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EXTENDED PRODUCER RESPONSIBILITY FOR ENERGY TRANSITION TECHNOLOGIES

Electric vehicle batteries, solar photovoltaic panels, and wind turbines under the spotlight

Background document

Geertje Grootenhuis, Alexandros Dimitropoulos and Daan in 't Veld
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Colophon

Extended producer responsibility for energy transition technologies: Electric vehicle batteries, solar photovoltaic panels, and wind turbines under the spotlight

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Corresponding authors
alexandros.dimitropoulos@pbl.nl, daan.intveld@pbl.nl

Authors
Geertje Grootenhuis, Alexandros Dimitropoulos and Daan in 't Veld

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Contents

Summary 6

1 **Introduction** 8

2 **Priority materials for EV-batteries, solar panels, and wind turbines** 11
2.1 The Netherlands is undergoing an energy transition 11
2.2 The energy transition heavily relies on metals and minerals 12
2.3 Priority critical materials for solar panels, electric vehicle batteries, and wind turbines 16
2.4 Technological advancements will impact material dependencies 20

3 **EPR Policy Background** 23
3.1 EPR Policy Design 23
3.2 EPR Policy Frameworks in the EU and the Netherlands 24
3.2.1 Policy Frameworks Governing EPR for Electric Vehicle Batteries 26
3.2.2 Policy Frameworks Governing EPR for Photovoltaic Panels 27
3.2.3 Policy Frameworks Governing EPR for Wind Turbines 27
3.2.4 Enforcement of EPR 27
3.2.5 PRO Consolidation 28
3.3 Incentivising repair and reuse through EPR schemes 28

4 **Evaluating the effectiveness of the EPR scheme for EV batteries** 30
4.1 Are the existing EPR targets being met? 30
4.2 What is the current end-of-life pathway for electric vehicle batteries? 31
4.3 Where are EPR policies falling short in promoting circular economy goals and safeguarding priority materials? 33

5 **Evaluating the effectiveness of the EPR scheme for solar panels** 35
5.1 Are the current EPR targets being met? 35
5.2 What is the current end-of-life pathway for solar panels? 37
5.3 Where are EPR policies falling short in promoting circular economy goals and safeguarding priority materials? 37

6 **Considering an EPR scheme for wind turbines** 39
6.1 What is the current end-of-life pathway for wind turbines? 39
6.2 Are current practices stimulating circular economy goals and safeguarding priority materials?41

7 **Conclusions** 43

References 45

Appendices 50

Appendix 1: Definitions of material security, environmental and economic indicators 50
Appendix 2: Material-at-a-glance Factsheets 51

Summary

This report explores the role of Extended Producer Responsibility (EPR) in promoting the sustainable management of products considered critical for the energy transition at the end of their lifecycle. EPR is a policy approach in which the responsibility of producers is extended to the post-consumer stage of a product's lifecycle. It has been successful in increasing the separate collection and recycling of end-of-life products, and holds promise for stimulating the recovery of critical raw materials and a more sustainable reuse of other materials with a potentially high environmental impact, such as composites.

By assessing the end-of-life pathways for three product groups critical to the energy transition in the Netherlands – electric vehicle (EV) batteries, solar panels, and wind turbines – we discuss the strengths and weaknesses of existing and potential EPR schemes. Our study relies on desk-based research and interviews with stakeholders to provide recommendations on how to increase the lifespan of the products in question and how to foster the recycling of critical materials within them.

This study also identifies eight critical raw materials (CRMs) deserving priority attention due to their importance for the three product groups, as well as for their material scarcity and environmental impact. These are copper, nickel, silicon, manganese, lithium, cobalt, graphite, and neodymium (a rare-earth element). Existing EPR schemes for EV batteries and solar panels, and end-of-life treatment options for all three product groups, are assessed in part for their role in supporting the recovery of these critical materials.

Electric vehicle batteries

A take-back requirement for EV battery producers and a minimum recycling efficiency target – currently 50% by average weight of collected lithium-ion batteries – have been in place through the 2006 EU Battery Directive. This Directive was replaced by a new Batteries Regulation in August 2023, which strengthened EPR for EV batteries by introducing separate provisions, tightening weight-based recycling targets, and introducing material recovery targets. The Regulation also introduced recycled content requirements for new batteries in order to stimulate demand for secondary materials. Furthermore, it established information-based measures, including a digital product passport and a carbon footprint declaration. Finally, the Regulation introduced EPR for second-use batteries and stipulated parameters for state of health and capacity assessment testing to promote safe battery reuse. As with other pieces of EU legislation, implementation and enforcement of the new regulation depend on EU Member States themselves. Ensuring that all producers meet the requirements, either within a collective EPR scheme or independently, is key for the effectiveness and equity of national policy implementation.

Solar panels

An EPR scheme exists for solar panels in the Netherlands through the EU-wide Waste from Electrical and Electronic Equipment (WEEE) Directive, which includes two main instruments: a 65% separate collection target based on the average weight of all WEEE placed on the market in a Member State in the previous three years, and an 80% recycling target for solar panels specifically. The 65% collection target is virtually unattainable for solar panels at present, because it does not take into consideration their long lifetimes, while simultaneously undermining repair and reuse. The weight-based solar panel recycling target of 80% is, at the time of writing, achieved in the Netherlands, but it mainly sustains downcycling practices rather than promoting the recovery of priority materials like high-purity silicon.

The EPR scheme for solar panels can be improved through the revision of the existing collection target and through the establishment of recovery targets for CRMs. Introducing a specific collection target for solar panels that takes into consideration their long lifetime and promotes their repair and reuse would ensure an alignment of incentives towards more efficient resource use. In addition, the introduction of material recovery targets for high-purity silicon and other CRMs would further incentivise their reuse in new solar panels.

Wind turbines

There is currently no EPR scheme for wind turbines in the Netherlands. The majority of Dutch wind turbines that reach the end of their so-called economic lifetime (around 15 years after installation) are exported abroad for the remainder of their technical lifetime, an additional 10-15 years. Wind turbines are mainly composed of steel (85-90%), which can easily be recycled with other bulk metals. Wind turbine blades, which are usually made of composite materials, currently pose a technical challenge for recycling.

New legislation introducing an EPR for wind turbines and minimum recycled content requirements for new blades, preferably at the EU level, could promote a more sustainable future for end-of-life wind turbine blades. The long lifetimes of wind turbines and flexibility towards evolving technologies would need to be incorporated in potential policy. Other proposals from within the wind turbine industry for improved circularity include: cement co-processing as a form of recycling end-of-life composite blades, the introduction of size limits for wind turbines to promote reuse, and incentives to stimulate wind turbine owners’ demand for refurbished parts (instead of new parts) during periodic maintenance activities.

Broader suggestions for the improvement of EPR policy

More generally, EPR requirements can be revised to better align with circular economy objectives. Moving from collection targets that uniformly apply to diverse product groups towards product-specific targets would facilitate accounting for different product lifetimes and rewarding repair and reuse. Accompanying product-level recycling targets with material recovery targets can further incentivise the recovery of CRMs and other materials whose extraction and processing generates high environmental impacts. Complementary policies like recycled content requirements and design-for-recycling are essential to introduce waste prevention stimuli earlier in the product lifecycle and to foster strategic, EU-based industrial ecosystems.

Empirical evaluation of the effects of EPR schemes, provisions in EPR schemes allowing for their periodic assessment and adjustment to technological advances, and stakeholder collaboration are essential for navigating the complexity of EPR. The design of EPR policies is complex in nature due to the level of product-specific knowledge required. Information asymmetry and rapidly evolving technological landscapes introduce a risk that policies can be poorly designed. In considering the suggestions outlined herein, it is essential to recognise the complexity and heterogeneity of the EPR policymaking landscape.

1 Introduction

The linear economic model is characterised by ‘take, make, waste’ consumption and production patterns that rely on the extraction of dwindling finite natural resources. The use and extraction of primary materials (i.e. metals, minerals, fossil fuels, and biomass) is projected to double from 2015 to 2060 (OECD, 2019). This results in significant environmental impacts: the extraction and processing of raw materials contribute to approximately half of global greenhouse gas emissions as well as emissions of various pollutants to air, water and soil resources (Nelen & Bakas 2021). Within the linear economic model, the expansion of otherwise ‘green’ technologies like renewable energy and e-mobility systems will strain resource stocks and contribute to accumulating waste streams (International Energy Agency 2021). Overall, global waste is expected to increase by 70% by 2050 (World Bank 2018). Poorly managed waste is contaminating ecological habitats, threatening biodiversity, and harming human health (United Nations Department of Economic and Social Affairs 2022).

Circular economy strategies are key for safeguarding the supply of materials necessary for the energy transition

The circular economy (CE) offers a much-needed alternative to the linear economic model. CE emphasises green design, circular business models, repair, reuse, remanufacturing, and recycling to cultivate a regenerative economic system (Fullerton et al. 2022). The transition to a circular economy promises to not only improve resource efficiency and reduce environmental impacts, but also to add jobs in the repair and recycling industries (Dufourmont & Goodwin Brown 2020). By reducing demand for primary materials, CE can also help to improve material security. This is especially important for critical raw materials (CRMs), which are defined as raw materials with a high economic value and high supply risk due to decreasing geological reserves. They are also defined through their restricted availability, being predominantly located in only a few countries (European Commission 2023a). The demand for CRMs is expected to increase tenfold in the next decade, as they are especially important for their applications in the renewable energy and e-mobility sectors (Huisman et al. 2020).

At the EU level as well as in the Netherlands, political support for the dual transitions towards a circular economy and carbon-neutral energy system has risen in recent years. The European Commission’s Circular Economy Action Plan emphasises the need for substantial increases in resource efficiency and the acceleration of the transition to a circular economy (European Commission 2020). In the Netherlands, the national government has announced its related goals to both become a fully circular economy and to transition towards a carbon-neutral energy system by 2050 (Ministry of Infrastructure and Water Management 2016). In this context, the Dutch National Circular Economy Programme 2023-2030 puts forward a number of policy options for the period up to 2030, which could bring the country a step closer to achieving its 2050 CE goal (Ministry of Infrastructure and Water Management 2023).

Extended producer responsibility is a means to promote the transition to a circular economy

Extended producer responsibility (EPR) is a policy approach supporting the transition to a circular economy by extending a producer’s responsibility to the post-consumer stage of a product’s lifecycle (OECD 2001, 2016). In other words, manufacturers/producers become responsible for the entire lifecycle of their product, including end-of-life (EoL) management. This responsibility usually includes financial and/or operational commitments like collecting, sorting, and treating end-of-life products (Dimitropoulos et al. 2021).

EPR was initially adopted as a waste management policy instrument in the early 1990s in various north-western European countries to shift the responsibility of waste management from the public to the private sector (Vermeulen & Weterings 1997). Today, EPR policies feature prominently in EU legislation for several waste streams, including end-of-life vehicles, electronics, batteries, and packaging. As a result, the Netherlands' two-decade history of implementing EPR policies is contextualised within this broader European setting.

In its most recent Integrated Circular Economy Report, PBL Netherlands Environmental Assessment Agency found that little progress had been made to reach the country's circular economy goals, and that more binding policies are needed (Hanemaaijer et al. 2023). The report recognised that existing EPR instruments, which are largely focused on increasing the quantity of material that is recycled, are not well-suited to curb a trend of downcycling, in which material is recycled into lower-value applications rather than acting as a replacement for primary materials.

With increasing demand for CRMs driven by the energy transition, there is a growing need to understand how EPR can best be leveraged to support the transition to a circular economy

Reliable access to CRMs is a growing concern for the EU due to finite resource stocks and the concentration of production and refining in just several non-EU countries (European Commission 2023a). Furthermore, the extraction, processing, and use of CRMs can have significant environmental impacts, including resource depletion, energy and water consumption, pollution, and greenhouse gas emissions (Huisman et al. 2020). Recent reports point to clean energy technologies as making up the fastest-growing segment of CRM demand (Carrara et al. 2023; Graulich et al. 2021; International Energy Agency 2021). Among these, photovoltaic solar panels, wind turbines, and lithium-ion batteries for e-mobility and energy storage are identified as being especially reliant on CRMs. As early installations reach the end of their lifespan and demand for renewable energy and e-mobility grows, the waste streams for these technologies are expected to expand in the coming years (Graulich et al. 2021).

In contrast to a fossil fuel-based system where fuels are consumed upon use, the materials utilised in clean energy systems can be recovered and reused when installations or devices reach their end-of-life (Carrara et al. 2023). An emerging stream of academic and policy literature outlines the challenges and opportunities for the end-of-life management of solar panels, wind turbines, and electric vehicle batteries, but generally falls short in offering specific policy recommendations for EPR for these product groups (e.g. Franco & Groesser 2021; Majewski et al. 2022; Maisel et al. 2023).

PBL recently conducted research on EPR in the Netherlands, outlining policy design and functioning in one report, and focusing on product-specific case studies for batteries, end-of-life vehicles, and medicine in another (Dimitropoulos et al. 2021; Tijm et al. 2021). EPR policies were found to be successful in increasing the quantity of products collected and recycled, as well as in improving the monitoring and tracking of end-of-life products. EPR's impact on improving recycling quality and promoting reuse and eco-design were deemed to be minimal.

EPR has been identified as a potential strategy for helping to safeguard CRMs, which, as outlined above, will be intensively required for the energy transition (Campbell-Johnston et al. 2022; Graulich et al. 2021; International Energy Agency 2021). Although some studies have evaluated EPR implementation in the Netherlands for specific product groups like tyres, portable batteries, and end-of-life vehicles (Campbell-Johnston et al. 2020; Tijm et al. 2021; Winternitz et al. 2019), no published literature has examined EPR for products critical to the energy transition. Solar panels, electric vehicle batteries, and wind turbines therefore offer particularly relevant case studies due to their escalating waste streams and outsized demand for CRMs.

