify their current business model to include services or spare part supply.

2.2 How to recycle Wind turbine components

In terms of the wind energy industry, different recycling technologies are implemented depending on the materials included in each component. In this section, we will focus on understanding the variety of materials found in a wind turbine and what recovery process is used in each one of them.

Table 6.
Main components material composition.

Material vs Component	Foundation	Tower	Nacelle	Rotor hub	Blades	Powertrain	Gears	Generator	Inverter	Cabling
Concrete	○									
Steel	○	○			○		○	○	○	
Polymers			○	○	○			○	○	
Glass/carbon composites			○	○	○					
Aluminum (Al)								○	○	○
Chromium (Cr)										
Copper (Cu)					○			○	○	○
Iron (cast) (Fe)			○	○				○		
Zinc (Zn)								○		
Nickel (Ni)	○	○					○	○		
Manganese (Mn)										
Molybdenum (Mo)	○	○					○			
Boron (B)										
Rare Earths (Nd, Dy, Pr, Tb)								○		

From the materials listed in Table 7, there are a few which are alloys and are sent directly to transfer stations where they implement specific alloy recycling processes. These materials are: zinc, nickel, manganese, molybdenum, boron and chromium.

The rest of the materials follow different recycling cycles as explained below:

Concrete ⟶ There is no easy way to recycle concrete. The material is crushed to allow for the separation of the steel bars used for reinforcement, and the remaining material crushed again to produce a homogenously-sized material to be used as a filler or for use in the construction sector. The value of the residue is limited, so it does not pay for the cost of the process.

Steel ⟶ Steel can be recycled, and the value of the material recovered covers upfront costs because of the value of steel scrap. Steel is the most recycled material on the planet. After recycling it does not lose its main properties of strength, ductility and formability.

Since steel is an alloy of iron it has other elements in it as well that are added to achieve the quality required for the final purpose of the steel. Hence, it is important to sort similar alloys together so that the end material is known and a cost-effective result delivered.

If alloys are not properly sorted, additional steps to separate those alloying elements or other metals must be done in a cost-effective way when recycling. The most difficult to extract from scrap are copper, tin, nickel, and molybdenum. If they are not extracted, their concentration increases with each recycling loop.

The process of recycling steel is simple. There is a sorting process, so it gets separated from other materials and crushed into large blocks. These blocks are processed in steel mills where they get mixed in with other steel scrap, melted, and finally new steel is produced.

Glass / Carbon composites ⟶ Nowadays, landfill or incineration is the main solution for disposal of glass fiber or carbon fiber composites.

Glass fibers are considered incombustible so burning composites for heat purposes is mostly determined by the proportion of polymer in it. Denmark has experience in mixing composite waste with municipal solid waste to enhance the incineration process. The main problem of the incineration process is the ashes, as composites contain a high quantity of non-organic material. These ashes can be a potential pollutant and they are either landfilled or recycled as a substitute construction material. The low heating value of the composites is not helpful for the incineration approach.

Another possibility is to burn fiber-reinforced composites in cement kilns for cement production. According to some studies, around 10% of the fuel input could be replaced by GFRC and ashes perhaps incorporated into the cement to enhance properties.

Landfilling remains the most common solution because composite materials are inherently inert and non toxic, and so classified as non-risk. However, factors such as the visual impact and long life of those residues is placing pressure on the industry to find viable recycling solutions.

The main alternatives at the research and development stage are:

- Mechanical processes: Shredding the materials and using them as fillers in low value applications, especially in the construction sector, where they can play a role as insulation material.
- Thermal processes: The quality of the process must be measured in terms of how clean of resin the fibers can be. The major problem in reusing the fibers, for those processes that can extract them, is the non-homogeneity in fiber length that requires a further process to make its use viable.
  - Gasification (fluidised bed): The process uses hot air over a fluidised bed to gasify the resin and liberate the fibers. Potential products are fibers, fillers and flue gas.
  - Pyrolysis: Thermal oxidation of the resin to free the fibers. The temperature must be controlled so that the fibers are not burnt or oxidised. Potential products are fibers, fillers and char. In addition,

There is no easy way to recycle concrete. The material is crushed to allow for the separation of the steel bars used for reinforcement, and the remaining material crushed again to produce a homogenously-sized material to be used as a filler or for use in the construction sector

hydrocarbon products can be extracted or even reused to help the thermal process.

- Chemical processes:
  - Solvolysis: A reactor is used to dissolve organic components. Potential products are fibers and mineral compounds.
- Fragmentation processes:
  - High Voltage Pulse: Breaks the interface between matrix and fibers in an extreme process using a high voltage pulse in a short period of time.

Pyrolysis is one of the most promising options owing to its maturity and its flexibility of use for glass and carbon fiber materials. Still to be resolved is the issue of post-processing fibers to increase the value of the residues.

Aluminium ⟶ The aluminum recycling industry is leading other recycling industries. Long-term efforts to promote aluminum recycling and reuse have paid off, and no product material is more frequently returned to recycling plants than aluminum.

The modern process of aluminum recycling is fast and efficient. This is vital given that so much of this eminently practical metal is now available for reprocessing and reuse.

The standard steps in recycling aluminum are:

1. Sorting
2. Shredding
3. Cleaning
4. Melting
5. Removal of by-products
6. Creation of alloy
7. Compounding

Copper ⟶ Copper is an easily recyclable material. The recovered material can be worth up to 90% of its original cost.

Depending on how free the copper is, there are several alternatives ranging from pure melting of the material to chemical dissolution followed by an electro-deposition.

Cast Iron ⟶ Cast iron is fully recyclable. It can easily be recovered and processed for reuse without limitation. The process is very similar to that of steel.

As it is magnetic, iron can be quickly separated from other recyclable metals in a metal recycling facility using powerful magnetic belts. After that, shredders with rotating magnetic drums extract iron and steel from a mixture of metals and other materials. This is followed by another level of separation that may involve electrical currents, high-pressure air flows, and liquid floating systems. For the larger components, the next step in the process is shearing. This involves hydraulic machinery or other cutting techniques. The final step is the baling, compacting of iron products into large blocks making them significantly easier to move and transport.

Rare earths ⟶ Mostly included in the permanent magnets of the generators, rare earths have strategic importance and attract the interest of research. The main difficulties of extracting rare earths from permanent magnets are:

- Difficulty to decompose the chemical compounds.
- Low concentrations of rare earths.
- Expensive processes compared to the value of recovered elements.

Different separation and recycling methods in development are:

- Hydro-metallurgical processes.
- Pyro-metallurgical processes.
- Gas-phase extraction using corrosive chlorine processes.
- Direct reduction with hydrogen.

2.3 Legal framework to achieve circularity in the Wind industry

As part of the decarbonisation effort, and related to the EU Green Deal, in 2020 the European Commission has published the latest vision for the circular economy action plan (CEAP). Even though the wind energy sector is not identified as a key product value chain, some principles established for electronics and ICT, and construction and buildings may be considered applicable.

The European Commission is to set a sustainable product policy legislative initiative that will widen the ecodesign directive.

Moreover, circularity in the production process is set to be aligned with the European industrial strategy with the aim of achieving the following fundamental goals, among others:

- Assessing options for further promoting circularity in industrial processes.
- Promoting the use of digital technologies for tracking, tracing and mapping of resources.
- Promoting the uptake of green technologies through a system of solid verification by registering the EU environmental technology verification scheme as an EU certification mark.

2.3.1 Existing regulations in different EU markets

Dismantling of wind turbines is regulated by national legislation. There is no single European directive that harmonises this process. Most relevant regulations are:

Table 7.
Most relevant national regulations on wind turbine dismantling in Europe.

Country	Regulation
Denmark	The municipality typically sets the conditions for decommissioning in the building and initially issues an operating permit.
France	• Regulated by the *'arrêté du 26 août 2011 relatif à la remise en état et à la constitution des garanties financières pour les installations de production d'électricité utilisant l'énergie mécanique du vent'* and the *'code de l'environnement'* • Amendment by the *'arrêté du 22 juin 2020'* • Specific provisions are also provided under Article R 515-107 of the Environmental Code.

Continues >

Country	Regulation
Germany	• Regulated by the Renewable Energy Sources Act, 2017. • Provisions in the Building Code.
Italy	Regulated by the Ministerial Decree of 10 September 2010 titled "Guidelines for the authorisation of plants powered by renewable sources".
Netherlands	Regulated in the Building Decree 2012.
Spain	• No specific regulatory framework. • Requirements are included in the Environmental Impact Assessment (EIA) for each project.

2.3.2 Legislation relative to materials

In parallel, there are also legislations which are specific to the materials. Here is a list of the existing standards affecting concrete, metals, composites and rare earths.

Concrete

- European standard EN 197-1.
- No explicit legislation at member state level relative to wind turbine foundations or concrete waste. Under the EU Waste Framework Directive (2008/98/EC), at least 70% by weight of non-hazardous concrete must be reused or recycled by 2020.
- In Spain the Royal Decree 105/2008 of 1 February regulates the management of construction and demolition waste.

Metals

- Article 10(2) of the EU Waste Framework Directive (2008/98/EC) states separate collection shall be set up for paper, metal, plastics and glass by 2015.
- Article 11 of the EU Waste Framework Directive 2009/98 states that "member states shall take measures to promote high quality recycling and, to this end, shall set up separate collections of waste where technically, environmentally and economically practicable and appropriate to meet the necessary quality standards for the relevant recycling sectors".
- Spain transposed the Directive in the Law 22/2011 on Waste and Contaminated Land. Regions also have their own legislation.

Composites

- According to the European classification of waste, composite blade waste is most often categorised as plastic waste from construction and demolition with the code 17 02 03.
- The European Strategy for Plastics in a Circular Economy stresses that the low reuse and recycling rate (less than 30%) of end-of-life plastics is a key challenge to be addressed. So far, the focus has been on single-use plastics, microplastics, oxo-plastics and plastics packaging and not on composite waste.
- Only four countries in Europe - Germany, Austria, The Netherlands, and Finland - have banned blades being sent to landfill.
- The sector has called for a Europe-wide landfill ban by 2025.
- From July 2022, owners of existing wind farms in France will have to recycle 40% of blade materials by mass.

Rare earths

- Under the EU Waste Framework Directive (2008/98/EC), rare earth elements are

listed as non-hazardous. To date, there is no specific European or national legislation related to rare earths.

Electric cables

- The WEEE Directive 2012/19/EU article 2 section 4(c) states that ''this Directive shall not apply to the following EEE: large-scale fixed installations, except any equipment which is not specifically designed and installed as part of those installations".
- Under Annex VII of the EU Waste Electrical & Electronic Equipment (WEEE) Directive (2012/19/EU), external electric cables must be removed from any separately collected WEEE and be disposed of or recovered in compliance with the Waste Framework Directive (2008/98/EC).

The European Strategy for Plastics in a Circular Economy stresses that the low reuse and recycling rate (less than 30%) of end-of-life plastics is a key challenge to be addressed

3

Batteries

3.1 Introduction to the End of Life Management of Batteries

A section dedicated to the battery recycling market must begin by stating how crucial it is to the success of the green energy transition. Batteries are key for 2 of its main axis: the electrification of mobility and the increase of renewables in the energy mix. The rocketing demands of batteries forecast for the near future demand an increase in raw materials that mining can not provide, especially in Europe, with its long permitting periods (mining projects need between 5 and 10 years to be developed until start of operations). So, alongside the general needs that recycling seeks to fulfil (waste reduction, advancement of circular economy), battery recycling plays a vital role: mitigating the dangers of a shortfall of raw materials to fulfil the demand of batteries, necessary for the green transition in Europe and worldwide.

Given critical raw materials' propensity to be the perfect bottleneck for the energy transition, recycling is crucial to its fulfilment.

Batteries are required for all electric cars as well as for all stationary storage that supports compact renewable energy generation units. Battery recycling is therefore certainly required, and more precisely, Li-ion battery recycling.

We are going to center this analysis mainly on Electric Vehicle Batteries. It is estimated that more than 80% of the Li-Ion batteries made are going to be for this application. With time, more and more stationary storage batteries will be repurposed end of life electric vehicle batteries. Therefore, electric vehicle batteries are going to be the main driver of the Li-Ion battery market and therefore, its recycling.