Accordingly, this study contributes to the EPR literature by looking at products relevant for the energy transition from the perspectives of material scarcity and environmental impact, and by exploring how EPR policies can be designed to minimise these impacts and promote longer product lifetimes and high-value material recycling.

We assess EPR's potential to tackle the material-related challenges posed by the energy transition through desk-based research and interviews with stakeholders

To this end, we start with an analysis of the material composition of the three product groups of interest: electric vehicle (EV) batteries, solar panels, and wind turbines. We identify a set of critical raw materials that meet two conditions: (i) they are essential for manufacturing products of at least one of these groups; and (ii) energy transition technologies are responsible for an important share of global demand for these materials. We then assess the current end-of-life pathways of EV batteries, solar panels, and wind turbines, and explore how EPR – where implemented – has helped shaping them. Finally, we examine how EPR policy can better promote resource efficiency through higher circularity strategies – so-called R-strategies – including reuse, repair, and high-value material recycling, as well as through its joint implementation with production-side policies stimulating secondary material use.

This study is based on desk-based research and interviews with stakeholders. Desk-based research involved an extensive review of the academic and policy literature, and descriptive analyses based on data from various primary and secondary sources, including available material flow analyses. Interviews were selected as a method to supplement limited publicly available information about material flows in the Netherlands and to document industry-specific expertise, complexity, and nuance related to current policy implementation. Thirteen interviews were conducted between April and August 2023 with representatives from ministries and government agencies, international organisations, producer responsibility organisations, industry stakeholders, and research institutes. The interviews offered in-depth insights, perspectives, and experiences related to current end-of-life pathways for the three energy technologies of interest and EPR policy effectiveness. They also provided ideas for policy improvements to achieve circular economy goals.

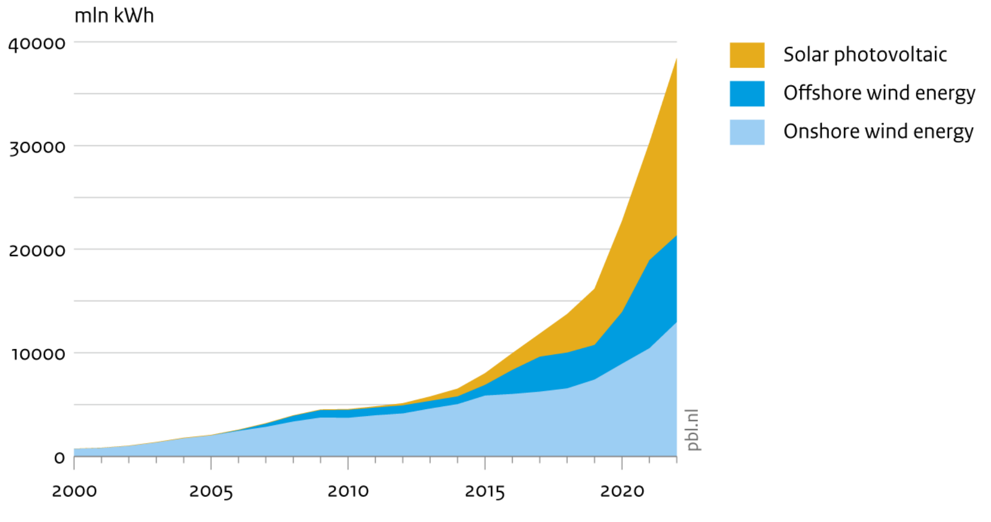
2 Priority materials for EV-batteries, solar panels, and wind turbines

2.1 The Netherlands is undergoing an energy transition

The uptake of wind and solar energy, as well as of electric vehicles, has been steadily rising in the Netherlands, reflecting national ambitions to transition away from fossil fuels (Figures 1 and 2). Subsidy programmes and the establishment of ambitious national targets have helped to spur this momentum. With the 2019 National Climate Agreement, the Dutch government set targets to generate at least 35 terawatt-hours (TWh) of energy through large-scale land-based renewable sources – solar panels and onshore wind turbines – and 49 TWh through offshore wind turbines by 2030 (Ministry of Economic Affairs 2019). In 2021, about 22 TWh of energy were generated through land-based renewables and 8.5 TWh through offshore wind turbines. The Climate Agreement also aims that all *new* cars sold in the Netherlands are (tailpipe) emission-free by 2030, five years before this requirement enters into force across the whole of the EU.

Figure 1

Gross production of electricity from wind and solar energy sources, 2000-2022

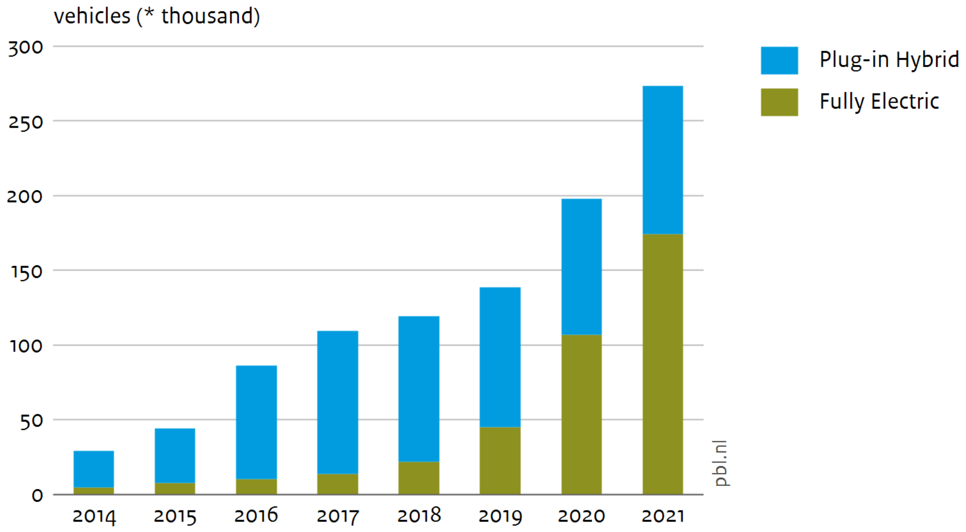


Source: Statistics Netherlands (2024)

Note: Numbers for 2022 are estimates by Statistics Netherlands at the time the data were retrieved.

Figure 2

Number of battery electric vehicles and plug-in hybrids in the Netherlands



Source: Statistics Netherlands (2021)

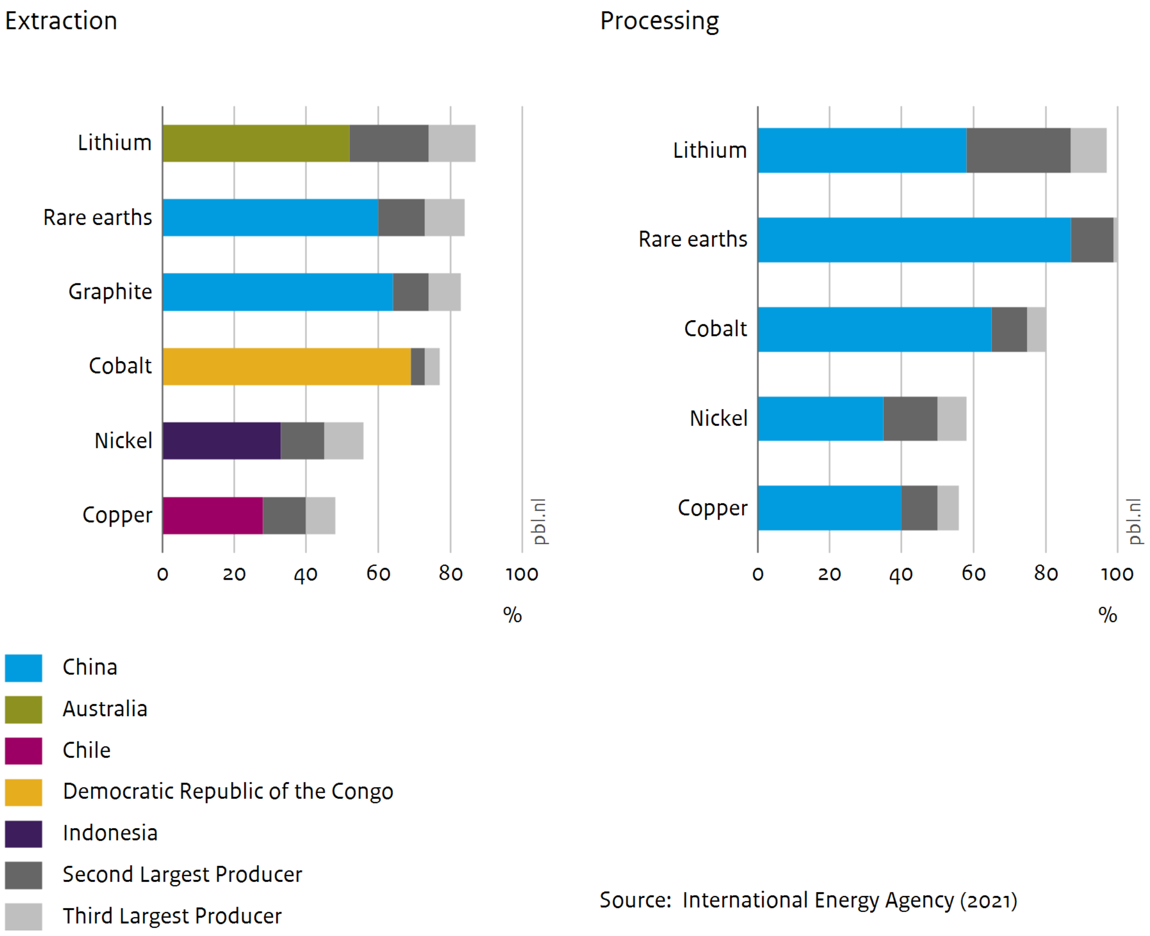
Note: All data refer to January 1st of the year shown.

2.2 The energy transition heavily relies on metals and minerals

The demand for critical minerals in the clean energy sector is expected to rise significantly, potentially reaching three-and-a-half times its current level by 2030 (International Energy Agency 2023). From a geopolitical perspective, this will shift the dependence of the Netherlands and other EU countries away from countries that supply fossil fuels, like OPEC countries, Russia, and the United States, towards countries that supply metals and minerals considered necessary for the energy transition, like China (Figure 3) (Hanemaaijer et al. 2023).

Driven by surging demand and elevated prices, the market size of key minerals for the energy transition – copper, nickel, lithium, graphite, cobalt, rare-earth elements – has experienced remarkable growth, doubling over the last five years to reach a value of USD 320 billion in 2022 (International Energy Agency 2023). This rapid expansion has propelled energy transition minerals from a relatively minor sector to a prominent force in the mining and manufacturing industries. These trends are best evidenced by the rise in demand for lithium, cobalt, nickel, neodymium, and copper, which have been identified by the International Energy Agency (IEA) as key materials for sustainable energy technologies (Figures 4-8).[1]

Figure 3



Top 3 countries in extraction and processing of critical raw materials, 2019

Source: International Energy Agency (2021)

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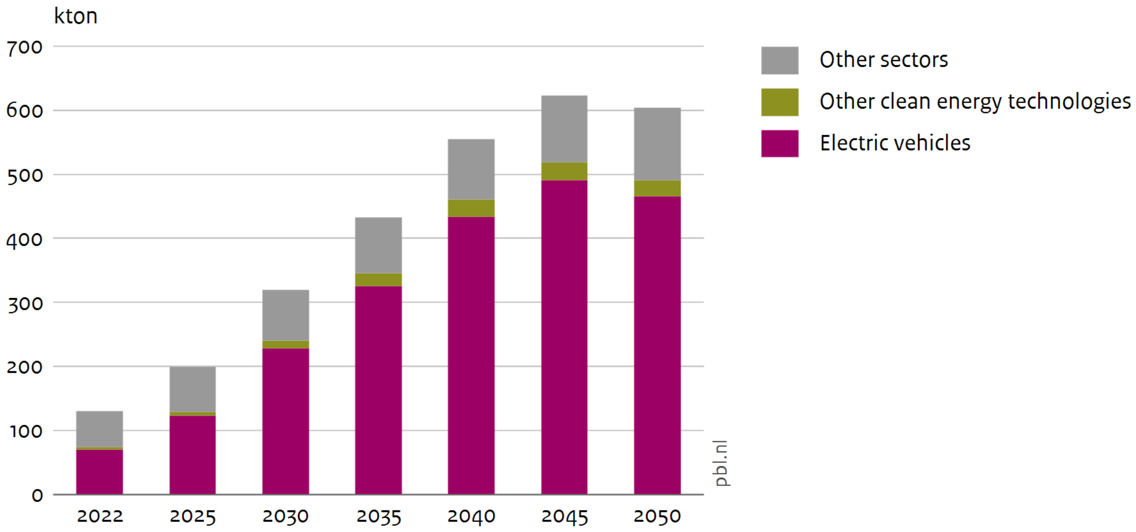
[1] All data for years beyond 2022 in Figures 4-8 reflect a Stated Policies Scenario. This scenario maps out a trajectory that reflects current policy settings, based on a detailed assessment of what policies are actually in place or are under development by governments around the world (International Energy Agency 2023).

Figure 4

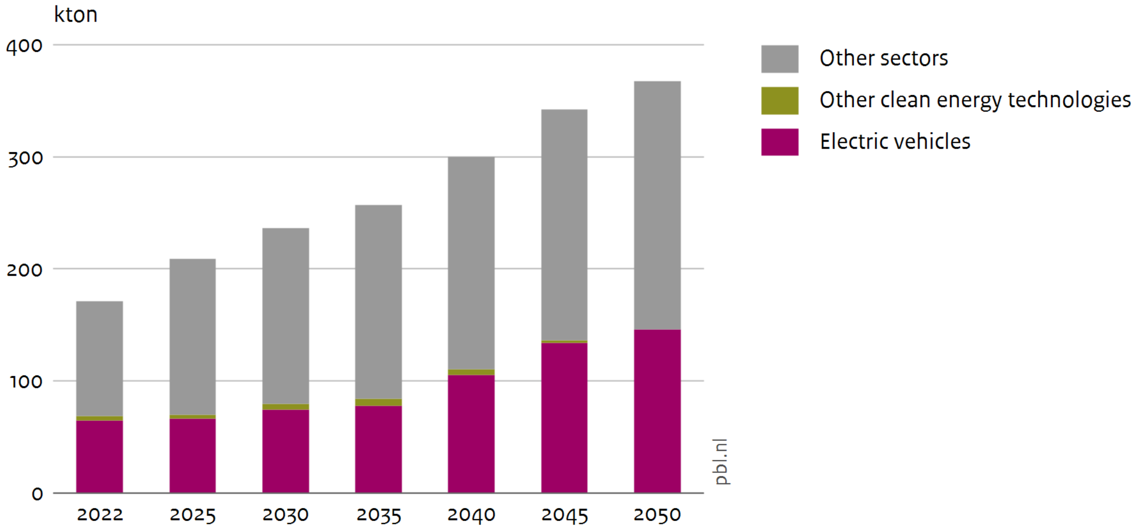
Breakdown of lithium demand by technology



Source: International Energy Agency, 2023

Figure 5

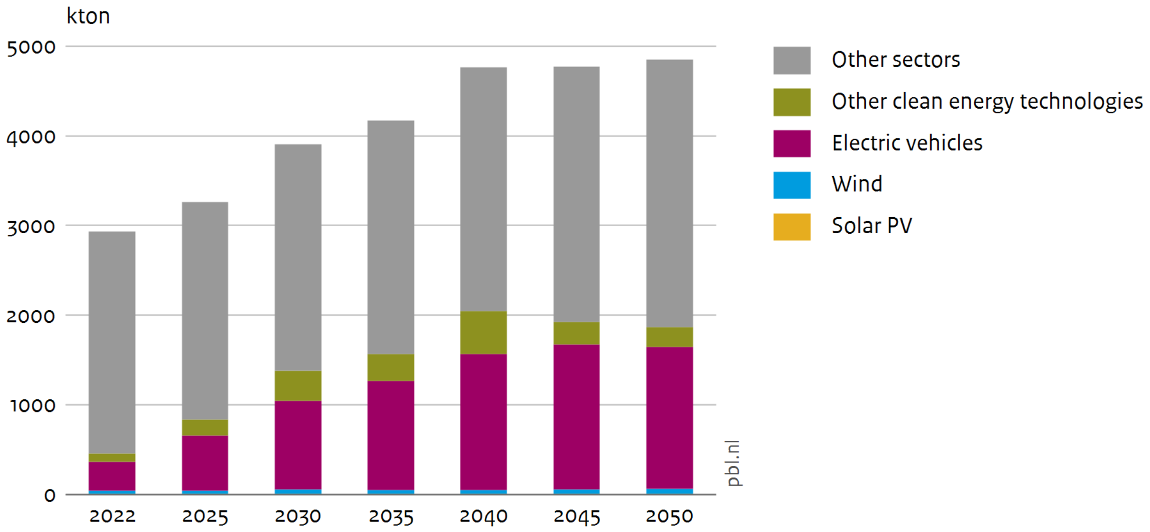
Breakdown of cobalt demand by technology



Source: International Energy Agency, 2023

Figure 6

Breakdown of nickel demand by technology

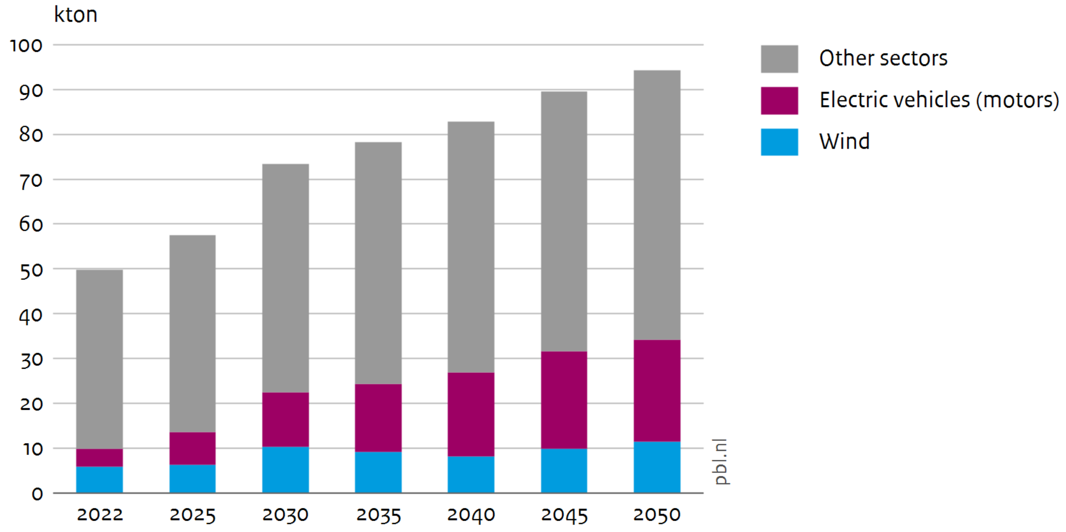


Source: Source: International Energy Agency, 2023

Note: Other clean energy technologies refer to grid battery storage, other low-emissions power generation, and hydrogen technologies.

Figure 7

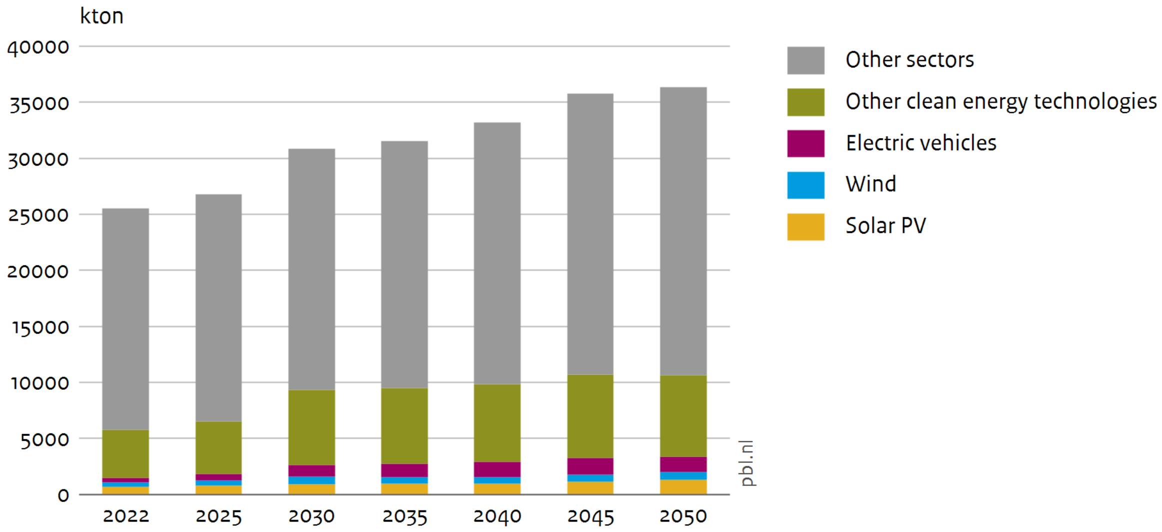
Breakdown of neodymium demand by technology



Source: International Energy Agency, 2023

Figure 8

Breakdown of copper demand by technology



Source: International Energy Agency, 2023

Note: Other clean energy technologies refer to grid battery storage, other low-emissions power generation, and hydrogen technologies.

In the period between 2017 and 2022, the clean energy sector was the primary driver behind a threefold increase in total demand for lithium, a 70% surge in cobalt demand, and a 40% increase in nickel demand (International Energy Agency 2023). This sector now makes up a significant share of total demand for these materials. In 2022, 56% of lithium demand was attributed to the clean energy sector, and this share is expected to grow to 81% by 2050 (International Energy Agency 2021). For cobalt, approximately 40% of demand came from the energy sector in 2022, and this ratio is expected to remain the same in 2050. Although the energy sector was responsible for 16% of nickel demand in 2022, this share is expected to increase to over 40% in 2040 (International Energy Agency 2021, 2023). The energy sector's contribution to demand for neodymium will increase from 20% in 2022 to 36% in 2050 (International Energy Agency 2023). Meanwhile, clean energy technologies' share of demand for copper will rise from 22% to 29% between 2022 and 2050 (International Energy Agency 2023). About 70% of this share is attributed to electricity networks.

2.3 Priority critical materials for solar panels, electric vehicle batteries, and wind turbines

In the latest European Commission Critical Raw Materials (CRM) list published in March 2023, 34 materials were identified as CRMs, and 16 were identified as Strategic Raw Materials (SRMs) (European Commission 2023a). While CRMs are characterised by their high economic importance to the EU's economy and their susceptibility to supply disruptions, SRMs are characterised by their unique significance for Europe's industrial ecosystems, innovation capacity, and strategic autonomy (Carrara et al. 2023). Furthermore, SRMs possess properties that render them difficult to replace in strategic technologies, such as renewable energy and aerospace (European

Commission 2023a). Most materials on the SRM list also meet the thresholds for the CRM list, except for copper and nickel, which 'do not meet the CRM thresholds but are included on the CRM list as strategic raw materials in line with the Critical Raw Materials Act' (European Commission 2023b). CRMs and SRMs play an important role in the composition of lithium-ion batteries (such as those used in electric vehicles, wind turbines, and solar panels), hence their status as 'critical' and 'strategic' (Carrara et al. 2023).

This study identifies eight critical raw materials deserving priority attention based on their importance for the three product groups, as well as for their material scarcity and environmental impact. These are copper, nickel, silicon, manganese, lithium, cobalt, graphite, and neodymium. While CRM and SRM status offers one indication of material significance, it is important to note that other characteristics, such as extraction volume, material scarcity and environmental impacts, can offer alternative perspectives. The following paragraphs of this section delve deeper into the identified priority materials for the three product groups, explaining their significance and role in production processes. Appendix 1 provides the definitions of the indices used to capture the relevance of priority materials for the environment and resource scarcity, and Appendix 2 presents factsheets on each material.

Copper

Due to its unique properties as an electrical conductor, copper is an important material for solar PV systems, wind turbines, and electric vehicles. In addition to its direct role in the material composition of these three product groups, copper is also relevant for its crucial role in electricity networks, which form the foundational backbone of renewable energy infrastructure. Copper is the best electrical conductor after silver (which is much more expensive), is corrosion resistant, ductile, and malleable, making it very difficult to substitute (SCRREEN 2023c).

Copper is, moreover, one of the most recycled metals, with significant recycling capacity located in the EU. In 2022, 55% of copper input into the EU production system came from the recycling of scrap from end-of-life products (the 'End-of-life Recycling Input Rate') (Eurostat 2023). As a result of this mature recycling market, the EU Supply Risk Index for copper is rather low compared to other materials. Regardless, complex and longer-term vulnerabilities still remain in the copper supply chain.

The EU is reliant on other countries for the remainder of its copper needs not met by recycling. These countries include Chile (28% of share between 2000 and 2020), Peru, Indonesia, Brazil, and Argentina (18%, 12%, 11%, and 7%, respectively) (SCRREEN 2023c). Operations in Chile are experiencing issues with declining ore grade and water shortages (International Energy Agency 2023). More generally, over 50% of global copper production is located in areas with high water stress levels, making these areas especially vulnerable to the consequences of climate change, which could then, in turn, impact copper production (International Energy Agency 2021). On a global scale, the copper market risks turning into a deficit due to outsized future demand compared to a lack of investment in future supply growth projects (International Energy Agency 2023). Pointing to the critical role of copper in achieving the Paris Agreement climate goals, Goldman Sachs estimated a global supply gap of 8.2 megatonnes (Mt) by 2030 (Snowdon et al. 2021).

Environmental impacts associated with copper production – including global warming, abiotic elements resource depletion, and freshwater ecotoxicity – are estimated to double or triple (depending on the scenario) between 2010 and 2050 (Kuipers et al. 2018). Importantly, secondary copper production has lower environmental impacts than primary copper production. Kuipers et al. estimate that the global warming potential of secondary copper production is a factor of 4 to 5 times lower than that of primary copper production. The authors identify reduced copper demand, a shift from primary to secondary copper production, and a shift from fossil energy to renewable energy as key solutions for reducing the environmental impacts of refined copper production.

Nickel

Nickel is mainly used in the wind turbine and electric vehicle battery product groups, though there are small quantities present in solar panels as well. There are two types of nickel corresponding to their purities: Class 1 (highest purity) and Class 2. Class 2 nickel is used for industrial alloys (i.e. in steel and stainless steel) within the construction of solar panels and wind turbines, while Class 1 nickel is used in battery cathode applications in electric vehicles. Two popular electric vehicle battery chemistries depend on nickel: Lithium Nickel Manganese Cobalt Oxide (NMC) and Lithium Nickel Cobalt Aluminium Oxide (NCA). The demand for high-quality, battery-grade nickel is expected to outpace supply in the coming years (International Energy Agency 2021).

The nickel supply chain has been rattled by economic and supply volatility in recent years. The COVID crisis led to reduced demand for nickel, while the war in Ukraine spurred a significant increase in nickel prices, even causing a market freeze on the London Metal Exchange in March 2022 (SCRREEN 2023b). Indonesia, the world's largest nickel miner, has enacted increasingly extensive bans on the export of nickel ore, with the goal of strengthening domestic processing capabilities. The European Union then opened a lawsuit against Indonesia, alleging that such regulations violate international trade agreements (International Energy Agency 2022).