Alongside the general needs that recycling seeks to fulfil (waste reduction, advancement of circular economy), battery recycling plays a vital role: mitigating the dangers of a shortfall of raw materials to fulfil the demand of batteries, necessary for the green transition in Europe and worldwide

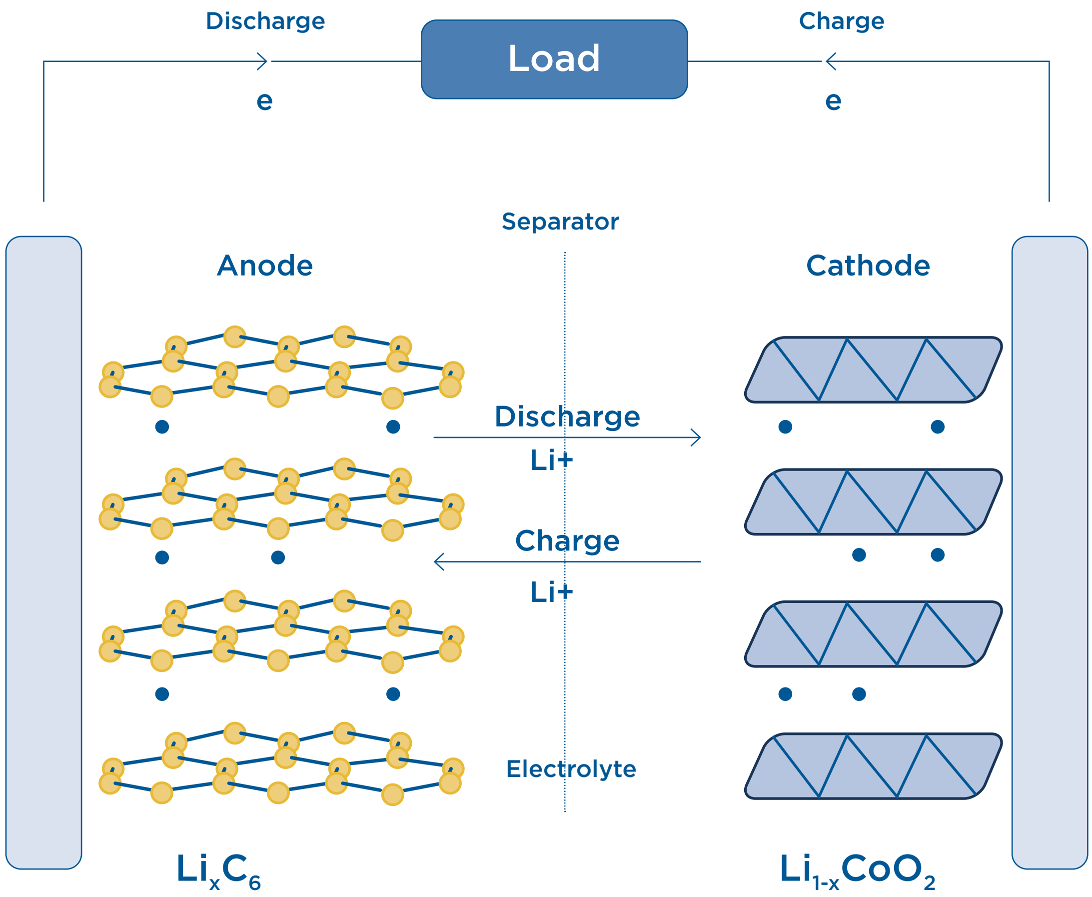
3.1.1 Materials and composition of Batteries

Even though the materials used and wind turbine power ratings have evolved in recent decades, the average consumption of materials per MW has remained stable.

This can help us define the quantities used or needed for use, and establish the requirements of managing such disposals now and in the future.

As shown in Table 4, below, most differences are derived from the introduction of permanent magnet.

Figure 15.
Functioning of a Li-ion battery. Source: Md Ashiqur Rahaman Khan.



Li-ion batteries are classified according to the chemistry allocated in the cathode. The first one to be used in automotives was LCO (lithium oxide and cobalt), but

it is now residual. Other chemistries are LMO (lithium and manganese oxide), NMC (nickel, manganese, cobalt) and LFP (lithium and iron phosphate). The latter two are the ones that are being deployed today.

The anode is usually made of graphite, although silicon anodes are currently in development to reduce the impact of raw materials. However, the state-of-the-art production process of silicon anodes is still much more contaminating than using graphite flakes, so further technological advancements are required.

The separator is a membrane that is usually made of a polymer material, and filled with a liquid, the electrolyte, that allows the movement of ions from one electrode to another. This electrolyte is usually made of lithium salts.

What we want from a battery is, basically:

- **High energy density** (the maximum energy in the minimum space).
- **High cycle life** (the number of charging-discharging cycles the battery can last before it loses 80% of its initial capacity).
- **Long calendar** life (the amount of time in which the battery, being inactive, can keep 80% of its charge).

These properties don't usually come together, and there are trade-offs between chemistries with respect to these parameters.

We will concentrate now, when talking about the realities and challenges of battery recycling, on LFP and NMC chemistries, which are the most common. They have different recycling processes and different business model challenges. The electrolyte and the cathode, being similar for all chemistries, do not introduce particularities in these aspects.

Briefly, the main performance difference between LFP and NMC is in energy density, where NMC is higher, and cycle life, where LFP can last longer. So, NMC is a chemistry that is being used mainly for mobility given the long range it can provide. LFP is more dedicated to short range urban mobility applications, and also for stationary storage. Another very important factor that differentiates these two chemistries is heat: NMC batteries generate lots of energy in a form that has to be cooled to avoid explosions, whereas LFP's reaction is not that exo-thermal.

3.1.2 Upcoming demand of batteries for the Mobility market

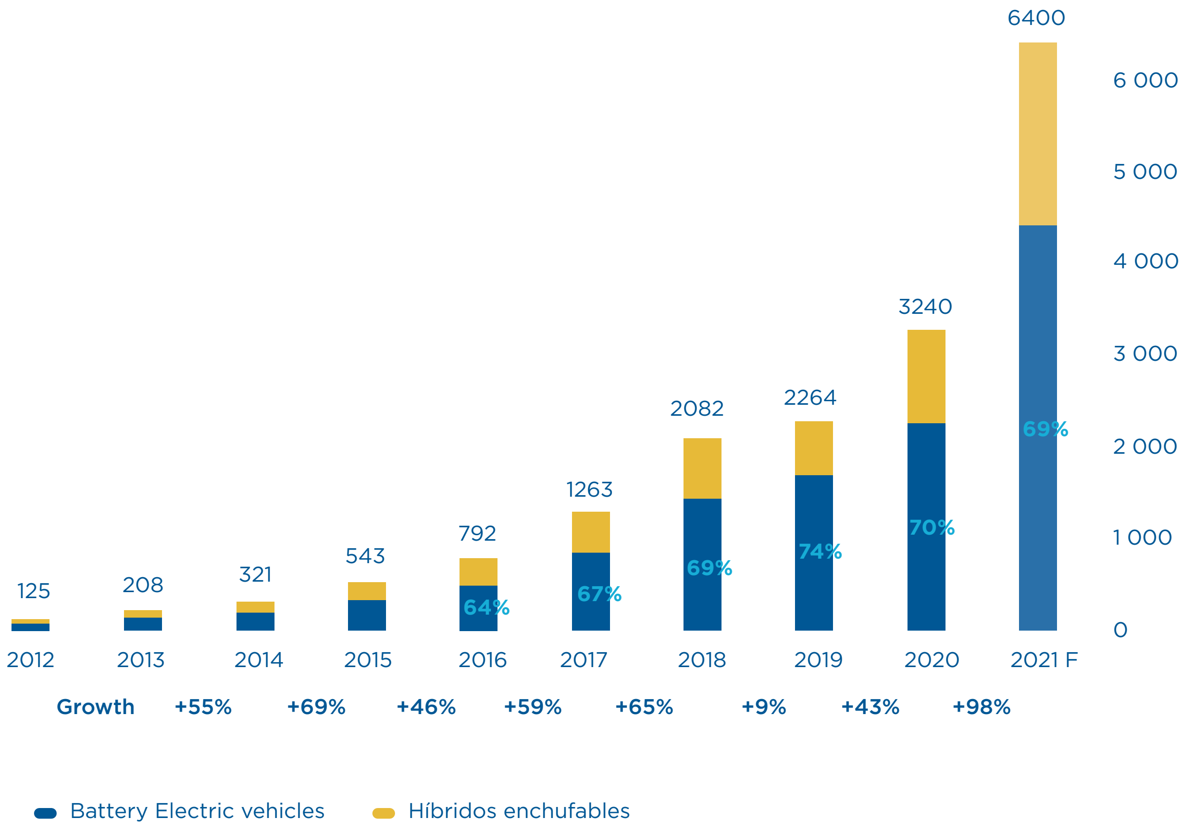
The Li-ion battery market is automotive centred, with Electric Vehicles accounting for more than 80% of total battery needs. The evolution of EV sales is going to be the main driver for the battery market, and the average life of a battery will set the time delay between the EV market and the recycling requirements derived from it.

The EV market is in rapid evolution. Since 2010 the number of electric vehicles

sold has dramatically increased. From a total worldwide sale of less than 15.000 units in 2010, sales were over 6 million units by 2021. In Europe, the EV sales market exceeded 2 million units that

same year. The following graphic traces the exponential growth of electric vehicle sales worldwide, as well as the increase of pure EVs in terms of market share, with that of plug-in hybrids (containing smaller batteries) diminishing bit by bit. This trend, in our view, will continue.

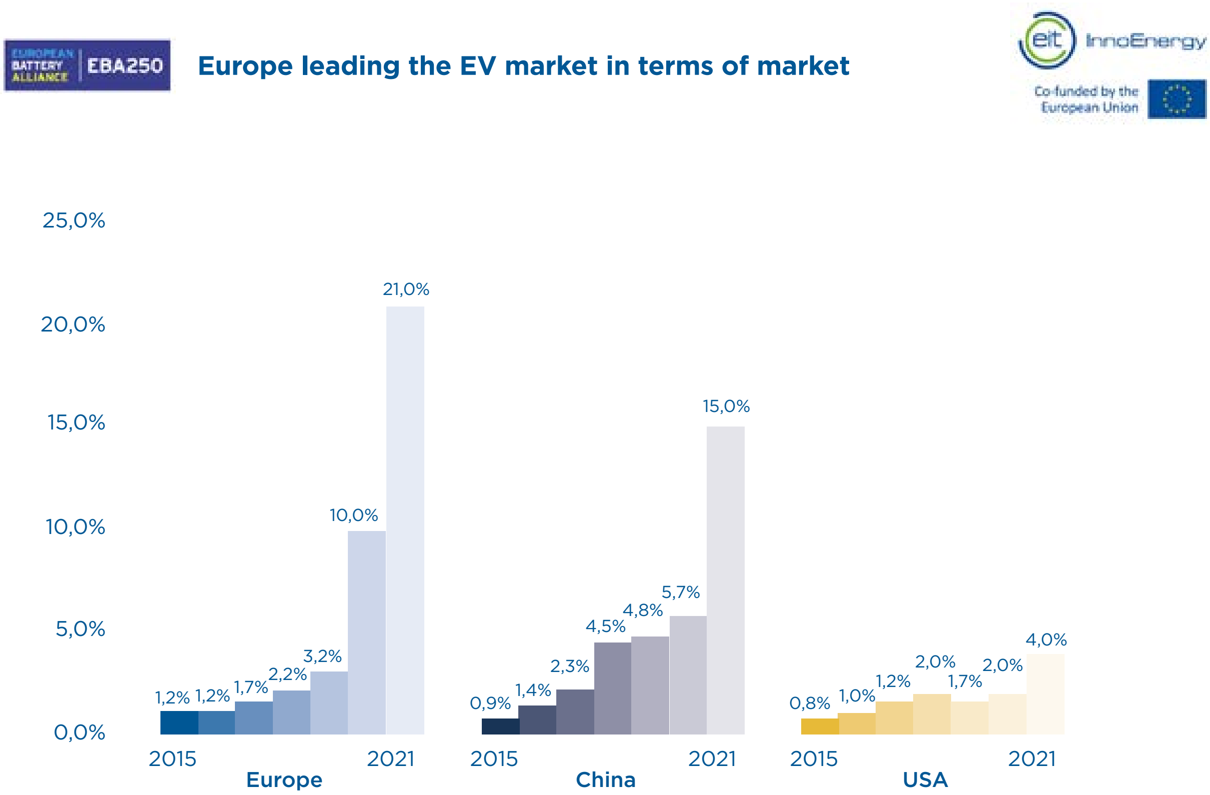
Figure 16.
Global plug-in vehicle sales. Source: EV volumes. (www.ev-volumes.com)



In numbers, China has been and still is the biggest actor in this market. But in terms of market share, it is Europe who is winning the race, as the following graph shows. This means that tension for the development of recycling infrastructures for battery packs put on the market will have to be tackled in a shorter time scale, as the landscape is evolving much quicker than in China. Europe started the race later, but is running faster.

million units sold by 2021 vs 15.000 units in 2010

Figure 17.
Market share of new plug-in electric passenger cars by region/country (2015-2021).
Source: European Battery Alliance.