Other countries with significant nickel production include the Philippines (14% of global ore production between 2016 and 2020), Russia (10%), Canada (9%), and Australia (8%) (SCRREEN 2023b). Meanwhile, China is a leader in nickel refining. The EU is responsible for 2% of global nickel production, with the majority (66%) of reserves located in Finland (SCRREEN 2023b). In 2016, domestic nickel extraction in the EU represented less than 9% of the total input to EU manufacturing (Matos et al. 2020). Interestingly, although there is some nickel recycling capacity in the EU, a considerable fraction of nickel collected for recycling is exported. In 2016, the collection rate for nickel was 73%, while, in comparison, the end-of-life recycling input rate was 16% (Matos et al. 2020).

Nickel production is very energy intensive, and therefore also emissions intensive. In a study comparing seven metals, nickel stood out as having the highest cumulative energy demand and greenhouse gas (GHG) emissions per kilogramme produced (in primary production) (Van der Voet et al. 2019). That study estimated that the energy demand and emissions intensity required for secondary nickel production are nearly twenty times less than those required for primary nickel production, illustrating the scale of the potential environmental benefits of recycling.

Silicon

Silicon is essential for its semiconductor properties within the solar cells of crystalline silicon panel technology, which account for about 95% of the world's installed photovoltaic capacity (Carrara et al. 2020). The electric vehicle sector is also increasingly utilising silicon to improve the capacity of battery anodes. Silicon is the second most abundant material in the Earth's crust as it is extracted from vein quartz and quartz pebbles (SCRREEN 2023d). However, a high-purity grade of silicon metal – polysilicon – is required for solar and electric vehicle applications, a grade of silicon which demands significant purification and processing.

China is responsible for 70% of the global production capacity of polysilicon; a geographical concentration posing a significant supply risk (Huisman et al. 2020). The vulnerability of this supply concentration is illustrated by an event in 2017, when the closure of several polysilicon factories in China due to environmental regulations led to a 35% spike in silicon prices (Ryan and Martin 2017). Furthermore, China's leading position in polysilicon extraction and refining contributes to its dominant position in the production of solar wafers: as of 2023, China accounts for 97% of the global output of solar wafers (Carrara et al. 2023).

Manganese

Manganese is a metal used in Lithium Nickel Manganese Cobalt Oxide (NMC) electric vehicle battery chemistries as well as in the steel and alloys that make up parts of a wind turbine (Huisman et al. 2020). Nearly all battery-grade manganese (97%) is produced in China (International Energy Agency 2023). China has gained substantial experience and expertise in producing high-purity manganese, which involves a complex process tailored to specific ore types (International Energy Agency 2023). This accumulated knowledge makes diversifying the battery-grade manganese supply chain challenging.

In the context of electric vehicle batteries, NMC technologies which incorporate larger ratios of manganese and nickel instead of cobalt are gaining in popularity. As such, the demand for manganese within the electric vehicle sector is projected to increase dramatically by a factor of 13 in the coming decades, from 75 kt in 2022 to 994 kt in 2050 (under a stated policies scenario) (International Energy Agency 2023).

Lithium

Lithium is the lightest (i.e. least dense) metal and has excellent electrical conductivity and electrochemical properties, which explains why it is such a key ingredient in the makeup of electric vehicle batteries (SCRREEN 2023a). Lithium is used in the electrolyte and the cathode of electric vehicle batteries, where lithium-ion chemistries such as NMC, NCA, and Lithium Iron Phosphate (LFP) dominate. More broadly, the electric vehicle sector makes up the largest share of global demand for lithium: in 2022, electric vehicle batteries accounted for 54% of total demand for lithium, and in 2050, this ratio is expected to rise to 77% (International Energy Agency 2023). Lithium mining mainly occurs in the 'lithium triangle' (Chile, Bolivia, and Argentina) and in Australia, areas that are vulnerable to high levels of climate and water stress (International Energy Agency 2021). Meanwhile, China dominates the refining stage for lithium, posing a potential supply risk (Matos et al. 2020).

The lithium market has been experiencing a rapid expansion in recent years, both on the demand and the supply side (International Energy Agency 2023). Lithium demand doubled in 2021 compared to 2017, while production levels have been growing with an annual growth rate between 25% and 35% (International Energy Agency 2023). Simultaneously, investments in lithium have been growing significantly, with spending for exploration increasing by 90% in 2022 compared to 2021 (International Energy Agency 2023). However, these market shifts have also been accompanied by some price volatility, though prices for battery-grade lithium are expected to remain high due to high demand from the electric vehicle sector (International Energy Agency 2023).

Cobalt

Cobalt is essential for several electric vehicle cathode chemistries, including NCA and NMC chemistries. Cobalt is not abundant in the Earth's crust; about 90% of cobalt is produced as a by-product of nickel and copper mining (International Energy Agency 2021; Matos et al. 2020). The Democratic Republic of Congo (DRC) dominates the production side of the value chain (about 70% in 2022), while China dominates refining (about

75% in 2022) (International Energy Agency 2023). Detrimental environmental and human rights impacts, including child labour, have been documented in artisanal cobalt mines in the DRC (International Energy Agency 2021; Sovacool 2021). Meanwhile, Indonesia has recently become the second-largest supplier of mined cobalt, tripling its production in 2022 (International Energy Agency 2023).

Recent trends in electric vehicle battery cathodes are moving away from chemistries reliant on heavy quantities of cobalt. This has contributed to decreased cobalt demand in recent years, which coincided with an upsurge in supply, leading to a consistent downward trend in cobalt prices (International Energy Agency 2023). Currently, electric vehicles account for 38% of total cobalt demand. This ratio is expected to remain rather stable over time, increasing slightly to 40% in 2050 (International Energy Agency 2023).

Graphite

Graphite is a material used in the anodes of all lithium-ion electric vehicle batteries (International Energy Agency 2023). Graphite can be sourced from natural deposits/mines as ‘natural graphite’, but it can also be manufactured as ‘synthetic graphite’. Synthetic graphite has been favoured in anode applications due to its higher purity and reliability (Fastmarkets 2022). However, the production of synthetic graphite is more costly and energy-intensive than its natural counterpart. The market share of natural graphite is expected to grow in the coming years as recent technological developments are allowing for increased reliability in anode applications. China is the main producer of both natural and synthetic graphite.

Neodymium

Neodymium is a rare-earth element whose strong magnetic properties make it an essential component in wind turbine generators as well as in electric vehicle motors. Within the context of wind turbines, neodymium is a key ingredient in the neodymium-iron-boron magnet (NdFeB), which is used to manufacture permanent magnet synchronous generators found in wind turbine configurations (International Energy Agency 2021). China holds an 85-90% share of NdFeB magnet production, with the remaining 10% produced in Japan, the USA, and the EU (Huisman et al. 2020). For this reason, the Supply Risk Index for neodymium is very high: it ranks ninth on a list of 87 materials assessed for their supply risk by the European Commission (Carrara et al. 2023). This reflects broader supply risk issues facing all rare-earth elements, as the production and refining of these materials are highly concentrated in China (International Energy Agency 2023). Furthermore, leakage of toxic and radioactive materials produced during rare-earth elements processing have caused major health and safety issues (International Energy Agency 2021).

2.4 Technological advancements will impact material dependencies

The energy sector is ripe with research and innovation as companies seek to improve efficiencies and reduce costs while maximising energy generation. Due to the rapid and accelerating rate of technological innovation in this field, shifting technological outlooks may impact future demand of specific minerals.

The EV battery sector is experiencing two main shifts in cathode chemistry preferences: (i) a shift within lithium NMC cathode chemistries towards lower-cobalt content chemistries; and (ii) wider adoption of LFP battery chemistries

EV batteries are classified based on their chemistries; the dominant variants include Lithium Iron Phosphate (LFP), Lithium Nickel Cobalt Aluminium Oxide (NCA), and Lithium Nickel Manganese Cobalt Oxide (NMC).

Within NMC battery chemistries, variants with high cobalt content and low nickel content are losing popularity and are being succeeded by variants with low cobalt content and high nickel content (International Energy Agency 2023). In turn, mineral demand is shifting away from cobalt and towards nickel.

In addition, there is a growing adoption of LFP battery cathodes, which rely on one CRM, lithium, as opposed to three or more like the other battery chemistries. LFP market share in the global electric vehicle market has grown from under 10% in 2018 to about 30% in 2022 (International Energy Agency 2023). The growing market share of LFP batteries signals lower material security impacts by eliminating the need for cobalt, nickel, and manganese, which have concentrated supply chains and are susceptible to disruptions (International Energy Agency 2023). Although they represent an overall promising alternative to other CRM-dependent chemistries like NMC and NCA, LFP batteries contain phosphorus, which has the competing use case as an important input for fertiliser production. Furthermore, phosphorus is not devoid of its own material security issues; possible imbalances within the phosphorus supply chain may arise due to the concentration of extraction and processing located in only a few countries (International Energy Agency 2023).

Finally, the potential for sodium-ion battery chemistries, which rely on sodium as the main conducting element as opposed to lithium, has been gaining attention. Currently being produced for stationary storage or micro-mobility applications only, it remains to be seen whether sodium-ion batteries can meet the requirements of EV range and charging time.

EV battery anode chemistries are increasingly being doped with silicon to help improve capacity

Graphite remains the dominant anode chemistry. However, recent years have seen an uptick in silicon-doped graphite, from 17% uptake in 2018 to about 30% of the market share in 2022. Doping the graphite anode with silicon has greatly enhanced the energy density and charging speeds of graphite anodes (International Energy Agency 2023).

Although silicon cells are expected to remain the dominant technology for solar panels, advancements in other technologies could reduce silicon demand

As mentioned earlier, crystalline silicon is the dominant technology for solar cells, accounting for about 95% of global installed PV capacity (Huisman et al. 2020). Silicon is expected to continue leading as the preferred solar cell technology, but advancements in alternative technologies could change this picture.

There are three alternative technologies to silicon solar cells that are gaining traction: Cadmium-Telluride (CdTe), Gallium-Arsenide (Ga-As), and perovskite solar cells (International Energy Agency 2023). According to IEA estimates, a scenario in which CdTe technology gains market share would require 30% less silicon in 2050 than the current silicon-dominant trajectory. This scenario assumes that progress is made by 2030 to increase cell efficiency, lengthen lifetimes, and reduce costs for CdTe technologies. Meanwhile, wider adoption of Ga-As faces issues with supply risks, immature technology, and high costs, leading to projections demonstrating a negligible impact on future silicon use. Finally, wider adoption of perovskite solar cells would reduce silicon demand for solar applications by 13% in 2050. Wider adoption of these technologies could therefore reduce the solar sector’s reliance on silicon, but significant uncertainties remain regarding their growth potential.

Wind turbine generators utilising permanent magnet synchronous generators are gaining market share and are heavily reliant on rare-earth elements

The type of generator used in a wind turbine has important implications for material demands. Broadly speaking, there are four types of wind turbine generators (International Energy Agency 2021). Double-fed induction generators (GB-DFIGs) are the most common choice for onshore wind turbines and require a gearbox, which increases the rotational rotor speed of turbine blades to the higher speeds required for the generator (Bauer et al. 2023). On the other hand, direct-drive generators, which are favoured in offshore installations, avoid the use of a gearbox and instead utilise permanent magnet synchronous generators (DD-PMSGs) or electrically excited synchronous generators (DD-EESGs). Direct-drive generators are gaining popularity thanks to their higher efficiency and reduced maintenance needs, but they rely extensively on permanent magnets which are composed of critical rare-earth elements such as neodymium (Bauer et al. 2023; International Energy Agency 2021). The last type is a hybrid generator, which combines a simplified gearbox with a smaller permanent magnet generator, and is fittingly termed the gearbox permanent-magnet synchronous generator (GB-PMSG).

Within the onshore wind market, GB-DFIGs represent about 70% of the global market share, while DD-PMSGs have doubled their market share from about 10% in 2010 to 20% in 2020 (International Energy Agency 2021). In the offshore sector, the IEA shows that DD-PMSGs lead with 60% of the global market share. It is expected that demand for permanent-magnet synchronous generator (PMSG) technologies will increase in the wind turbine sector; the IEA assumes in base case scenario modelling that, by 2040, PMSG technologies will account for about 95% of the offshore market and 40% of the onshore market. This transition toward PMSG technologies will correspond with increased demands for rare-earth elements, which puts these materials at a high supply risk and could, in turn, influence technology choices (International Energy Agency 2021).

Copper needs for wind turbines increase with direct-drive generators and offshore installations

Copper wiring is an important building block for the proper functioning of wind turbines. It plays a role in the inner workings of the generators, while also grounding the towers from lightning strikes and carrying electricity (Bauer et al. 2023). Direct-drive generators require about twice the amount of copper (tonnes/MW) than their gearbox counterparts in onshore applications (International Energy Agency 2021). In offshore installations, copper demand increases even more due to the need for longer cabling (Bauer et al. 2023). Within the wind energy sector's total demand for copper, offshore installations contribute to 40% of the copper demand, despite constituting only 20% of total wind capacity additions (International Energy Agency 2021).

3 EPR Policy Background

3.1 EPR Policy Design

The first definition of EPR can be traced back to a report by Thomas Lindhqvist in 1990 for the Swedish Ministry of Environment: 'Extended Producer Responsibility is an environmental protection strategy to reach an environmental objective of a decreased total environmental impact from a product, by making the manufacturer of the product responsible for the entire life-cycle of the product and especially for the take-back, recycling, and final disposal of the product' (Lindhqvist 2000). Today, EPR is considered a rather flexible policy strategy encapsulating a variety of policy instruments (Kaffine & O'Reilly 2015).