Combined sales EU-EFTA-UK.

What's more, the future sees more growth, with EV sales projected to account for more than 50% of the overall vehicle market share by 2030, with more and more automakers making bold announcements about their electrification plans. While we were in the process of writing this report, Stellantis announced that 100% of their European vehicle sales will be electric as early as 2026, and that is just one example.

The future sees more growth, with EV sales projected to account for more than 50% EV market share by 2030

Figure 18.
Global EV Sales Penetration curve.
Source: UBSe

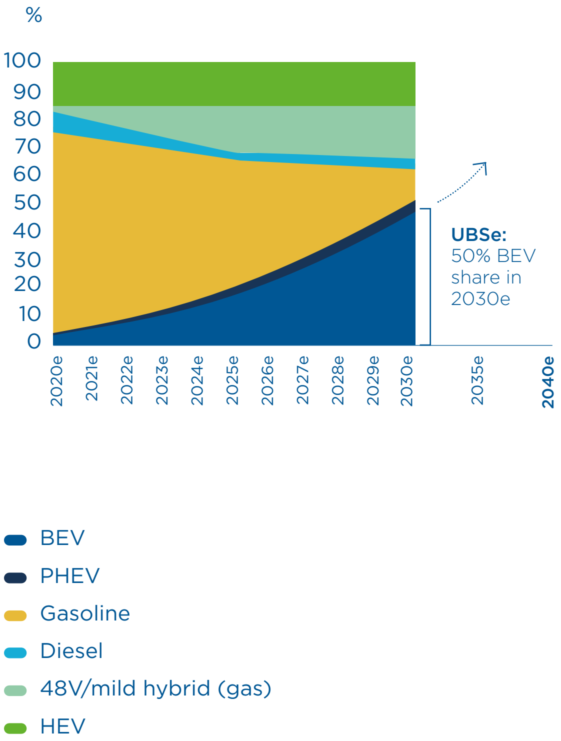
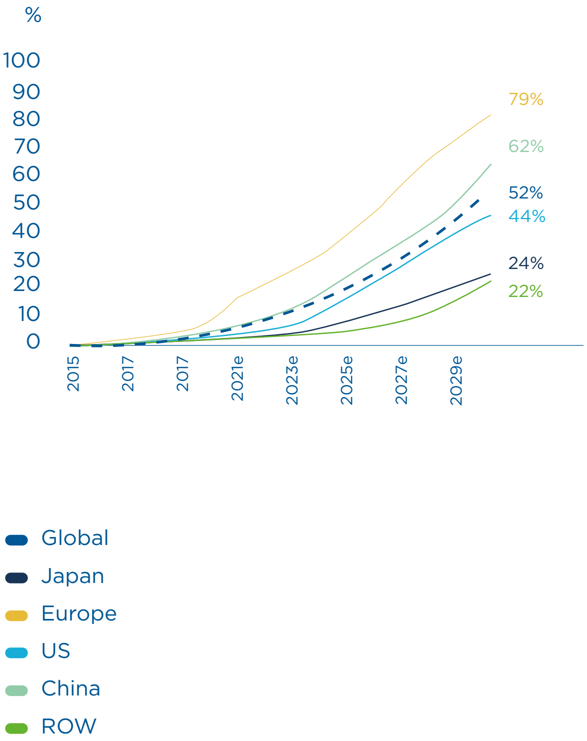


Figure 19.
EV Penetration rates by major markets.
Source: UBSe

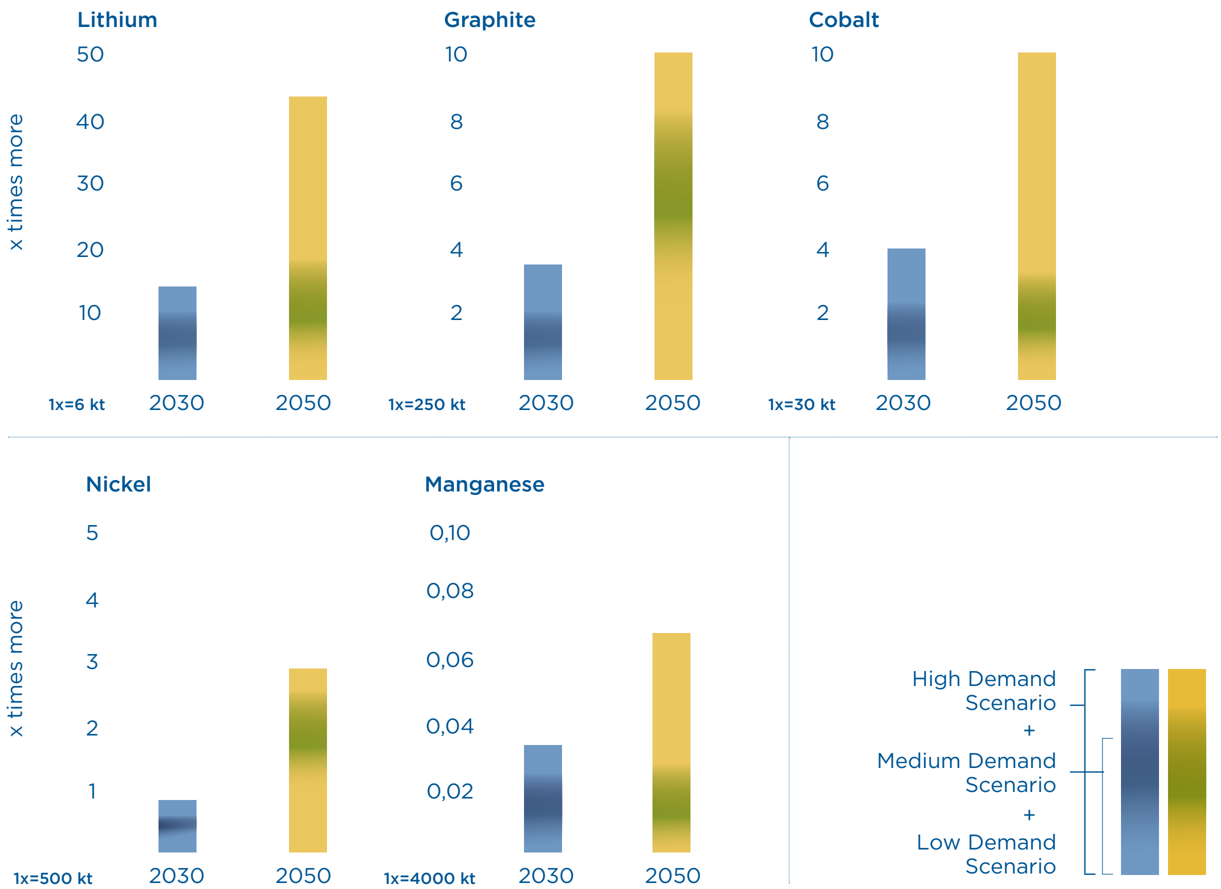


So, battery demand is booming, and will continue to do so. So, where will the raw materials come from to feed it? Here, recycling plays a critical role, as mining will not be able to provide them: in Figure 20 we see the evolution of basic battery material demand from now to 2050: lithium needs will be multiplied by 40, graphite and cobalt by 10... It is not possible (nor desirable) to sustain these demands simply from extraction.

To summarise: without recycling, there'll be a shortfall in raw materials. No raw materials means no green transition.

Recycling plays a critical role, as mining will not be able to provide. From now to 2050: lithium needs will be multiplied by 40, graphite and cobalt by 10...

Figure 20.
Additional material consumption for batteries in e-mobility only in 2030/2050 compared to current EU consumption of the material in all applications Source: Benchmark Minerals.



The Lithium Example: Will Europe provide?

Lithium is the most crucial raw material for the Li-ion battery. No matter which chemistry we use, it always contains lithium, in the cathode and the electrolyte. And it's the element in which demand will grow the most; some forecasts extend it to more than 40x from 2020 to 2050.

Until the eruption of the Li-ion battery, lithium was used in low value added applications, basically linked to ceramics and construction. It was a cheap product, and complex to process, so was very often left aside unexploited as a tailing or by-product of mining.

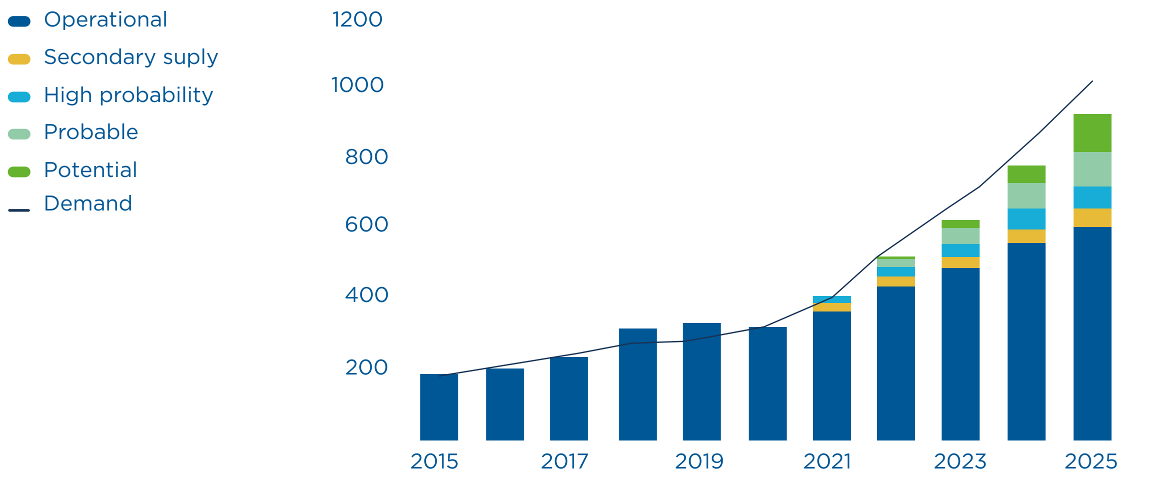
Today, the supply chain of the lithium needed for battery markets is extremely lengthy and complex: mined in Australia from rock or in South America from brine, it is then sent to China for refining, then to Japan or Korea to be introduced into a cathode. It subsequently travels to a battery factory that may well be in North America, only to then head to Germany to be installed in a car.

Apart from the huge CO_2 footprint derived from logistics, the pandemic has taught us that long supply chains can be very fragile, so this is why in **Europe, through instruments like the European Battery Alliance and the new Batteries Regulation, local supply chains must be developed.**

As a matter of fact, in Europe we can call this a success story: more than 35 gigafactories are being currently built here and a number of Asian players are looking for locations for their cathode plants. But, again, what about raw materials to supply them? What about lithium?
In the 2 years that the European Battery Alliance has been active in the raw material market, the number of Li extraction projects has not increased that much. Lithium prices were lowering until Q3 2020, so financing for projects in development was very difficult and scarce. Since then, the markets are providing those projects with enough funding. Now, the key to success in Europe is permitting: which is slow and very often problematic. We have not been a mining continent for long (with the exception of Scandinavia and a few other places), and it is complex for citizens

to accept that mines are back and perhaps even next door. As examples are the cases of Spain and Portugal, where there is very little acceptance from the citizens and there is a lack of greater involvement by the local governments in monitoring the situation. This is a clear case where European measures would come in handy; there is a risk being of being unable to use resources which are actually available. **Creating the figure of a "strategic project" can be a way of simplifying the permitting path for specific projects of high importance, but this cannot reduce approval standards, in which Europe plans be a leader.**

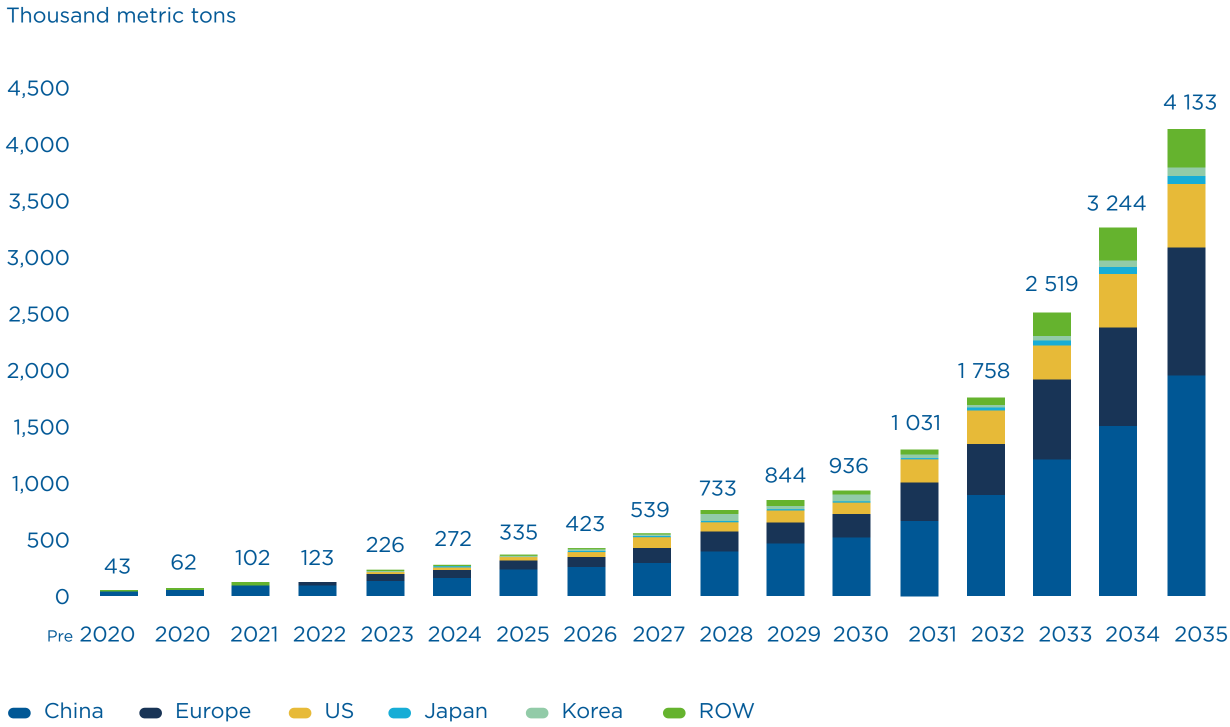
Figure 21.
Potential deficit from 2021/2 and widening. Source: Benchmark Mineral Intelligence.



3.1.3 Expected waste from the battery industry

So, we have a hockey stick type of EV market demand being developed worldwide and especially in Europe, and the batteries put on the market will reach their end of life in around 8 to 10 years. This means that, **as of today, the number of end-of-life batteries reaching the market is negligible, but that recycling capacity will have to be quickly deployed, as from 2026-27 the numbers will start to be significant.**

Figure 22.
Annual Battery Retirements by Region. Source: Bloomberg.



8-10

to ten years end of life

As the above figure shows, vehicle batteries don't start reaching massive numbers for a few years yet, but they are already growing at a 50% rate.

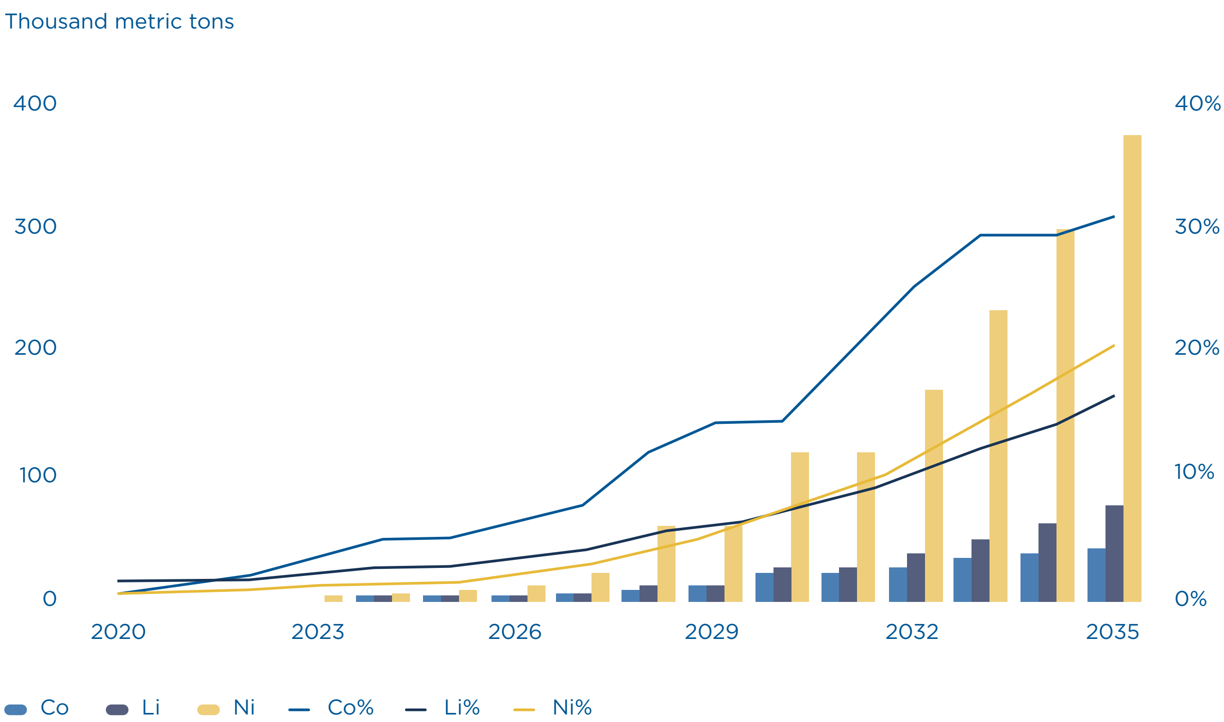
Until the mid 2020's, China will hold the majority of battery retirements, with almost 100% currently and around 70% of the predicted flows by the middle of the decade. From then on, the rest of the world will begin to accelerate and by 2032 it will surpass China, and increase in velocity.

China began betting on the electric vehicle 8-10 years before the rest of the world, and, with its huge production numbers, will be the main provider of end-of-life batteries for some time yet. As we will see in the technologies section below they are quite advanced in this sector too.

If numbers do not reach significant levels until 5 years from now, will that mean that recycling companies will not have a real inflow of material until then? The answer is no: until then, they can be fed with out-of-spec cells and production scrap from cell manufacturing plants. As a matter of fact, gigafactories are very inefficient during their ramp-up period, amassing 2-digit percentages of out-of-spec products. So, they are structuring themselves with recycling capacity so that they can reuse their scrap and increase their economic viability. This is why many of the big players in battery recycling are linked to a gigafactory. ReVolt in Sweden (belonging to Northvolt) and SungEel in Korea (with Samsung as shareholders) are two such examples.

To finish this section, and to really emphasise the importance of recycling in the supply of critical raw materials, let's take a look at the estimation that Bloomberg makes on the amounts of recovered metals required to meet demand for the 3 metals on the critical raw materials list.

Figure 23.
Metal recovery rates needed to meet global market demand. Source: Bloomberg.



Cobalt reaches 30% by 2035, and lithium and nickel remain at around 20%. That is quite a bold result, because we are feeding a big part of these demands with batteries that were put on the market many years ago (in the case of scrap from cell manufacturing, the delay is very short). This means that the assumptions on the % of metals that are going to be recycled when the battery reaches its end of life are quite substantial. Are there technologies ready for that? We'll see in the next section.

3.1.4 The Spanish market and Existing initiatives for battery recycling

Spain is a slow adopter to electric mobility. At the end of 2021, the total number of EVs and PHEVs vehicles on the streets was less than 130000 units, and it held a market share in 2021 of 2,8% of total car sales. In the same period, 21% of cars sold in Europe were EVs and PHEVs.

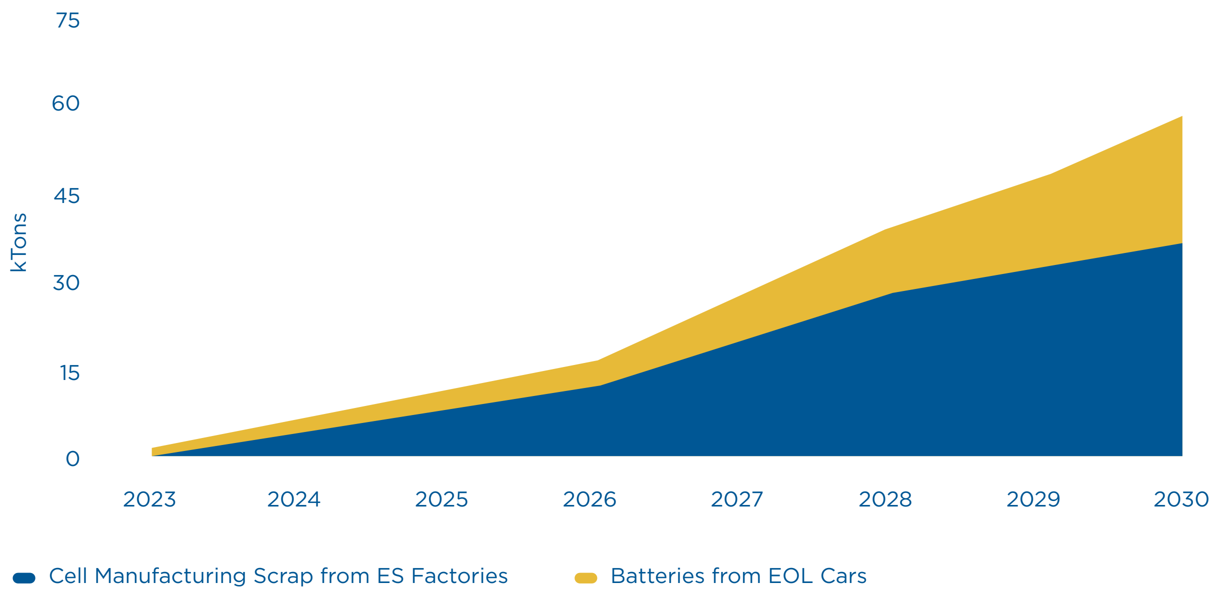
So, the need for battery recycling capacity in Spain will be less urgent, and more based on scrap from cell manufacturing facilities.

We have made a simulation of the battery retirements for Spain based on the following assumptions:

- **Cell Manufacturing Scrap** calculated according to Spain's manufacturing capacity today, and assuming that 50% of this capacity will be battery based. As the cars built in Spain tend to be of a small size, we believe that the share of electrification of this segment will be smaller than average, as electrification usually begins in premium segments. The amount of battery capacity needed for production will give us the number of GW required for installation in gigafactories in Spain. We assume 10% scrap from gigafactories production will head to recycling facilities to be recovered.
- **Batteries coming from EVs at end of life.** We have based our numbers on the sales figure forecast calculated by the Business Association for the development and promotion of the Electric Vehicle AEDIVE*. We have used an average life of 8 years with normal distribution, and a ratio of 50% recycling rate. This 50% recycling assumption is made by Dr. Eric Melin**, and based on the fact that technologies are being developed that are constantly lengthening battery life, adding the fact that batteries will also be exported to developing countries where performance needs are less strict, more applications for end-of-life batteries will be developed... With all this in mind, assuming that 50% of the batteries will be recycled when they reach 8 years of life actually seems quite prudent.

* From its name in Spanish: *Asociación Empresarial para el Desarrollo e Impulso del Vehículo Eléctrico.*
** Hans Eric Melin, "The Lithium Ion Battery Life Cycle Report 2021".

Figure 24.
Battery retirements in Spain.



As can clearly be seen in Spain, because of the late adoption of EVs by its population, but as an important manufacturer, inflow is mainly based on manufacturing scrap from gigafactories. This means that the initiatives being established in Spain should be aligned with a cell manufacturing plant that provides them with an inflow. If they rely only on batteries from end-of-life cars, profitability will be difficult: too many battery models with too few of each make the possibility of streamlined production quite complex.

As of today, we have 2 initiatives taking place in Spain with respect to Li-ion battery recycling:

- **BeePlanet Factory**, a company based in Navarra making 2nd life batteries, that is working on a plan to build a recycling facility with Asian technology linked to a cell manufacturer.
- A project by **Endesa** and **Urbaser** to build a recycling facility in **Cubillos del Sil** (León), in partnership with the Swedish cell manufacturer Northvolt.

Making an assumption of 10-15kT recycling capacity per player, we can see that there is still room for more initiatives.

3.2 Recycling processes for Batteries

Li-ion battery recycling as of today is a complex reality. There is a lack of standardisation amongst battery and/or cell manufacturers, leading to a wide variety of product designs, formats and chemistries that have been created not always with recycling in mind. However, we believe that there are some factors that will simplify this. On one side, the increase in volume seen in the last chapter will lead to economies of scale. Also, the increasing participation of automotive OEMs and cell manufacturers in the recycling value chain (that we will comment on in the section 4.3 "Batteries Recycling Busines"s) will bring homogenisation in end-of-life battery flows reaching the factories and making automated dismantling economically possible. We believe that the participation of OEMs will also encourage ecodesign, enabling the recycling industry to lower its costs significantly in the future.