For the research done for this report, EU legal definitions inform the types of policy instruments that are considered as falling under the scope of EPR. According to EU Directive 2018/851, EPR is 'a set of measures taken by Member States requiring producers of products to bear financial or financial and organisational responsibility *for the management of the waste stage of a product's life cycle* including separate collection, sorting, and treatment operations. That obligation can also include organisational responsibility and a responsibility to contribute to waste prevention and to the reusability and recyclability of products' (Directive (EU) 2018/851 2018).

In keeping with the EU definition, EPR policy instruments largely pertain to the post-consumer, waste management stage of products. Theoretically, by shifting the entire financial burden of waste management responsibility to producers, EPR can *indirectly* incentivise producers to design more sustainable and recyclable products. This way, they can reduce the costs of collecting, sorting, and treating end-of-life products. In practice, the costs associated with meeting mandated collection and recycling targets have usually been too low to influence producers' product design choices (Dimitropoulos et al. 2021). Moreover, incentives for product design changes are diluted because those carrying financial responsibility (e.g. importers and retailers bringing products to the market) are often not the original product manufacturers (Kunz et al. 2018). However, changes to existing EPR policy instruments that would shift the entire financial burden of end-of-life management costs to producers and consumers rather than taxpayers, including internalised 'hidden' environmental and health costs, could induce more sustainable design choices.

Meanwhile, policy instruments *directly* stimulating eco-design and waste prevention (e.g. requirements for minimum recycled content used in a product) or taxes and subsidies with similar goals, can be viewed as complementary policy instruments to EPR. Since this document focuses on the Netherlands, the EU legal definitions which are also adopted in Dutch legislation are followed.

Another important choice in EPR policy design is its organisation, which can be implemented through collective schemes, by individual producers, or through a combination of collective and individual schemes. Most EPR schemes are organised collectively, through third-party entities called producer responsibility organisations (PROs). Most PROs collect a fee from producers to cover the expenses associated with waste collection, sorting, and treatment of products (OECD 2001). Advantages of collective systems include economies of scale, reduced free-riding, shared risk, and simplified logistics (OECD 2016). On the other hand, in an individual scheme, each producer manages the collection and recycling of their own products. Since this can be logistically challenging, individual schemes are usually reserved for products that have concentrated markets, where it is viable for producers to manage an individual take-back system (OECD 2016).

3.2 EPR Policy Frameworks in the EU and the Netherlands

At the EU level, the Waste Framework Directive first set the hierarchy framework for waste management in the EU and outlined general minimum requirements for EPR schemes (Directive 2008/98/EC 2008). In 2018, an amendment to the Directive introduced more detailed requirements for EPR, including criteria such as the identification and expansion of stakeholders in EPR systems, the use of reporting systems, the coverage of certain costs categories by producers' contributions, and requirements for monitoring and enforcement (Directive 2018/851 2018).

In the Netherlands, the Decree on Extended Producer Responsibility is the principal legal mechanism governing EPR (Besluit Regeling voor Uitgebreide Producentenverantwoordelijkheid 2020). This Decree aligns with the EPR guidelines outlined in the Dutch Environmental Management Act (Wet milieubeheer) and enforces the minimum operational requirements for EPR systems as defined by the EU Waste Framework Directive (Dimitropoulos et al. 2021).

Another legislative arrangement related to EPR in the Netherlands is a 'general binding agreement' (Algemeen verbindend verklaring or AVV), which formalises a collective EPR scheme for a particular product group. The AVV requires all producers and importers for that product group to participate in the EPR scheme by contributing a waste management fee (Tijm et al. 2021). AVVs are valid for five years, and in order to be considered, several conditions must be met by applying groups. For example, companies applying for an AVV must have at least a 75% combined market share and demonstrate that the AVV will ensure effective, efficient, and reliable management of end-of-life products (Tijm et al. 2021).

There are currently seven obligatory EPR schemes in the Netherlands, five of which stem from EU directives. The five schemes regulate electrical and electronic equipment, batteries and accumulators, passenger cars and vans, packaging, and single-use plastics (Dimitropoulos et al. 2021; Rijkswaterstaat 2023a). In addition, the Netherlands has implemented EPR for passenger car tires, and, more recently, for textiles. AVVs have also been set for the collection and responsible treatment of three additional product groups: mattresses, paper and cardboard, and flat glass (Rijkswaterstaat 2023b). The following paragraphs describe how some of these obligatory schemes impact electric vehicle batteries, solar photovoltaic panels, and wind turbines.

Table 1 provides an overview of the EU-level and Dutch policies impacting EPR for electric vehicle batteries, solar panels, and wind turbines. It is important to note that a 'producer' is defined as the entity responsible for bringing a product onto market in the Netherlands (Besluit Regeling voor Uitgebreide Producentenverantwoordelijkheid 2020). As such, a 'producer' is not by definition the original product manufacturer; in fact, it is often an importer.

Table 1

EPR-related policies affecting electric vehicle batteries, photovoltaic panels, and wind turbines in the EU and the Netherlands

<table>
<tr><th colspan="3">Overarching policies</th></tr>
<tr><td colspan="3">Waste Framework Directive 2008/98/EC
Waste Framework Directive 2018/851
Set the waste management framework for the EU and outline general minimum requirements for EPR schemes.</td></tr>
<tr><td colspan="3">Besluit regeling voor uitgebreide producentenverantwoordelijkheid
Implements minimum requirements for EPR schemes in the Netherlands.</td></tr>
<tr><td colspan="3">European Critical Raw Materials Act 2024/1252
Ramps up recyclability and recovery efforts for critical raw materials. It entered into force in May 2024.</td></tr>
<tr><td colspan="3">Ecodesign for Sustainable Products Regulation 2024/1781
Establishes a framework for eco-design requirements for all physical goods. It replaced the EcoDesign (Directive 2009/125/EC) in July 2024.</td></tr>
<tr><td>Policies impacting photovoltaic panels</td><td>Policies impacting electric vehicle batteries</td><td>Policies impacting wind turbines</td></tr>
<tr><td>WEEE (Waste Electrical and Electronic Equipment) Directive 2012/19/EU
Establishes 65% collection target based on the average weight of all electrical and electronic equipment placed on the market in the 3 preceding years.
For collected solar panels: 85% shall be recovered by weight, and 80% shall be prepared for re-use and recycled by weight.</td><td>European Battery Directive 2006/66/EC
Establishes a take-back requirement: producers must take-back EV batteries at their end-of-life.
Sets recycling efficiency targets, including a minimum recycling efficiency of 50% by average battery weight. Prohibits the disposal of EV batteries by landfilling or incineration.</td><td>Landfill Waste Directive 2018/850
Introduced restrictions on landfilling from 2030 of all waste that is suitable for recycling or other material or energy recovery.</td></tr>
<tr><td>Regeling afgedankte elektrische en elektronische apparatuur
Implements EU WEEE Directive 2012/19/EU in the Netherlands.</td><td>Batteries Regulation 2023/1542
Replaced EU Battery Directive 2006/66/EC and entered into force in August 2023. Introduces a new category for electric vehicle batteries. Implements product take-back requirements for producers, minimum recycled content targets, and information-based instruments (battery passport).</td><td>Besluit stortplaatsen en stortverboden afvalstoffen
Bans composite waste (e.g. wind turbine blades) from landfills.</td></tr>
</table>

AVV for Stichting OPEN Effective from March 1, 2021, through December 31, 2025.	**Regeling Beheer Batterijen en Accu's** Implements EU Battery Directive 2006/66/EC in the Netherlands.	COLOUR KEY **EU policies** **Dutch policies**

3.2.1 Policy Frameworks Governing EPR for Electric Vehicle Batteries

The European Battery Directive establishes EPR obligations in the form of a take-back requirement and a recycling target. Producers must take back electric vehicle traction batteries, and recycling processes must meet a 50% efficiency target by battery weight (Directive 2006/66/EC 2006). In addition, producers have a requirement to report batteries and accumulators brought onto the Dutch market to the government through the database myBatBase.

In the Netherlands, most car companies partner with the producer responsibility organisation Auto Recycling Nederland (ARN) to fulfil EPR obligations through the collective ARN Beheerplan (ARN Battery Management Plan). The companies who do not fully utilise the ARN scheme and instead organise collection and recycling on their own, include brands of the PSA group (part of Stellantis), Nissan and Renault (use ARN for micro EVs), Tesla, and Volvo (uses ARN only for vehicles that end up in scrapyards). ARN charges producers in their network an advance waste management fee based on proprietary models that estimate future collection and recycling costs of the vehicle battery.

The new Batteries Regulation, which entered into force in August 2023, introduced sweeping new requirements for the sustainable management of batteries. In contrast to the old Battery Directive, where electric vehicle batteries were lumped under the 'industrial batteries' category, the new regulation introduces a separate category for electric vehicle batteries, and specifically implements EPR for this battery type. In addition to take-back requirements, the regulation also introduces new recycling and material recovery targets. By the end of 2025, the recycling rates by average weight for lithium-based batteries must meet a 65% recycling target, while nickel-cadmium batteries must attain 80% and lead-acid batteries must reach 75%. By the end of 2030, these recycling targets will rise to 80% for lead-acid batteries and to 70% for lithium-based batteries. By the end of 2027, all recycling efforts should achieve material recovery targets of 90% for cobalt, copper, lead, and nickel, and 50% for lithium. These targets will further increase, by the end of 2031, to 95% for cobalt, copper, lead, and nickel, and to 80% for lithium.

To support this recycling market, the regulation also introduces mandatory minimum levels of recycled content for new batteries. The minimum recycled content requirements will be set in 2031 at 16% for cobalt, 85% for lead, and 6% for lithium and nickel; this will increase in 2036 to 26% for cobalt, 85% for lead, 12% for lithium, and 15% for nickel. New information-based instruments introduced by the regulation include a carbon footprint declaration and a digital battery passport. The regulation also seeks to improve the safety and tracking of second-use applications for electric vehicle batteries (i.e. stationary energy storage systems) by introducing EPR for these applications, as well as by stipulating a set of testing parameters to assess battery state of health and capacity before it can be deemed fit for reuse.

3.2.2 Policy Frameworks Governing EPR for Photovoltaic Panels

The Waste Electrical and Electronic Equipment (WEEE) Directive establishes take-back requirements in the form of collection, recovery, and recycling targets. The collection target is a cumulative target for all WEEE products: a 65% separate collection target based on the average weight of all WEEE placed on the market (POM) in the Member State in the previous three years (Directive 2012/19/EU 2012). Alternatively, producers can choose to meet a separate collection target of 85% of the electronic waste generated in a year. In that case, the amount of electronic waste is estimated according to a method developed by the European Commission. The recycling and recovery targets are specific for solar panels and are set at 80% and 85% by weight of collected end-of-life products, respectively (Directive 2012/19/EU 2012).

Stichting OPEN (Foundation OPEN) is the producer responsibility organisation that holds the AVV for all WEEE products in the Netherlands. Producers are obliged to pay an advance waste management fee to the foundation, which is calculated based on the weight of solar panels brought onto the Dutch market. Starting July 1st, 2023, the advance management fee increased from EUR 6.5 to EUR 40 per tonne of solar panels. According to Stichting OPEN, this is equal to about EUR 0.80 per panel (de Wit, 2023).

3.2.3 Policy Frameworks Governing EPR for Wind Turbines

There is currently no all-encompassing EPR policy framework for wind turbines in the EU or the Netherlands. However, in the latter, composite waste is banned from landfills via the Decree for Landfill and Waste Disposals Ban (Besluit stortplaatsen en stortverboden afvalstoffen). In effect, wind turbine blades, which are constructed out of composite materials, should be banned from landfills. However, a report by WindEurope posits that, in practice, wind farm operators can claim an exemption to this regulation. The exemption to the landfill ban applies if the costs of alternative treatment are higher than 205 EUR/tonne. WindEurope estimates that the cost of alternative treatment for wind turbine blades (mechanical recycling) ranges between 500-1,000 EUR/tonne, therefore allowing Dutch wind farm operators to claim the exemption (Schmid et al. 2020).

3.2.4 Enforcement of EPR

EPR enforcement mechanisms are essential for reducing free-riding and ensuring producers meet their obligations. In the Netherlands, the Human Environment and Transport Inspectorate (Inspectie Leefomgeving en Transport, or ILT), which is overseen by the Ministry of Infrastructure and Water Management, is the entity responsible for enforcing EPR policies for sectors with binding legal targets. ILT monitors industries to ensure EPR targets are being met and can issue fines for noncompliance (Dimitropoulos et al. 2021). Box 1 provides more information about ILT's role in the enforcement of EPR systems.

Box 1. A closer look – ILT's role and enforcement

ILT has a policy of visiting all producer responsibility organisations (PROs) about twice a year. ILT meets with PROs of both voluntary and obligatory EPR schemes to learn about issues they may be encountering and to discern whether they are meeting goals or falling behind.

ILT can follow different tracks to ensure enforcement. The administrative/legislative track (bestuurlijk spoor) includes coercive administrative actions (bestuursdwang). If a producer/PRO fails to meet the EPR scheme requirements, they can be charged a penalty (dwangsom); for example, based on each percentage point that they are not meeting the requirement. However, because the producer/PRO can claim dependency on other parties in the waste management chain, these warnings and penalties can be difficult to execute. An administrative fee (bestuurlijke boete) could also be charged, but this has not yet been defined. Criminal law (strafrecht) is the final option. ILT can help to build a case for this, but the prosecutor (Officier van Justitie) is ultimately responsible in deciding whether a case will be taken on or not.