We can divide battery recycling technologies into 2 main categories:

- Pyrometallurgy
- Mechanical Pre-treatment + Hydrometallurgy

There are also companies combining the 2 techniques.

3.2.1 Pyrometallurgy

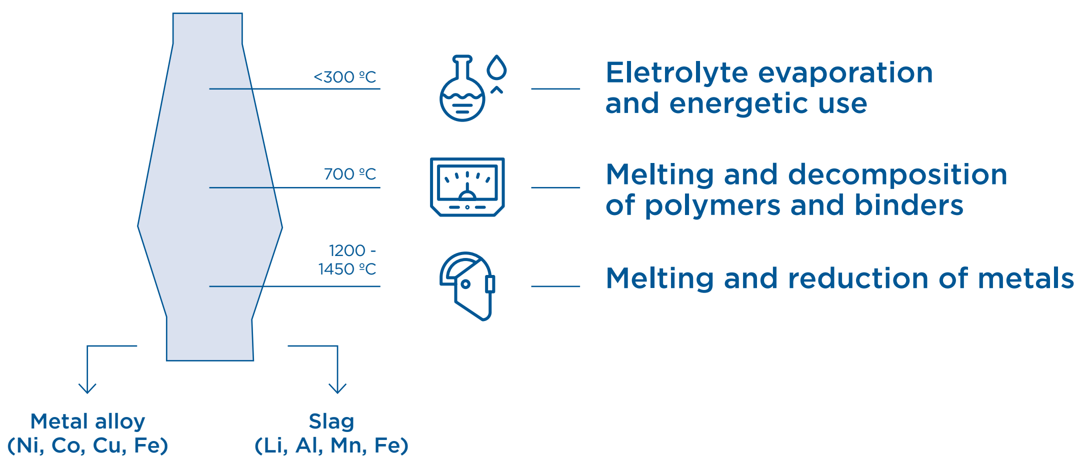
Battery Cells are put into a furnace without any previous mechanical treatment. Scrap can also be added to increase thermodynamic properties and obtain a better final product.

The outflows of this process are a gas where lithium salts, plastics and separators are evaporated, a slag containing Aluminium, Manganese and Lithium, and a metal alloy containing Nickel, Cobalt, Copper and Iron.

Both flows are unsuitable for battery making and go to lower value applications. To recover these metals for battery grade applications, a further hydrometallurgical process has to be applied to the metal alloy.

The efficiency of the process increases if a mechanical treatment is made prior to the pyro process, however, this is used more in hydrometallurgy than in pure pyro systems.

Figure 25.
Battery recycling. Pyrometallurgical process. Source: Aachen University



3.2.2 Hydrometallurgy

Hydrometallurgy uses a two-stage process, starting with a mechanical pre-treatment that makes what is called the "black mass", followed by the chemical plant. These processes often take place at a distance from each other and, as the difference in CAPEX for the two is very large (the hydro part being easily 10 times higher), this provides a reason to scatter various mechanical processing plants around a territory which supply one centralised hydro plant, saving logistical costs.

Pre-treatment and production of "black mass"

The pre-treatment plant consists of various phases:

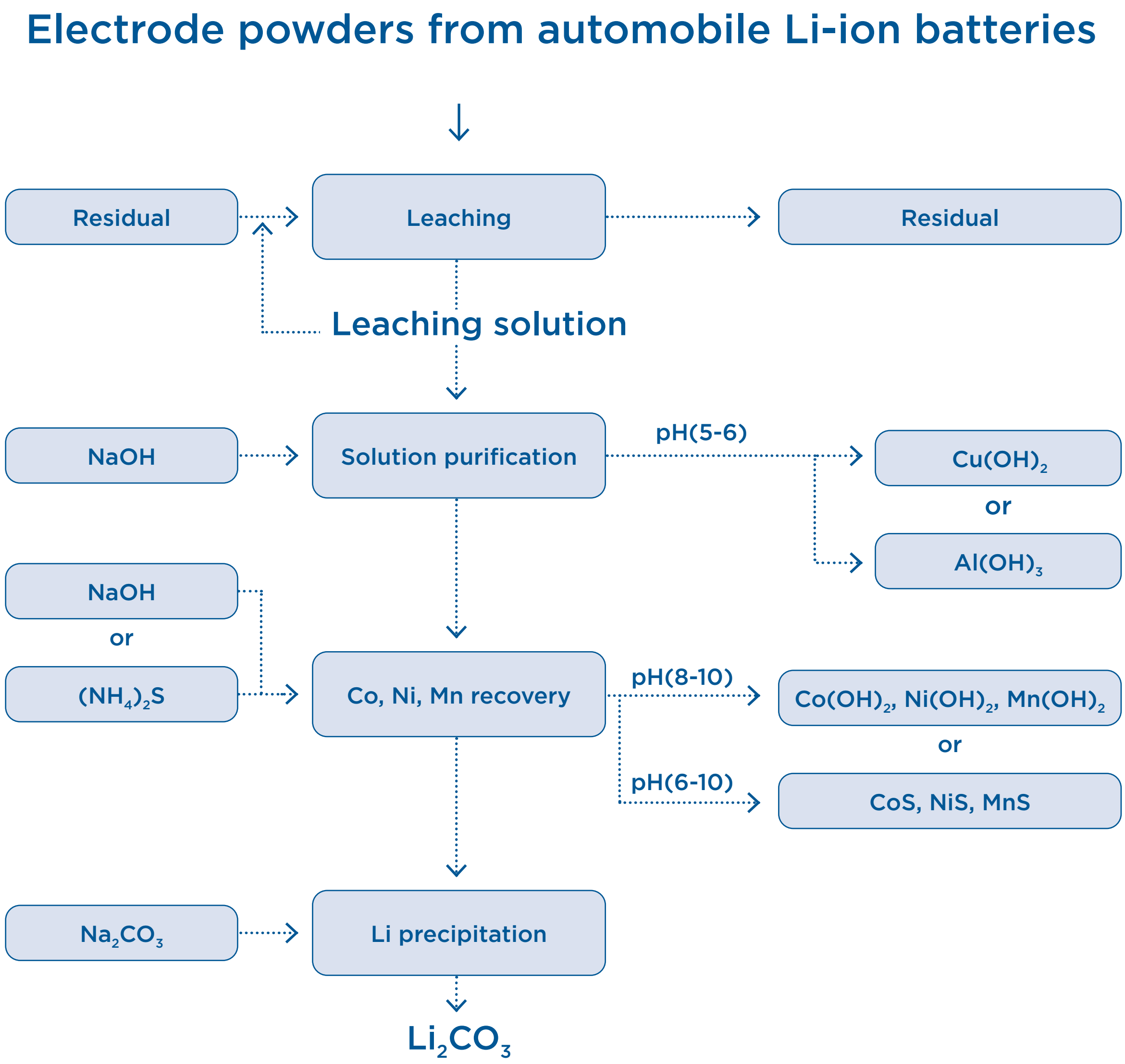
- **Electrical discharge**, in order to avoid any risk on the manipulation that will take place afterwards.
- **Dismantling of external parts**, to be able to access the different modules (cases, cables, electronics).
- **Crushing of the modules**. This is usually made by batches organised by chemistry to maximise the effectiveness of the process, avoiding cross contamination between chemistries. This phase is made in an inert atmosphere (dry or wet) for safety reasons. Some recyclers do a second crushing phase to decrease the particle sizes and be able to separate impurities much better.
- **Material separation.** Some metals can be extracted already via mechanical processes: sieving, magnetic separation, hydrophobia, densimmetry, etc.

At the end of these phases of pre-treatment, we obtain separate flows of plastics, ferric materials, aluminum, copper, carbon and a black powder known as "black mass". This latter flux contains the cathode materials: nickel, cobalt, lithium and manganese. This flux is what enters the "hydrometallurgical process".

Sometimes, the black mass is also passed through a pyrometallurgical process to eliminate the organic impurities it can contain from binders and separators.

Chemical process

Figure 26.
Hydrometallurgical process for battery recycling. Source: Aachen University



We are going to describe below the most utilised system in the industry as of today, although it is certainly not the only one.

Firstly, the black mass is introduced into a **leaching** solution (normally sulphuric acid). This dissolves the different metals contained in it.

Next step is **purification**, in which sodium hydroxide (NaOH) is added to precipitate impurities, Cu, Fe and Al. In this process it is very important to control pH so that we can avoid precipitations of metals we want to keep in the process. This process is repeated a number of times through recirculation.

Next phase is r**ecovery of valuable metals**, in 2 stages:

In the first stage, adding sodium hydroxide again (or ammonia sulphur (NH4)2S) and taking the solution to a higher pH, precipitation of Co, Ni and Mn is provoked in the form of hydroxide or sulfur. Then, in a second stage, the resulting solution is attacked with sodium carbonate (Na_2CO_3) to precipitate Li in carbonate form (Li_2CO_3).

Each stage we have described is repeated various times via recirculation until the required levels of purity are achieved.

3.2.3 Combined pyro and hydro metallurgy

Some recyclers use a combination of pyro and hydro methods. Concretely, during the mechanical phase of the hydro process explained in the former section, a furnace is used to eliminate organic elements and increase the purity of the black mass before entering the hydro part of the process.

Table 8.
Description and recovery rates. Source: Faraday Institution.

Chemical Component	Li	Ni	Co	Cu	C
Pyrolisis	0%	40-60%	40-60%	n.c.	0%
Pyrolisis + Hydrometallurgy	50-60%	>95%	>95%	>95%	0%
Mechanical + Hydrometallurgy	>90%	>99%	>99%	>99%	0%

Table 9.
Profitability of Recycling. Source: Faraday Institution.

Cathode Chemistry	Li	Ni	Co	Mn
NMC622	13%	61%	19%	20%
NMC811	11%	75%	9%	9%
NMC111	15%	40%	40%	37%
LFP	10%	0%	0%	0%
NCA	10%	67%	13%	0%

The profitability of battery recycling is intrinsically linked to the value of the by-products obtained at the end. The more raw materials contained in the black mass, the more income can be cashed in by the recycler. Therefore, the chemistries containing more raw materials in the cathode will be the most profitable for the recycling activity. In the former graph, we can see that NMC batteries are the ones using more critical materials. NMC chemistries are evolving to contain less cobalt, and higher nickel and manganese. LFP batteries contain only lithium as a critical material, they are Co, Mn and nickel free. This makes them less vulnerable to raw material shortages, their recycling is also much less profitable. We can see that in the following graph, where LFP recycling is around 60% less profitable than that of the average NMC chemistry.

Table 10.
Battery recycling profitability per cathode chemistry. Source: Circular Energy Storage.

Material	USD/kg	NCM111	NCM523	NCM622	NCM811	NCA	LFP	LMO	LCO
Casing									
Steel	0.29	10%	10%	10%	10%	10%	10%	10%	10%
Aluminum	1.8	10%	10%	10%	10%	10%	10%	10%	10%
Current Collectors									
Aluminum	1.8	5%	5%	5%	5%	5%	5%	5%	5%
Copper	6.0	7%	7%	7%	7%	7%	7%	7%	7%
Anode material									
Graphite	1.2	18.1%	18.1%	18.1%	18.1%	18.1%	18.1%	18.1%	18.1%
Catode material									
Mangenese	2.4	6.1%	5.5%	3.6%	1.8%			19.4%	
Lithium	70.0	2.3%	2.3%	2.3%	1.9%	2.3%	1.4%	1.2%	2.3%
Cobalt	30.0	6.5%	3.9%	3.9%	1.9%	2.9%			19.3%
Nickel	12.0	6.5%	9.7%	11.6%	15.4%	15.6%			
Aluminum	1.8					0.4%			
Iron	0.4						11.3%		
Value $/kg		5.42	5.02	5.19	4.77	5.32	1.97	2.26	8.30

3.2.4 Recycling of future chemistries

The trend towards new chemistries in Li-ion batteries leads to solid-state and semi-solid state batteries. We don't foresee great technological challenges in achieving good recovery results in recycling these chemistries, as the process will not be very different to the one being used already for NMC chemistries. It is even expected to be just the opposite, with improved recovery rates for solid state batteries, since anode metal foil will be replaced by a full lithium metal, and separation of a solid electrolyte will be an easier process than managing a saturated electrolyte.

Another future trend is in Na-ion chemistries (sodium ion), where the first units being built are still at R&D stage. For this chemistry, which does not require lithium, the challenge is more that of recuperating salts and finding applications for them, rather than returning them to the battery industry again. Sodium is not scarce in nature, and the recycling paradigm for this type of battery is much more standard: waste cannot be deposited, and new applications will have to be found, but the OEMs themselves will not find it so crucial to get involved in the business.

3.3 The present and the future of the Batteries regulatory framework

3.3.1 Today

Legislation referring to Li-ion battery recycling in Europe today is based on 3 EU directives:

- 2006/66/CE, referring to batteries, accumulators, and their recycling. This directive is transposed today in Spain by the Royal Decree RD106/2008, and also RD 710/2015 and RD 27/2021 that modify it.
- 2000/53/CE, referring to end-of-life vehicle management. This directive is transposed today in Spain by the Royal Decree RD1383/2002, and also RD 774/2016 and RD265/2021.
- 2012/19/CE, referring to waste electrical and electronic equipment. This directive is transposed in Spain through RD110/2015 and RD 27/2021.

Basically, this corpus introduced to the market the obligation that producers recycle batteries, forbidding landfilling and forcing them to establish producer responsibility organisations (PROs) that finance the collection and recycling of batteries introduced on the market.

In Spain, the main PRO for battery recycling is Ecopilas, with almost 45.000 collection points collecting over 7.300 tonnes of batteries in 2021, among which Li-ion automotive batteries are still in very small numbers.

3.3.2 The immediate future: new battery regulation

In December 2020, the EU announced a proposal for a new battery regulation concerning batteries and waste batteries that would substitute the 2006/66/EC Directive mentioned in the previous section. The fact that this will be a regulation instead of a directive (therefore, law from the day of its publication, without the need of being transposed by the member states) gives an idea of how crucial Europe considers this topic.

It broadens the ambitions of battery recycling, with the following key points made:

- It establishes a category for vehicle batteries.
- It establishes recycling goals, per battery weight (recycling efficiency) per metal -Li, Co, Ni and Cu- (recovery rates), and of recycled content in newly produced batteries.
- It gives responsibility of the EOL product to producers and distributors.
- It obliges those responsible for the product to establish collection points near end users, even if they are not profitable.
- It emphasises traceability through the obligation of reporting, labelling and the establishment of a battery passport, an electronic identifier unique to every battery.
- Second-life batteries are considered new products. No targets on them. Producers of these kits are held responsible for their EOL treatment: these batteries become a new product when they are repurposed for second life.

The new battery regulation is expected to be published during 2022.

Table 11.
Battery Regulation Requirements on Recycling.

From	2025	2026	2030	2035
Recycling Efficiency	65% of average Li-Ion battery weight		70% of average Li-Ion battery weight	
Recovery Rate		90% of Co, NI and Cu	95% of Co, Ni and Cu	
		35% on Li	70% on Li	
Recycled Content in Batteries				20% on Co
			12% on Co	35% on Ni
			4% on Ni and Lu	10% on Li

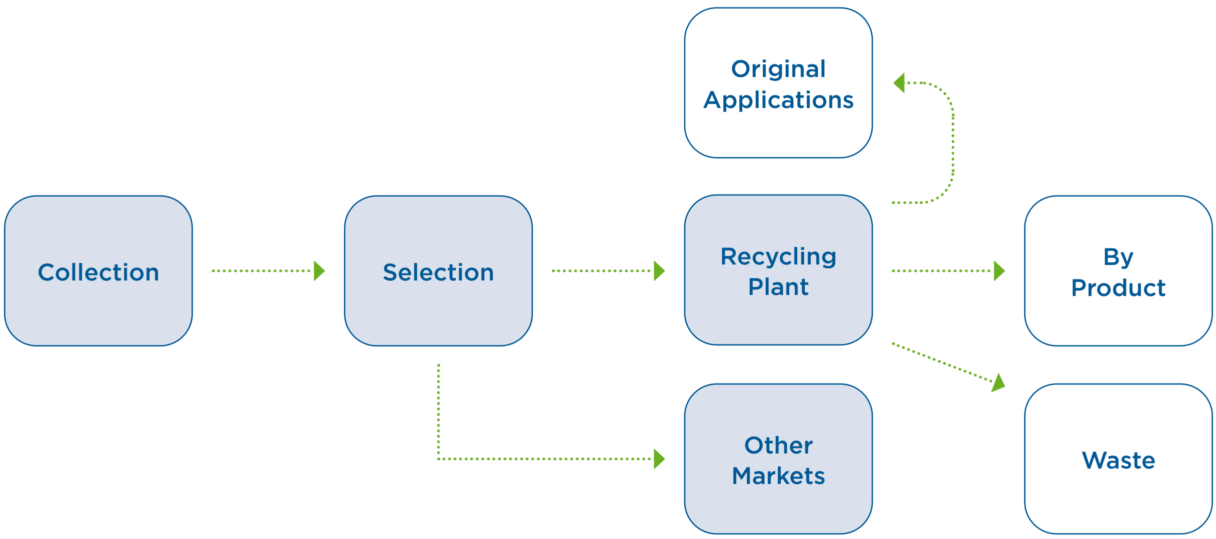
New battery regulation is expected to be published during 2022.

4

Discussion: how to define the right Model for a recycling Business?

We could classify any recycling model as shown in the following:

Figure 27.
Basic steps of a product recycling business model.



First, there is a collection phase, that will be more or less complex depending on the capillarity needed for the collection of thewaste fluxes. A very capillar system will be one that has to collect waste generated in households, for example, and one without need for capillarity will be one that needs to collect waste generated in very niche industrial applications, like for example, electric arc furnace dust generated at steel mills, and used afterwards in the electrolytic zinc industry.

Then there is a selection process thatseparates the waste flux in 2 basic fluxes: one that is capable of having a second use in other markets "as is" (e.g. like old clothes that are given a second use through vintage stores) and the rest, that cannot have any further applications and need to go to the recycling process to be converted into other materials that can have further uses.

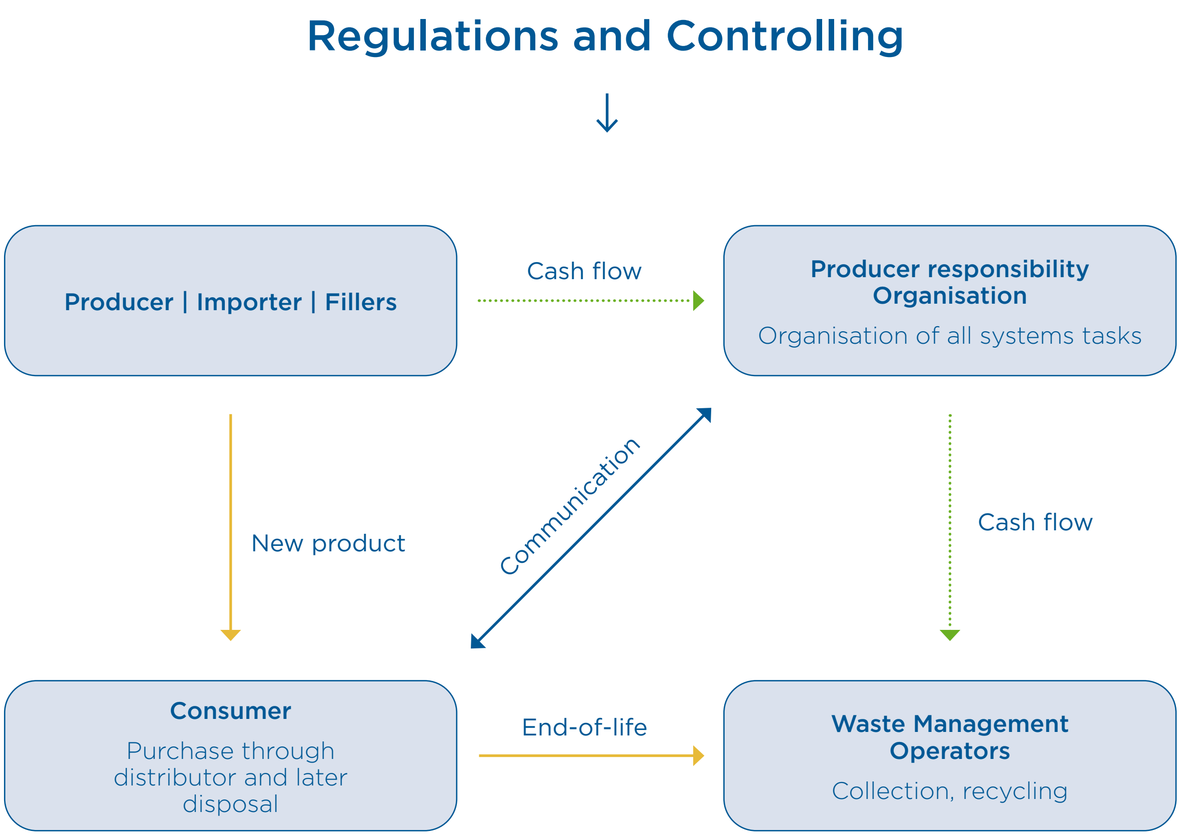
The recycling process (here simplified as "recycling plant", but that can have several steps even separated geographically) generates some by-products, some good enough to return to the original application they came from, and others needing to go on to other applications, generally (but not always) with lower value added

And, of course, there can be a flux of final waste in the recycling process that the operators of the plant will try to minimise.

To make a recycling system happen and be efficient, it has to rely not only on ethics and corporate social responsibility, but also on regulation and a sustainable business model. This is a key factor in understanding the different roles agents take in the business models.

The most usual situation in a recycling market is that it has to be funded, because the cost of the recycling process (from collection to the production and sale of byproducts) is more expensive than buying the virgin product directly, or because the by-products obtained are technically poor, so they have to be sold on to other applications with less added value. In Europe, recycling is compulsory by law, although landfilling practices are not completely abolished yet. The responsibility for recycling usually falls on the owners of the product, in most cases the producers. The usual method is to unite with other producers that share the same problem and create a PRO (producers' responsibility organisation) and fund it with a so-called "eco-tax" that the final clients pay when buying a new product. This eco-tax funds the whole collection-recycling process.

Figure 28.
How a Producers' Responsibility Organisation (PRO) works.



If the product owners can see recycling as a substitute for their virgin materials and they can make a profit on it, there is the possibility that the producers will actively enter the recycling business

In the case that the recycling system is profitable (i.e., the Costs of goods sold (COGS) from the collection and recycling process is smaller than the cash-in generated by the sale of by-products), then the recycling system is left to the market. The implication of the end of life product owners will basically depend on the percentage of the by-products returning to the original application: if the product owners can see recycling as a substitute for their virgin materials and they can make a profit on it, there is the possibility that the producers will actively enter the recycling business (organising their own collection systems, taking equity stakes at recycling plants, etc.) via entering closedloop agreements with the recyclers: "I take my EOL flux to your plant to be recycled, but the by-products will come back to me". As a matter of fact, this will mainly happen if the by-products that are going to be recuperated are scarce in the "virgin" market. If not, producers will tend to let the market take care of their by-products and not get involved in a business -the waste management business- that is usually seen as "complex", "di erent", and with the so called "Not in my backyard" (NIMBY) implications.