3.2.5 PRO Consolidation

In the Netherlands, there is a trend towards the consolidation of EPR scheme organisation, both within and across EPR schemes. Before Stichting OPEN received the AVV in 2021 for all electrical and electronic equipment, there were several different PROs managing collection and recycling for different WEEE products. For example, there were two organisations, Stichting Zonne-energie Recycling Nederland (Foundation Solar Energy Recycling Netherlands) and PV Cycle, serving as PROs for solar panels. Recently, the PROs for the WEEE and battery EPR schemes (Stichting OPEN, Stichting Batterijen, Stichting EPAC, and Stichting Stibat Services) also announced they will merge in 2024, marking further consolidation across separate EPR schemes (Stichting OPEN 2023). This trend in the Netherlands towards PRO consolidation contrasts with practices in some other EU countries, such as France and Germany, where there seems to be an implicit regulatory objective to prevent PRO monopolies. While the primary authority held by a regulator involves the ability to terminate an agreement with a PRO, this regulatory leverage falters when there is only a single PRO in existence. Therefore, the advantages of PRO consolidation, including economies of scale and easier oversight by enforcement authorities, should be thoughtfully balanced against the potential downsides, including diminished incentives for efficiency and a reduction in regulatory leverage.

3.3 Incentivising repair and reuse through EPR schemes

As described earlier, EPR policy instruments usually pertain to the end-of-life stage of a product's lifecycle. Incorporating repair and reuse into EPR policy schemes can be difficult for several reasons. Lobbying groups and actors representing the repair and reuse economies are under-represented in the policymaking arena, for example. Within the repair sector, there is a lack of expertise and human capital since this sector has been in decline for many years. Repair also often happens in local markets, leading to a dispersion of stakeholders. Furthermore, the product-specificity and information-intensity of repair services make for a complex context. Reuse can be similarly complex, especially due to difficulties with tracking and tracing products, particularly when they are shipped abroad for a second life.

Increasingly, policymakers and academics are advocating for a revision of EPR policy instruments to improve alignment with higher circularity strategies, or so-called R-strategies, like reduce, repair, and reuse (Campbell-Johnston et al. 2020; Vermeulen et al. 2021). One EPR policy instrument in particular – collection targets – provides a tangible example of how 'traditional' forms of EPR instruments can conflict with more recently formulated circular economy best practices. The 65% collection target established by the WEEE Directive, for example, incentivises the collection and end-of-life treatment of products with a longer lifetime over their repair and reuse. When a product is repaired, refurbished, or given a second life, it usually cannot be counted towards the WEEE collection target. In this way, EPR collection targets can conflict with higher R-strategies.

France is a pioneer in expanding the boundaries of EPR from a policy instrument focused on downstream waste management strategies, like recycling, towards more upstream strategies, such as waste prevention, repair, and reuse. Through the ambitious Anti-waste and Circular Economy Law, which was unanimously adopted by the French Senate and the National Assembly in January 2020, first-of-its-kind upstream reforms for EPR schemes were introduced (Ellen Macarthur Foundation 2021). These include the introduction of repair and reuse funds, the introduction of a repairability index for certain products, expanded eco-modulation fees (which factor in repair and reuse parameters), and a new requirement for individual producers to develop and submit waste prevention plans to the government. Because the introduction of these measures is so recent, there is no empirical evidence yet regarding their impacts. Nonetheless, these creative new measures offer inspiration for improving EPR and circular economy alignment.

The repair and reuse funds, which are both financed and managed by PROs, apply to a specific set of EPR schemes: WEEE, toys, sporting and recreational goods, home improvement and gardening goods, furnishing equipment, and textiles (Vernier 2021). The legal agreements between PROs and the French government now include requirements for the PROs to establish, fund, and manage repair and reuse funds. For the repair funds, each product is assigned a repair target using 2019 data as a baseline; for example, 10% more refrigerators should be repaired in 2027 compared to 2019. PROs must develop financing and action plans to meet these targets by partially subsidising repair costs for consumers and increasing accessibility to repair services. The objective of the reuse fund, on the other hand, is to financially support the ‘solidarity economy’, which includes nonprofit organisations and social enterprises who utilise second-hand items for a social mission. The reuse fund will be financed by a 5% share of the advance fees of applicable schemes, forming a total budget of 50 million EUR annually.

In addition to these two funds, the Anti-waste and Circular Economy Law also introduced an information-based instrument in the form of the ‘repairability index’, mentioned above, which provides a score between 0 and 10 that indicates how repairable a product is. Criteria such as the accessibility of spare components and technical documentation, as well as the ease of disassembly, factor into the index score. The mandatory display of this score for affected product groups – including smartphones, laptops, washing machines, and televisions – will inform customer purchasing decisions while simultaneously encouraging producers to improve the repairability of their products. In addition, fee eco-modulation now also incorporates repair in the French system. The availability of technical documentation and spare parts can help to reduce a producer’s share of advance fees. Finally, to stimulate eco-design, the new law requires all producers to submit five-year waste prevention plans to the government.

4 Evaluating the effectiveness of the EPR scheme for EV batteries

Table 2
Overview of EPR scheme for electric vehicle batteries as of January 2023

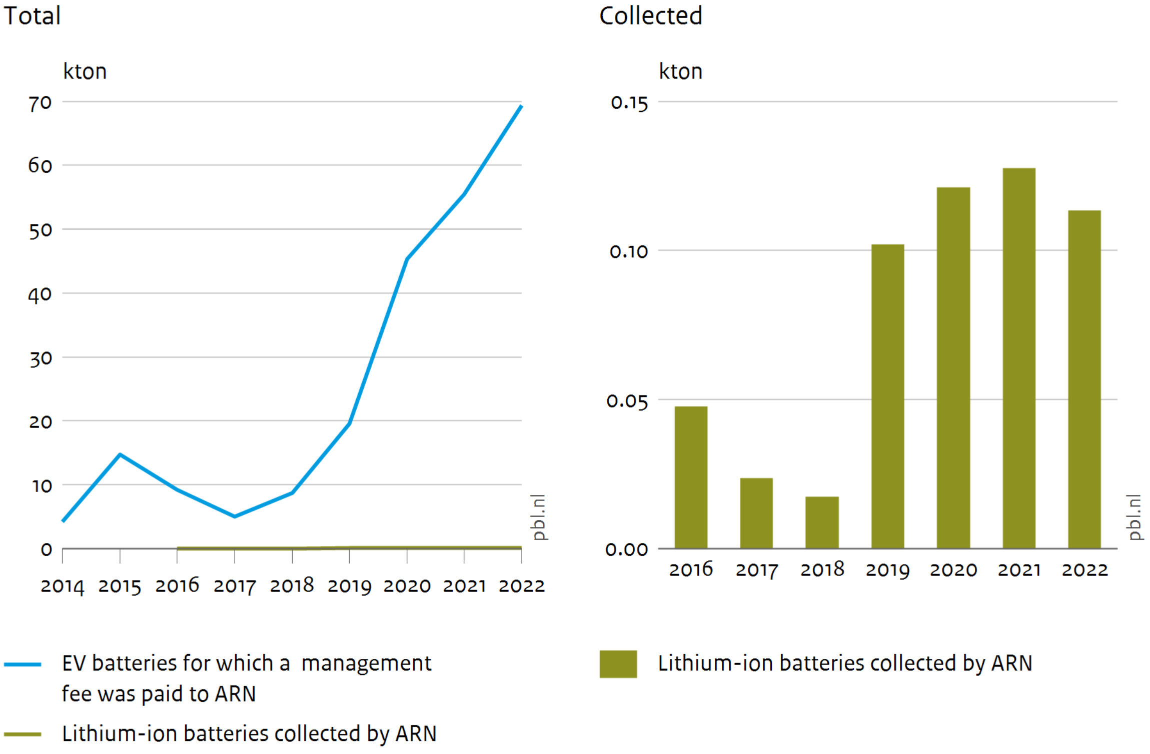
EPR Organisation	No general binding agreement (AVV) in place, but most producers participate in a collective EPR scheme: 'ARN Beheerplan' through Auto Recycling Nederland. Some producers organise collection and recycling on their own.
EPR Instruments	Producers must take-back EV batteries at their end-of-life.
	50% recycling target by weight for lithium-ion batteries.
	For those participating in the ARN scheme, an advance waste management fee varying with battery weight is calculated based on a proprietary model.

4.1 Are the existing EPR targets being met?

An overview of the organisation of the EPR scheme for electric vehicle batteries and of the main instruments used to achieve EPR goals is provided in Table 2. For electric vehicle batteries that fall under ARN's Beheerplan, the take-back requirement and recycling targets are being met. In 2022, the recycling rate achieved by ARN was close to 70%, compared to the 50% target (ARN 2024). For producers that do not fall under ARN's scheme, detailed information about existing collection and recycling routes is not publicly available. For example, Tesla claims to outsource collection and recycling to other companies, while it is building internal recycling capacity (Tesla 2022).

Lifetime estimates regarding the lifespan of electric vehicle batteries range from 8 to 15 years (Abdelbaky et al. 2021). Due to the longer lifetime of EV batteries and their relatively recent introduction onto the market, collection volumes are significantly lower than put-on-market volumes (Figure 9).

Figure 9



Weight of electric vehicle batteries put-on-market and collected under ARN's scheme

Source: ARN, 2015-2023

Note: The weight of EV batteries for which a management fee is paid to ARN is estimated by multiplying the number of EV batteries for which a management fee is paid (as published by ARN) by an assumed average battery weight of 450 kilos per EV.

4.2 What is the current end-of-life pathway for electric vehicle batteries?

Decline in battery capacity and battery life leads to the eventual end-of-life of an electric vehicle battery. However, modular battery repair, which is becoming a more common practice, may extend lifetimes of EV battery packs. In recent years, more than 90% of batteries collected from ARN came from still-driving vehicles. More than half of the batteries collected by ARN are now modules as opposed to complete battery packs.

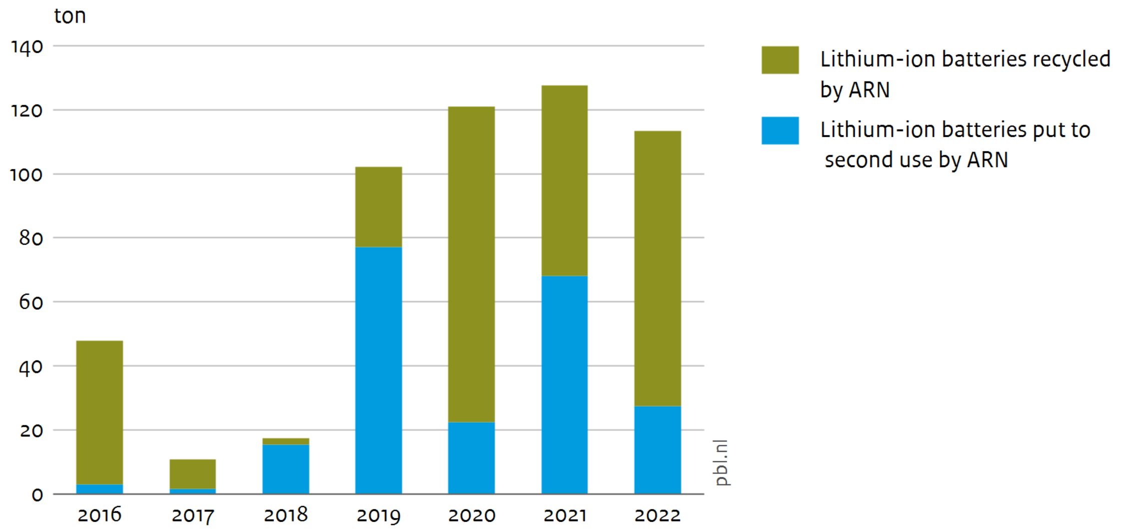
There are two potential pathways for end-of-life EV batteries: second use or recycling. For second use applications – mostly stationary energy storage systems – battery state of health and capacity should first be tested to ensure safety and adequacy. As shown in Figure 10, the volumes of EV batteries recycled and put to second use through ARN’s Beheerplan are highly volatile between years. When ARN provides second-use companies with EV batteries, these batteries are re-registered in myBatBase, and the second-use company becomes the new producer under the EPR scheme for stationary batteries, which is managed by Stichting OPEN. There is no systematic tracking of second-use applications for batteries that do not fall under ARN's plan.

Regarding the recycling pathway, there are three major recycling techniques for EV batteries, which are often used in combination with each other: physical treatment/mechanical separation, pyrometallurgical treatment, and hydrometallurgical treatment (Wagner-Wenz et al. 2022). The final materials produced at the end of each recycling process vary. The highest quality secondary materials – metal salts, which can ultimately be used as a replacement for primary metals – can only be achieved through hydrometallurgical treatment (Neumann et al. 2022).

ARN partners with a battery recycling company in another EU country that employs a state-of-the-art hydrometallurgical recycling process to recover aluminium, cobalt, manganese, nickel, graphite, and lithium metal salts. The contracted company gives priority to European customers for these high-quality secondary materials. It is unclear which recycling processes are used by producers that do not participate in ARN's plan. Most recycling facilities in Europe employ pyrometallurgical treatment, which is the most mature technology but results in the production of 'black mass' (alloys), a mix of shredded metals that need further treatment through hydrometallurgy to be separated into high purity metals (Wagner-Wenz et al. 2022). Black mass is often shipped to companies in Asia, primarily in China and South Korea, for further processing.

Figure 10

Second-use and recycling pathways for lithium-ion batteries collected by ARN



Source: ARN, 2017-2023

4.3 Where are EPR policies falling short in promoting circular economy goals and safeguarding priority materials?

The dearth of information from producers who do not engage in ARN's Beheerplan may obscure inadequate take-back and recycling practices

As mentioned previously, some producers do not participate in ARN’s scheme. Those producers are therefore responsible for arranging collection and recycling on their own. For these companies, information about existing collection and recycling routes in the Netherlands is not publicly available.