4.1 Solar PV recycling business

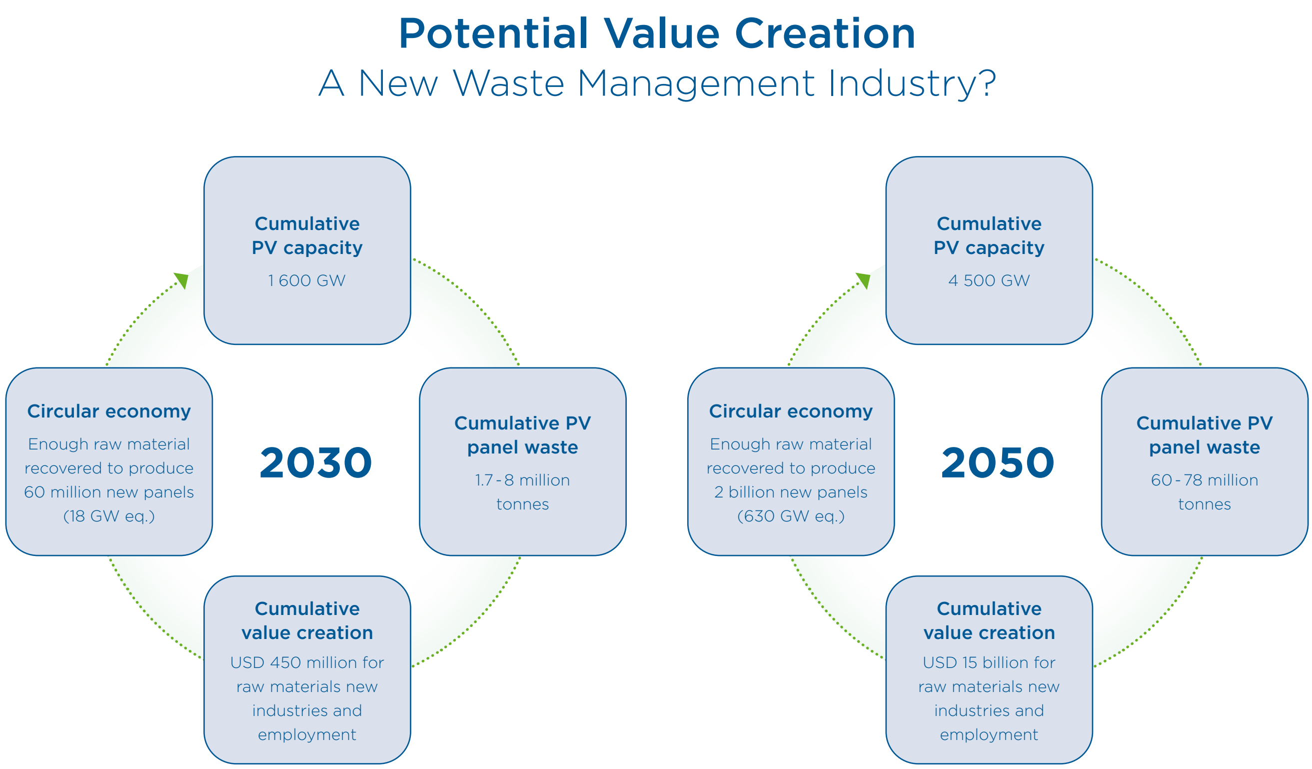
There is an important component of value creation in the business of PV waste management and circularity. A well thought out model can be very substantial, economically and in terms of job creation. According to a projection by the International Renewable Energy Agency, the global market value of raw materials recovered from solar panels could reach $450 million by 2030. In other words, this amount of raw materials would approximately be the same as that required to build 60 million new solar panels or to generate 18 GW of electricity. Same projection predicts that by 2050, the value of recoverable materials might surpass $15 billion, which would be enough to power 630 GW with two billion solar panels.

MDD 450

The global market value of raw materials recovered from solar panels could reach $450 million by 2030

These values are still to be challenged considering the annually revised ambitious goals in terms of global cumulative PV capacity, with a tendency to increase.

Figure 29.
Potential value creation from a PV waste management industry



The fact is that in a PV module almost everything is recyclable, but not profitable. Although technology improvements are reducing the use of materials notably, there are still some specific materials which are extremely valuable and not so abundant. So, the key to building a stable business is to properly separate all the components, so that the critical, most valuable materials can be recovered and reused in the same or in different industries. Think of last year's silicon price shock, a 300% increase owing to a shortage of the metal sparked by a production cut in China. And it is not just silicon, this is also happening with other raw materials, the prices of which are recording extraordinary growth in recent months. Silver is the other metal which Europe is highly dependent on, with constant importing activities.

This dependency of Europe on critical raw materials which are inputs of the PV supply chain creates a strategic situation that could determine the EU's future on PV deployment. The situation calls for an appropriate framework to mitigate this risk. Industries and R&I partners in Europe are working towards addressing the key challenges to set up the right business models to tackle recyclability and the carbon footprint of solar technologies.

To achieve a working business model, recycling technologies should be capable of working on a large scale, considering that there is currently too much PV waste and very little being recycled; tens of thousands of tonnes per year and only a few thousand tonnes inefficiently recycled, and this is just the beginning of the curve. On top of this, recycling infrastructure/equipment is expensive, so there is a need for a financing source to cover the high treatment and collection costs. And the biggest challenge is that existing technology is quite new and at the beginning there will be low volumes to treat, so companies are reluctant to invest based on the risk and uncertainty that it will become a profitable business.

Industries and R&I partners in Europe are working towards addressing the key challenges to set up the right business models to tackle recyclability and the carbon footprint of solar technologies

All in all, in terms of technology, the market is ready and proved, but the investment on scaling up is what is needed to cover the capacity. As an example, in the box below we explain how ROSI Solar has developed their own business model for the French recycling market.

ROSI Solar's Business Model

While interviewing ROSI, we also learned of their experience in positioning themselves on the French market, and the definition of their company's business model.

In France they have established a PRO called Soren that handles the collection from over 300 different points all over the country, from municipal solid waste points to big PV plant sites that are being dismantled. But the key question that really defines any business is always: who pays? In France, the cost of every new module includes an eco-tax, which is the financing source for the end-of-life management undertaken by Soren. In other countries where there is more than one PRO, this money is shared. In the Netherlands, for example, which has a similar tax to the one in France, it is a big challenge to give a good recycling service because the volume of modules they receive is too low. In France, there are more than 100 000 tonnes of PV material deployed in new plants every year, while Soren is only collecting around 5000 tonnes. This is why this model works at the moment, because there are actually 20 times more panels taxed than collected, but in the coming years with the expected increase of PV waste, the model and the tax will need to be adjusted.

The next step in the French business model is to select the collection operators in charge of delivering the waste. In this case, once a plant is dismantled, the modules can be turned in without extra charges for the plant owner/manager, since the recycling tax was already paid by the producer. Next, Soren selects the recyclers who receive the waste to be treated through a tender based on a recycling fee. Last year, ROSI won the tender to become one of the three recyclers selected for France.

So now the question is regarding ROSI's business model, how do they make a profit? In one way, from the recycling fee charged to Soren, in another, from the outcome recovered from the materials that they sell, which are of high value and thus in high demand by several buyers from different industries. In an ideal future scenario, PV waste should be recovered to be reused for PV manufacturing in order to create a closed cycle within the industry. Nevertheless, that reality is still far from being feasible.

Starting from next year, ROSI's first recycling line will be able to recover 60 tons of silicon. The amount of silicon embedded in PV panels put on the market in Europe last year reached more than 90 000 tons. Despite this crude reality, **the market is starting to see some silicon consumers in Europe who buy a small part of their input from recycled silicon as a means to reduce their environmental impact. This is a first step towards reaching such strategic environmental goal.**

Changes in module composition could also affect the design of the recycling systems and the value of the recovered materials. Thus, it will be important for the emerging module recycling market not only to be aware of changes in module composition, but also to initiate discussions with manufacturers both for information exchange and to explore the potential for module design to facilitate material recovery.

While it remains a goal and not yet a reality, in Europe the market is already talking about the panel of the future, one made with 100% recycled materials. Particularly in light of the millions in savings and other benefits that could be generated.

4.1.1 Ongoing business initiatives in Spain

In Spain, some business initiatives in the sector have been born directly from the manufacturing side. Last year, for example, the German company Rinovasol opened the first manufacturing, repair and recycling center in Pamplona to enhance the circular economy around the PV industry. Apart from having a production capacity of 50 MW for new panels, in the plant they receive used panels, fix them, certify them, and put them back on the market, with a new data sheet and a 5-year guarantee. In those cases where the panel cannot be recovered, it is sent to their plant in Germany to recycle the raw materials.

Other initiatives which enable the building of profitable business models around the PV circular economy in Spain are incentives including the recent certificate launched by the Spanish Solar Association (UNEF) on Excellence in Sustainability and Conservation of Biodiversity for PV Plants. The objective is to improve the local environment where PV is deployed by recognising social and environmental requirements, such as end-of-life treatment of the modules or integration of the technology with the surroundings.

There are, however, still many advances to make on a national scale. These are challenged by the risks previously mentioned concerning a not yet defined working business model. In addition to this, it is expected that the industry may suffer a period of waste scarcity after the repowering of the 2007–2008 PV plants ends. At the same time, research predicts that by 2050, this industry would be able to recover around 75% of the raw materials required to manufacture the PV module demand in Spain.

4.2 Wind Power recycling business

As mentioned earlier in this study, in the wind energy industry there are several flows and actions to be taken once it is decided to dismantle or extend the life of its assets. From a business perspective there are two fundamental approaches that the industry is likely to follow:

a. Concrete, plastics or even blades do produce low value recycled materials so unless there is a regulation in place that bans the use of landfilling this will be the cheapest and easiest solution for the industry. In most of the cases the alternative to the landfill is using those materials as fillers for the civil construction sector. In the particular case for blades, there are several technologies under development trying to separate fibers from resins. If this is achieved at a reasonable cost, there is a potential for re-using fibers through new fabrics or even used recovered resins as chemical additives for other products or to burn them in the recycling process to reduce the energy consumption. If there is no value in life extension or in the recycling process of the component, the industry will go for the cheapest solution. As per today's situation, this is landfilling the waste. Only for those cases where there is regulation in place restricting this disposal approach, the industry will look for alternatives to render them inert at the lowest cost possible. Blades may benefit from two revenue streams: the disposal of the blades not using landfills and the reintroduction of new products using clean fibers (i.e.; low grade fabrics / composites for the construction industry or even low value components for the automotive industry).

b. Most of the main components (gears, actuation systems, generator, gearboxes... do have a higher value if refurbished and re-introduced in the market as spare parts. This market maybe of extraordinary value for existing manufacturing companies as they have the knowledge and capacity and may represent a good diversification for their current activity that does not require extra investment. This last point may be extremely relevant as sector is evolving towards larger machines that require extra investments and some of the current suppliers may not want to follow that route. If there is value enough in the component or in the recycled materials within the component, the market will regulate the economic flows. At this stage, the dismantling may change from being a cost supported by the asset owner to be a cost supported by the company refurbishing or recycling the component. Technologies to be used will be driven by the capacity of creating a gap in between the processing costs and the value of the by-products created.

Most of the main components (gears, actuation systems, generator, gearboxes... do have a higher value if refurbished and re-introduced in the market as spare parts

An important factor to assess is the size of the market in the future. Past installations are easy to assess as is when disposals will require addressing. However, in the long run it is very relevant to study in what ways technological changes in the design and manufacturing of wind turbines will affect business potential.

As an example, VESTAS is leading a coalition of industry and academia to commercialise a blade recycling material technology using thermoplastics instead of thermo-stable resins. This can reduce the market potential of above-described technologies (pyrolysis, solvolysis, ...).

At the same time other companies are using decommissioned wind turbine blades as weights to store electricity in the latter's gravitational storage system in a re-purposing approach.

4.3 Batteries recycling business

Regarding the battery recycling industry, we expect a trend where product owners play a key role. As we have seen in the section on the Market of Batteries, the word that can best define the market situation for the coming years is "scarcity": a rocketing battery demand, a development time of new raw materials projects of 7-10 years until start of operations, and an average battery life of 8-12 years (so very few batteries reaching the recycling market compared to the number of new batteries introduced). On the other hand, raw materials may be the bottleneck of the Li-ion battery supply chain: we can see this with the evolution of lithium prices in the last 18 months. Battery manufacturers and automotive OEMs (that will be the owners of the recycling responsibility for batteries) will be the main "owners" of recycling business models, too. We are seeing some movement in this direction already (see graph below).

So, it is probable that, in terms of NMC chemistries, and driven by the scarcity of nickel, cobalt and lithium, the automotive OEMs are going to organise the recycling of their batteries in such a way that they can recuperate the by-products for them to be introduced again into new Li-ion batteries. They will organise their own collection systems, using their retail/after-sales network for this purpose, and will send these EOL fluxes into recyclers with whom they have reached closed-loop agreements. Very likely, recyclers will ask for an equity stake from the automotive OEMs in order to offset the weakness of their position in a closed-loop model, their position would be that of a mere service provider. This active participation of the automotive OEMs in the recycling process will enhance the performance of the recycling process: eco-design and homogeneous batching on the EOL fluxes will help reduce costs for the whole process through automation and better efficiency.

This structuring of the battery recycling business with such a high participation of the automotive OEM's is highly unusual. It is because of the great scarcity of the raw materials that they will be acting well beyond a mere financial position. In fact, we have to understand that batteries are the new heart of the electric car (not the engine anymore), so automotive OEMs will make bold movements to be strategically strong on this topic, even taking the lead in recycling and investing in mines, something that not long ago would have seemed implausible.