Few EU recycling facilities produce secondary materials that can replace primary materials, though this is expected to change thanks to the new Batteries Regulation

Battery recycling facilities in the EU predominantly employ pyrometallurgical techniques. Although these techniques meet the 50% recycling target, the secondary material produced – black mass – requires further refining into metal salts before it can be reused in new batteries. Most of this additional processing occurs in Asia. The critical materials found in electric vehicle batteries, such as cobalt, manganese, nickel, graphite, and lithium, therefore leave the EU. As a result of the Batteries Regulation, which mandates recycled content requirements for batteries, there appears to be a rising demand in the EU market for high purity metal salts, stimulating technological advancements to attain higher recycling rates, cost competitiveness, and improved energy and environmental impacts (Beaudet et al. 2020; Wagner-Wenz et al. 2022). This signifies the importance of combining EPR regulation with eco-design requirements to ensure a thriving market for secondary materials.

Future demand for EV batteries for second-use applications is uncertain, while unregulated second-use practices pose safety concerns

Uncertainty remains as to whether the business case for second-use applications will remain profitable amid ever-evolving battery technology (Abdelbaky et al. 2021). In 2022, only 19% of EV batteries collected by ARN were utilised in second-use applications, while the rest were recycled. In addition, the free market in unmonitored second-use applications is cause for concern. For example, individuals may attempt to repurpose electric vehicle batteries on their own or with the help of non-certified technicians for home energy storage systems. Presently, there are no regulations in place to prohibit such practices, which pose safety concerns due to the delicate nature of battery dismantling. This stream also leads to potential breaks within EPR, as a battery may disappear into an unsupervised reuse stream without further monitoring.

Battery technology advancements and recycling processes focused on production scrap jeopardise high-value material recycling

According to industry experts interviewed, EV battery recycling companies are currently focused on NMC (Nickel-Manganese-Cobalt) battery chemistry. However, LFP (Lithium-Iron-Phosphate) batteries are becoming increasingly popular. From a business case perspective, there is less profit to be made with LFP battery recycling because there are fewer CRMs in LFP batteries. Stakeholders expressed concern with the future availability of recycling avenues for LFP batteries.

Recycling companies utilise a larger share of production scrap as input rather than end-of-life batteries. The volume of production scrap is larger, constant, and predictable. Production scrap is usually also cleaner material. Stakeholders voiced apprehensions about recycling processes prioritising production scrap over end-of-life EV batteries. At the same time, production scrap can help to establish a business case for recycling in the short-term, where streams of end-of-life EV batteries are too small to justify investments in recycling infrastructure.

5 Evaluating the effectiveness of the EPR scheme for solar panels

Table 3
Overview of EPR scheme for photovoltaic solar panels

EPR Organisation	Collective EPR scheme through a general binding agreement (AVV) for Stichting OPEN for all WEEE products.
EPR Instruments	65% collection target based on the weight of all EEE products put-on-market in the previous 3 years, or, 85% collection target based on the weight of the estimated WEEE in the respective year.
	80% recycling target by weight (specific to solar panels).
	85% recovery target by weight (specific to solar panels).
	Advance waste management fee for Stichting OPEN, increased from EUR 6.5 to EUR 40 per tonne solar panel as of July 2023.

5.1 Are the current EPR targets being met?

The organisation of the EPR scheme for solar panels and the main instruments used to achieve its goals are summarised in Table 3. Stichting OPEN is the PRO that organises solar panel collection and recycling alongside all other WEEE products in the Netherlands. As outlined in Table 4, in the last several years, the 65% WEEE collection target was not met, the 80% recycling target for solar panels was met in some years, and the 85% recovery target was consistently met. The Netherlands is not alone in experiencing challenges with meeting the WEEE collection target; this trend is rampant across Europe. In 2019, 26 Member States did not reach the WEEE collection target (Baldé et al. n.d.).

Solar panels are a large contributor to the low WEEE collection rate, as they constitute about a third of all WEEE products put-on-market by weight (Eijsbouts & Jehee 2021). The volumes of solar panels collected are a tiny fraction of those put-on market (Figure 11). To put those figures into perspective, the collection rate is below 1%. The main reason for this large discrepancy is the long lifetime of solar panels. This is estimated to be between 25 and 30 years, since warranty contracts usually guarantee that the power output will not drop below 80% during this period (Späth et al. 2022). Generally, most of today's end-of-life panels are attributed to early failures (e.g. damage from weather events, defects) or from 'pioneer' systems (Wade et al. 2017).

Table 4
Actual collection rates for all WEEE, and recycling and recovery rates for solar panels

	Collection (for all WEEE products)	Recycling (solar panels only)	Recovery (solar panels only)
2019	49%	98%	99%
2020	43%	77%	100%
2021	31%	76%	93%
2022	28%	99%	100%
2023	29%	80%	100%

Source: Nationaal (W)EEE Register Rapportage, 2020-2024

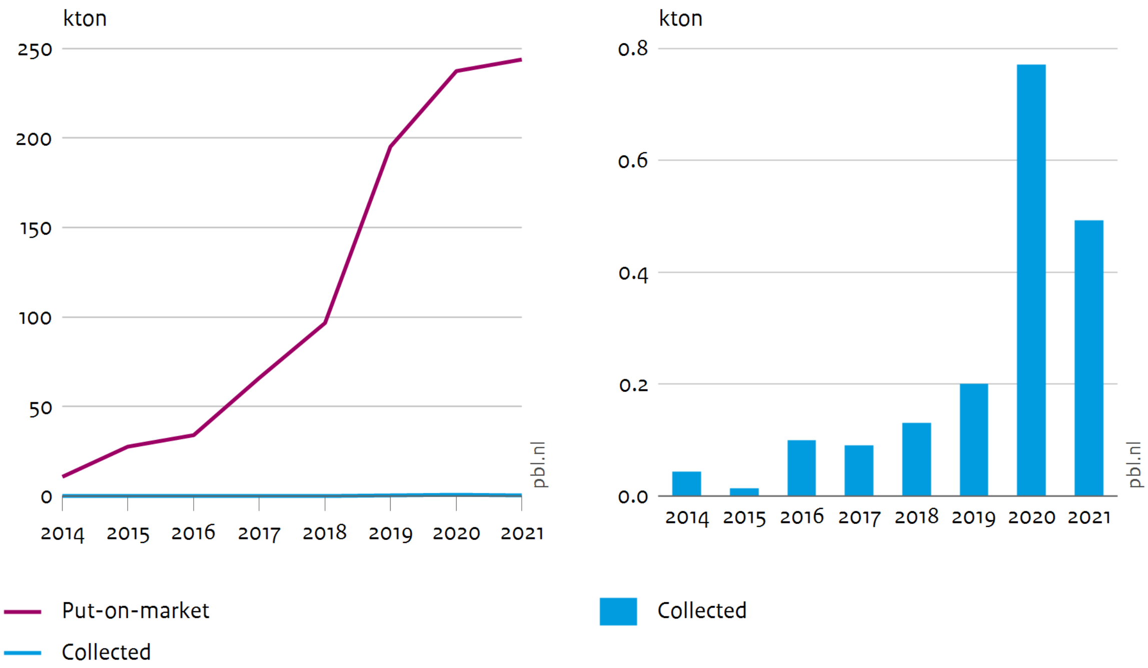
Note: The separate collection target for WEEE is 65%, while the recycling and recovery targets for solar panels are 80% and 85% respectively.

Figure 11

Amount of solar panels put-on-market and collected

Total

Collected



Source: Nationaal (W)EEE Register Rapportage 2021, 2022

Although the volume of end-of-life solar panels in the Netherlands is currently relatively low, a large influx is expected in the future, with the most rapid growth occurring after 2033 (Späth et al., 2022). Späth et al. predicted that the annual volume of end-of-life solar panels is expected to increase from about 500 tonnes in 2021 to 50,000 tonnes in 2042. Afterwards, the annual end-of-life volumes will grow rapidly before eventually plateauing at nearly 200,000 tonnes in 2046 and beyond. In their analysis, Späth et al. assumed that the maximum of all operational PV installations will be reached in 2044. From then on, the rates of new installations and decommissioning will be in equilibrium. Due to 15-year subsidy programmes in place for solar parks, Späth et al. estimated that, in the future, 30% of panels installed in solar parks will be decommissioned and exported after a service time of 15 years. With this extreme growth in the solar panel waste stream, it is important to assess end-of-life trajectories for solar panels and how these can be strengthened for circularity.

5.2 What is the current end-of-life pathway for solar panels?

Stichting OPEN currently sends the small quantity of collected solar panels to a recycling facility outside of the Netherlands, where the 'mainstream' recycling process for solar panels is used. This process involves removing the aluminium frame, junction box, and copper cables before mechanically crushing and shredding the rest of the material, which can then be used as an additive for construction materials (Späth et al. 2022). The existing recycling route is considered as 'downcycling', because the extraction of priority materials, such as high-purity silicon and silver, is not achieved. Furthermore, the crushed material resulting from the recycling process is not usable as a replacement for primary materials in solar panel production. In the report Roadmap for a Circular Photovoltaic Industry, Stichting OPEN acknowledged that downcycling is currently the dominant solar panel recycling practice and identified a need for financing to fund research and development of improved recycling technologies (Eijsbouts & Jehee 2021). By raising their advance waste management fee, Stichting OPEN hopes to be able to utilise a more circular recycling process in the future.

5.3 Where are EPR policies falling short in promoting circular economy goals and safeguarding priority materials?

The WEEE collection target is unattainable and undermines repair and reuse activities

Interviews provided various insights into the challenges associated with meeting the WEEE collection target. One key factor is the substantial variation in lifetimes across WEEE products, making the established cumulative target based on the previous three years put-on-market unsuitable. Solar panels have an especially long lifetime, are heavy, and have been installed at rapid rates in recent years, thereby inflating the total WEEE collection target. In addition, repair and reuse activities are poorly tracked, and run contrary to the objectives of the target. If a solar panel follows a repair or reuse pathway to extend its product lifetime, it will not be available for collection.

The lack of documentation of repair and reuse activities within the existing EPR scheme also threatens to exacerbate issues with waste exports. In the future, some panels will be replaced before their 25-year lifetime due to the availability of higher efficiency panels (Tao et al. 2020). In the Netherlands, it is estimated that at least 30% of solar panels will be exported before their end-of-life due to 15-year subsidy programmes for solar parks (Späth et al. 2022). Used solar panels can function at a reduced efficiency until they eventually reach their end-of-life due to the degradation of organic components over time (El-Khawad et al. 2022). Uncertainty remains as to whether a viable market for used solar panels will develop in Europe, especially considering that new modules are becoming cheaper and more efficient (Tao et al. 2020; Wade et al. 2017). Today, markets for refurbished solar panels are largely in developing countries, where electronic waste is often not regulated and improper disposal can lead to environmental and health risks (Wade et al. 2017).

The weight-based recycling target sustains downcycling practices rather than recovery of priority materials like high-purity silicon

Glass makes up 70-75% of a solar panel's weight, while the aluminium frames make up 10-15% of the weight (Graulich et al. 2021). By setting weight-based recycling targets, the WEEE policy incentivises the recycling of heavy materials like glass and aluminium rather than more valuable and critical materials found in solar panels like silver and PV-grade silicon (El-Khawad et al. 2022). The current recycling targets are therefore not effectively promoting the development of advanced recycling technologies capable of extracting CRMs. Nevertheless, some companies are researching mechanical, chemical, and thermal delamination recycling techniques to facilitate the separation and high-value recycling of CRMs from solar panels (Späth et al. 2022). Significant uncertainties remain regarding the profitability of these more advanced recycling technologies due to both their early development stage as well as fluctuations in material price levels (Späth et al. 2022). In addition, because solar panel manufacturers are mainly located in Asia, a local solar industrial ecosystem and market demand for secondary materials is missing.

The advance waste management fee is too low to incentivise circular practices

The advance waste management fee for solar panels – despite its recent increase to 80 cents per panel – remains very low compared to the price of a solar panel. It is possible that this low tariff is treated as a cost of doing business by companies subject to the tariff, rather than a stimulus to incentivise more circular practices. Furthermore, EPR obligations are carried out by importers and installation companies in the Netherlands, which further dilutes incentives for solar panel manufacturers in East Asia to improve eco-design.

Insufficient monitoring and enforcement undermine EPR scheme effectiveness

Enforcement is critical for identifying free riders and ensuring a level playing field. Some stakeholders interviewed expressed concerns about free riders within the solar panel EPR scheme. Notably, stakeholders had divergent interpretations about which entity was responsible for monitoring and enforcement of the scheme (i.e. the PRO versus ILT). As a result, it appears that there is room for improvement in the enforcement of EPR for solar panels.

6 Considering an EPR scheme for wind turbines

There is currently no EPR scheme for wind turbines in the Netherlands.

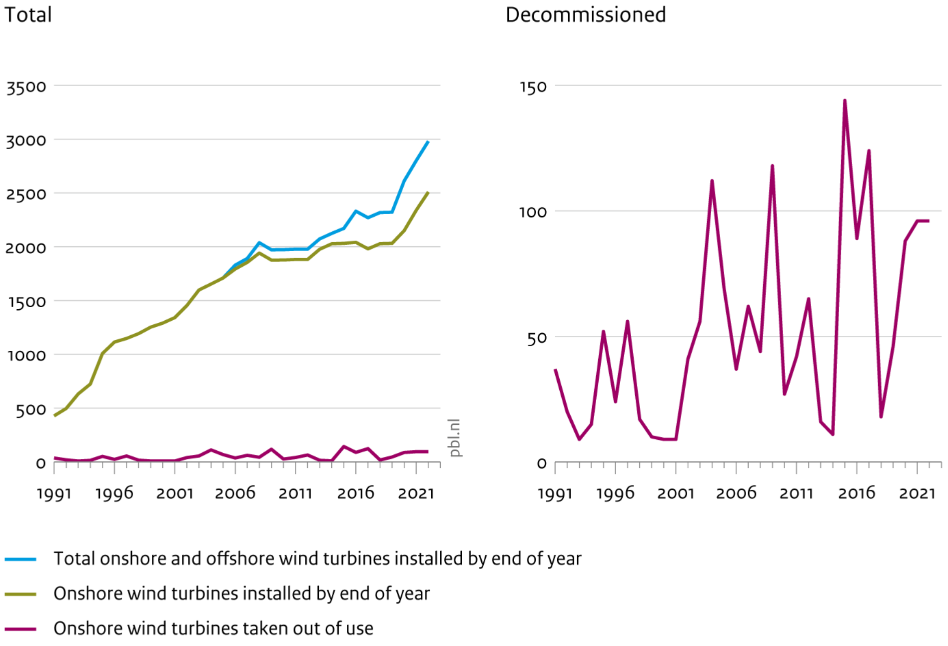
6.1 What is the current end-of-life pathway for wind turbines?