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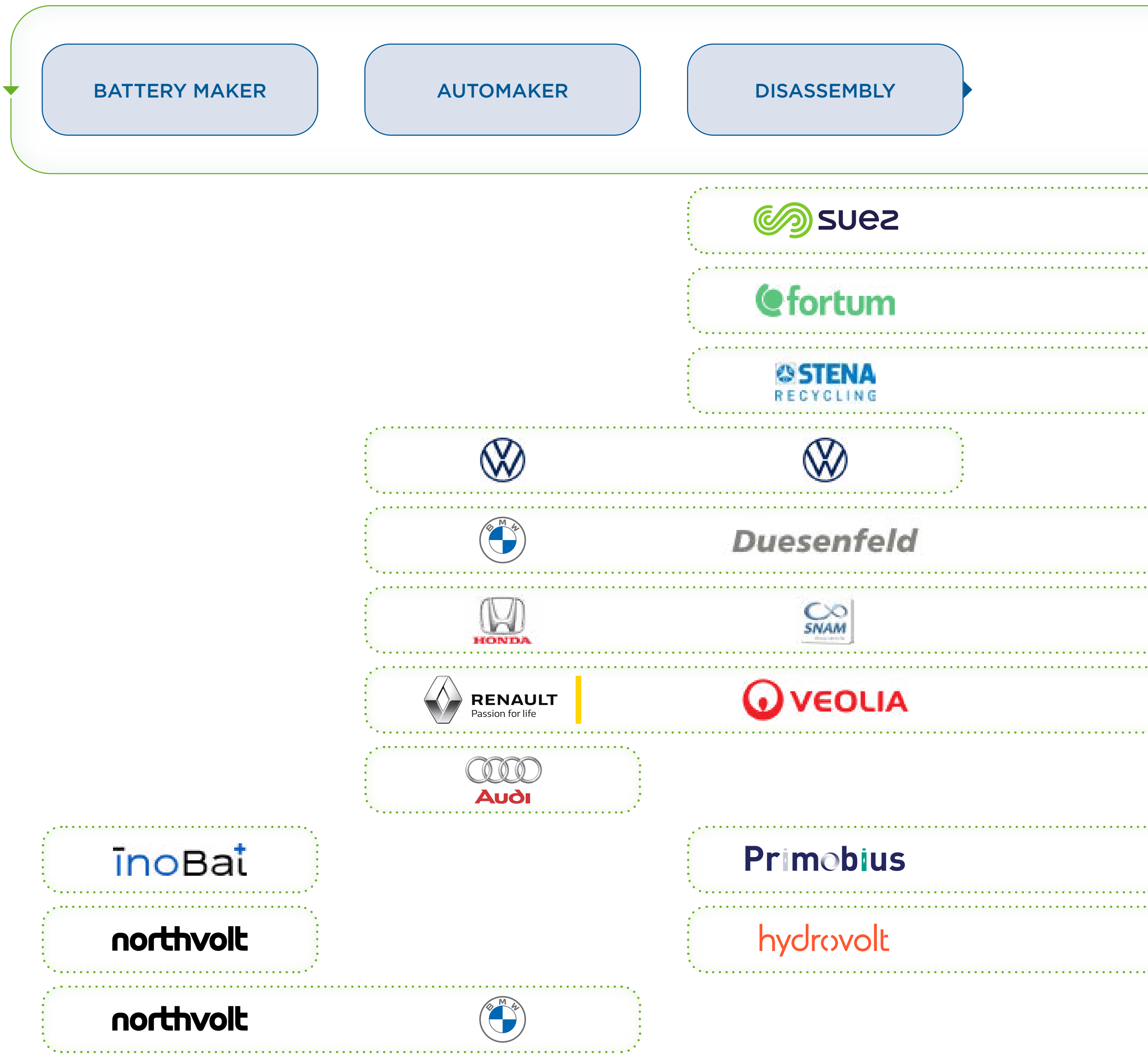
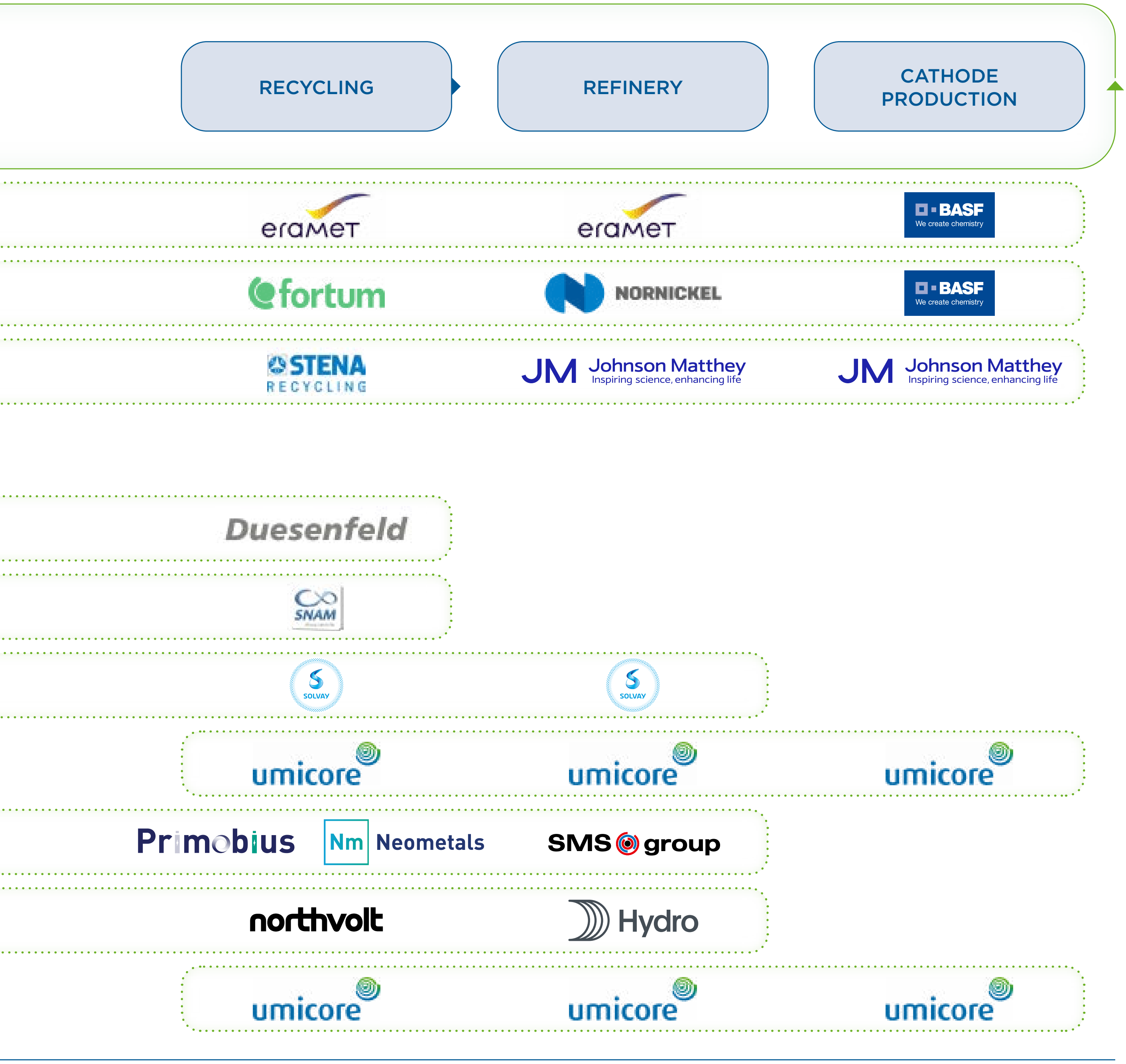
Figure 30.
European Partnerships around Battery Recycling. Source: BloombergNEF.



Note: The solid green line indicates joint ventures and in-house operation. The dotted lines indicate the strategic cooperation.

Second life. If we return to **Figures 20 and 21 in sections 3.1 and 3.2** that showed the scarcity of raw materials with respect to demand, then the question that comes to mind is: “is there going to be a market for second life?”. Second life will have its main competitor in automotive OEMs trying to get hold of the valuable metals within the cells.



If we take a look at the Chinese market, where they are 10 years ahead on establishing recycling business models, we can see that a second life will be based mainly on LFP batteries: aside from being less valuable to recycle (they only contain Li, and in lower amounts that NMC) they are also better suited for intensive cycling.

Conclusions

As explained along this study, the energy transition will not only require a widespread deployment of renewable energy sources but also an effective end-of-life management, to meet the objectives in a sustainable way.

The EU economy is heavily dependent on imported supplies of many minerals and metals needed by the energy industry. To the date, while 60% of the global material demand is extracted in China, in Europe we remain dependent on foreign imports for more than 80% of our raw materials. Securing access to a stable supply of such critical raw materials has become a major challenge for national and regional economies. The impact of raw material supply disruption could mean a loss of competitive economic activity in the EU, and in some specific cases, reduced availability of certain strategic final products. As a consequence, over the past decade, concern over an efficient use of resources and an increase in their recovery rate has grown.

In terms of environmental and climate protection, it is important that PV modules, wind turbines and batteries are used for as long as possible and recycled at the end of the product's life in a way that conserves the resources. However, this requires improved structures and guidelines for corrective maintenance, functional testing, waste collection, recycling, and eco-design. These areas of contribution will not only reduce the impact on the environment by avoiding millions of tonnes of unmanaged waste, but they will also strengthen Europe as a location for innovation. The right management of end-of-life treatment in the renewable energy sector is already recognised to be an economic enabler, which is being accelerated based on specific regulations for each industry.

To date there are already existing recycling initiatives in Europe with relevant recycling rates of over 80% in terms of mass. In the future, however, treatment operators will be required to not only treat the bulk material, but more importantly, the critical materials integrating the systems. This will most likely entail additional processing going beyond mechanical treatments, fostering the implementation of the minimum treatment requirements and related technical specifications for depollution.

In the future, however, treatment operators will be required to not only treat the bulk material, but more importantly, the critical materials integrating the systems

Nowadays, there is still a huge gap between producers and recyclers, which needs to be overcome to minimise product models and implement solutions such as eco-design and recycled materials.

Green procurement guidelines from the federal, state and local governments should give preference to comparable products that use recycled materials. At EU level, mandatory eco-design specifications, such as making materials easier to separate, should increase the recyclability of these technologies without limiting their useful life. On top of this, the deployment of dedicated recycling plants will allow for the increase of waste treatment capacity and maximise revenues, which will also translate into better output quality. In addition, it will contribute to increasing the recovery rates of valuable components.

Standard recycling markets, also need to overcome the many administrative implications on everyday tasks and improve the quality levels of the usual by-products so that they are suitable to serve as input for their original application. Nowadays, there is still a huge gap between producers and recyclers, which needs to be overcome to minimise product models and implement solutions such as eco-design and recycled materials. The stronger the producer-recycling relationship becomes, the more motivation and involvement from the producers there will be to achieve efficient recycling models.

In an ideal scenario, producers would identify the responsibility of end-of-life management of their products as their own. They would organise and finance their own producer responsibility organisations to tackle the problem of collection, sorting, recycling and later sell the by-products to other industries. In reality, although the sector is already changing, to the date producers still see recycling very distant from their core business, to such extent that even when recycling generates profit, they choose to let the market rule and let recyclers benefit from it without even a gate fee.

To date there are already existing recycling initiatives in Europe with relevant recycling rates of over 80% in terms of mass. In the future, however, treatment operators will be required to not only treat the bulk material, but more importantly, the critical materials integrating the systems.

By 2035 the battery sector will need to recover 30% of the cobalt and 20% of the lithium and nickel from the used batteries and by 2050 the deployment of wind turbines will require most of the rare earths currently available. Considering this future scarcity in raw materials in the years to come, this structure cannot last too long. With big percentages of metal recovery from recycling technologies, producers will want to keep a hand in the flux of their end-of-life products, with the aim of capturing the raw materials and reintroducing them into their production lines. In the battery sector, concretely, the automotive OEMs (responsible for EOL batteries in the new EU battery regulation) will directly invest in recycling plants and organise the logistics of their own EOL batteries.

EU's goals for the low-carbon energy transition are clear, and the plan is to achieve them in a sustainable way, not only by using renewable energy technologies but also by effectively managing the waste derived from these. Meeting the material demand will be Europe's challenge to successfully achieving this transition. As such, it is important to keep monitoring the changes in the supply, consumption and criticality of the materials used in the renewable energy sector. Efforts should be made to ensure stable and secure supplies of technology specific materials, in order to prevent any possible future shortages. To better assess EU resilience to such increasing demands for raw materials, additional studies are needed, looking at the evolution of future material supplies and comparing them with the material demand results presented in this report.

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Co-funded by the European Union

Naturgy Foundation