Few wind turbines currently reach an end-of-life stage in the Netherlands, but this is expected to vastly change in the future

A significant number of wind turbines have already been decommissioned in the Netherlands, and this trend will only grow as more turbines are installed. Data from Statistics Netherlands (2023) reveal that 1480 onshore wind turbines have been decommissioned between 1991 and 2021 (Figure 12).

Figure 12

Number of wind turbines installed and decommissioned annually in the Netherlands



Source: CLO (2023), Statistics Netherlands (2024)

The advent of offshore wind parks is relatively recent, and as such, few offshore installations have reached the end of their lifespan at the time of writing. The first offshore wind park decommissioned in the Netherlands was the Lely park, consisting of four turbines originally installed in 1994 and decommissioned in 2016 (van der Meulen et al. 2020). The number of offshore wind parks requiring decommissioning in the North Sea is expected to increase significantly in the coming years. A material flow analysis of wind parks in the North Sea projects that the annual number of wind turbines to be decommissioned will increase from 10-15 turbines in 2020 to 100-125 turbines in 2030, and will ultimately reach values of 250-300 turbines in 2050 (van der Meulen et al. 2020).

Onshore wind turbines are regularly decommissioned before the end of their lifespan in the Netherlands and then exported for reuse in other countries

After reaching their economic lifetime, many onshore wind turbines in the Netherlands are exported. In the context of onshore wind turbines, it is helpful to distinguish between two types of lifetimes: the economic lifetime and the technical lifetime. The *economic lifetime* refers to the economically viable lifetime of a wind turbine, which is heavily influenced by subsidy timelines and technology advances. For example, as part of the Stimulation of Sustainable Energy Production and Climate Transition (SDE++) programme, operating subsidies are provided to large-scale renewable energy project developers for a maximum duration of 15 years (Netherlands Enterprise Agency 2024). For wind parks, only onshore installations are eligible for these subsidies, not offshore ones. According to stakeholder interviews, it is common in the Netherlands that wind turbines are decommissioned and replaced with new and more efficient ones at the end of the 15-year subsidy contract (repowering). The SDE++ programme allows for applications replacing wind turbines under two conditions: (i) the capacity of the new wind turbines must be at least 1 MW larger than the previous turbines; and (ii) at the time of replacement, the wind turbine to be replaced must have been in use at the location in question for at least 15 years, and must have been commissioned at least 13 years before the subsidy application (Ministry of Economic Affairs and Climate Policy 2023).

At the end of the economic lifetime of wind turbines in the Netherlands, they are often decommissioned and exported to another country. There are several Dutch companies, including Business in Wind, DutchWind, and Reengineers, who specialise in logistics and sales of second-hand wind turbines. Some common destinations for second-hand wind turbines from the Netherlands include the United Kingdom, Italy, Sweden, Denmark, Poland, Ukraine, and Ireland.

The *technical lifetime* of a wind turbine includes two sub-categories: the design lifetime and the operational lifetime. The *design lifetime* is the lifetime that a wind turbine is supposed to function for based on design parameters, a period that is usually 20-25 years. At the end of a wind turbine's design lifetime, it is assessed and inspected to determine if it can continue running safely. In contrast, the *operational lifetime* can extend beyond the design lifetime and refers to the full duration of time that a wind turbine can continue running. The operational lifetime of a wind turbine can span 25-30 years. End-of-life wind turbines are dismantled and parts unsuitable for reuse are recycled, incinerated, or landfilled, depending on their material composition.

Wind turbines are mainly composed of widely recyclable metals, but the recycling of composite fiberglass blades remains a challenge

Wind turbines are mainly composed of steel and therefore have a high recyclability rate of 85–90% (Majewski et al. 2022). For example, the material composition of a Vestas wind turbine (model V162-6.2 MW) is about 88% metals (e.g. steel, iron, aluminium, and copper) and 10% polymer materials and glass/carbon composite materials, while the remaining 2% consists of electronics, lubricants, and fluids (Vestas 2023a). The metals can be dismantled and recycled alongside other bulk metals. The recycling of wind turbine blades, however, is more challenging. Wind turbine blades are constructed out of composite materials, which are inherently difficult to recycle due to the complex nature of their material composition and inability to be remoulded (Cherrington et al. 2012). In 2016, the wind power industry was responsible for a 6.8% share of demand in the global composites market (Martinez-Marquez et al. 2022).

There is a scarcity of recycling facilities capable of effectively recycling composite materials (Martinez-Marquez et al. 2022). For example, existing composite recycling capacity in the EU can only handle about 5% of the current waste stream (WindEurope 2023). For this reason, wind industry stakeholders are pointing to cement co-processing as a potential solution for recycling composite materials. Cement co-processing can be quickly deployed at a large scale, unlike other composite recycling techniques. In co-processing, composite materials can be used as both an input in cement production as well as a fuel source. To scale up cement co-processing as a viable composite recycling option, the EU regulatory framework would need to be revised to recognise co-processing as a recycling process (WindEurope 2023).

The end-of-life fate for wind turbine blades in the Netherlands includes recycling, repurposing, incineration, and landfilling. The quantities of end-of-life blades needing to be handled in the Netherlands are currently very low, because the majority of wind turbines (and their blades) are exported for a second life abroad. At least one company in the Netherlands claims to partner with a facility that is capable of recycling composite wind turbine blades (Jansen Recycling Group 2023). Alongside recycling, wind turbine blades can be repurposed as sound barriers, playgrounds, urban furniture, and bridges. The Dutch company Blade Made specialises in such applications. Other destinations are landfilling and incineration. As already mentioned, wind farm operators can claim an exemption to the ban on landfilling composite waste, because the costs of alternative treatment are much higher than the threshold set by the regulation (Schmid et al. 2020). Incineration is another potential end destination for wind turbine blades in the Netherlands. In an analysis of wind turbine demolition costs in the Netherlands, revenues from metal recycling and the costs for incineration are included, implying that while the metal parts of end-of-life wind turbines are routinely recycled, the remaining materials are more likely to be incinerated (KIJK 2023). This same analysis reveals that demolition and treatment costs currently make up a very small fraction, just 0.6%, of the total costs occurring in the lifecycle of a wind turbine.

The European wind turbine manufacturing sector offers a favourable industrial environment for policymaking

The wind turbine producers with the largest market share in the Netherlands are European companies with production facilities in Europe, including Enercon, Nordex, Siemens-Gamesa and Vestas. Therefore, the wind turbine manufacturing sector offers a favourable industrial environment for policy instruments to influence the adoption of circular industry practices. Wind turbine manufacturers are already actively exploring circular strategies, especially for wind turbine blades, indicating that they could respond positively to legislation that could support their existing efforts.

6.2 Are current practices stimulating circular economy goals and safeguarding priority materials?

For those wind turbines that are exported abroad, it can be difficult to trace the ultimate end-of-life fate

Although there are unique identification numbers present on a wind turbine, these numbers are not used to track movements. It is also not currently a manufacturers' responsibility to monitor their wind turbines after they are sold. Moreover, due to the long operational lifetimes of wind turbines, the number of second-hand wind turbines exported from the Netherlands that have reached the end of their operational lifetime abroad is likely very low. One specialist in second-hand wind turbine sales shared that in their 20 years in business, they had not yet – to their knowledge – had one of their second-hand turbines reach its operational end-of-life in a destination country.

Wind turbine manufacturers are at the forefront of research and development in the effort to design recyclable wind turbine blades

Both Siemens Gamesa and Vestas have developed novel blade technology based on epoxy and resin chemical structures (Siemens Gamesa 2021; Vestas 2023b). These new blades are constructed out of a blend of materials that can ultimately be recycled and reused as inputs for new wind turbine blades, completing a closed-loop cycle. In addition, many industry stakeholders (including the producers Vestas, Siemens Gamesa, and LM Wind Power) have partnered on the DecomBlades initiative, which seeks to advance recycling solutions for the existing volume of blades that are composed of difficult-to-recycle composite materials.

Wind turbine manufacturers repair and refurbish wind turbine parts to prolong lifetimes

Wind turbine manufacturers produce and sell wind turbines to wind park developers, such as utility companies. With every purchasing agreement, manufacturers typically also implement a service contract with a specified timespan. During this period, the manufacturer is responsible for servicing wind turbines and replacing/repairing components. Interviews with wind turbine manufacturers revealed that manufacturers refurbish components if possible to allow for reuse as spare parts. Although this is clearly a best practice from a circular economy perspective, manufacturers explained that they sometimes receive push-back from clients who insist on receiving new parts. This was identified as an area where government intervention could help stimulate acceptance of refurbished and reused wind turbine components. Although it is most common for the manufacturer to be the service provider, there are also situations in which the operator or a separate company is responsible for the maintenance.

The growing size of wind turbines is leading to shifts in industry practices that may hamper circular economy best practices

The size of wind turbines, including the length of the blades (rotor diameter), hub height, and rated power, has been increasing dramatically. In the late 1980s, the average wind turbine had a rotor diameter of 30m, hub height of 30m, and rated power of 300 kW. In 2014, these numbers grew to 92.7m rotor diameter, 87.7m hub height, and 2.1 MW (Serrano-González & Lacal-Arántegui 2016). According to interviews with wind turbine stakeholders, the growing size of wind turbines will eventually render the export of second-hand turbines financially infeasible. Moving a 2MW wind turbine incurs costs over three times those of a 1MW wind turbine, while moving a 5MW wind turbine costs ten times as much as moving a 1MW wind turbine. This implies that the cost difference between buying a used wind turbine and a new one will decline, and therefore the demand for large second-hand turbines is likely to shrink. The growing size of turbines is also hindering design for circularity and placing increasing demands on the installation supply chain. Some manufacturers are calling for the introduction of a size limit for offshore wind turbines. A size limit for offshore wind turbines would allow manufacturers to prioritise modularity and circularity in product design. In addition, the supply chain would be able to reuse equipment for the installation of wind turbines, rather than needing access to larger ships and cranes every few years.

7 Conclusions

The Batteries regulation was a very important step forward for battery circularity, but additional interventions would help ensure the safe removal and second use of EV batteries

The Batteries Regulation strengthened EPR for EV batteries by introducing separate provisions, tightening weight-based recycling targets, and establishing material recovery targets. The Regulation also introduced recycled content requirements for new batteries to stimulate demand for secondary materials. It also put in place information-based instruments, such as a digital product passport, that enable monitoring products throughout their lifetime, and facilitate dismantling and recycling at the end of their lifespan. However, additional policy interventions may be needed to put an end to unmonitored second-use practices that pose safety concerns, such as attempts to repurpose EV batteries for home energy storage systems without certified knowledge. It is important that clear rules are introduced that prohibit the non-certified removal and transformation of EV batteries, and stipulate that the EPR rests with the party that offers the battery for stationary applications.

Adjustments to the EPR scheme for solar panels needed to promote reuse and CRM recovery

Similar to the conclusions of other product-specific studies of EPR in the Netherlands (Campbell-Johnston et al. 2020; Tijm et al. 2021), this study finds that the existing EPR scheme for solar panels improves the coordination of collection and recycling activities, but does not stimulate reuse or eco-design. The continued loss of CRMs in low-value applications of recycled solar panels is also a significant concern. Interviews regarding the solar panel EPR scheme highlighted deeply rooted issues with the WEEE Directive's collection and recycling targets. Possible improvements to EPR for solar panels include revising WEEE targets to be product-specific and shifting towards material recovery targets for CRMs.

An EPR for wind turbine blades would promote a more sustainable treatment at the end of their lifespan

Regarding wind turbines, a scarcity of information on the end-of-life pathways of decommissioned wind turbines was encountered, similar to that observed in other studies (e.g. Graulich et al. 2021). Our findings show that composite blades continue posing the most important challenge to recycling and wind turbine circularity, thus echoing calls by other researchers for prioritising wind turbine blades for a new EPR policy, ideally at the EU level (Majewski et al. 2022; Martinez-Marquez et al. 2022; Mishnaevsky 2021). Such a new EPR policy would increase end-of-life transparency and stimulate a recycling industry for composite materials. Benefiting from the lessons learned from existing EPR schemes, such a new EPR could make use of recycling and material recovery targets, to give clear priority to high-value applications of the recycled material.

Improved monitoring and enforcement of EPR requirements would increase their effectiveness

By assessing the practical implementation of EPR, this report adds detail and nuance to previous findings. For example, on-the-ground experiences reveal monitoring and enforcement gaps in all waste streams, potentially allowing room for free-riding behaviour. In addition, issues with waste exports to developing countries were elevated as more rampant and problematic than national reporting reveals.

Even though fee modulation has been heralded as a mechanism for improving EPR in the literature (Brouillat & Oltra 2012; Dubois 2012; Dubois et al. 2016; Kunz et al. 2018), stakeholders voiced serious doubts about its efficacy in the context of costly products with long lifetimes, like the technologies studied in this report (see also Laubinger et al. 2021). Ultimately, stakeholders think that any difference in fees would be too minuscule an amount to change behaviour, especially when compared to the high prices of the products of interest in this study.

Expansion of the scope of EPR to products' use stage theoretically possible, but in practice scope limited to the end-of-life stage

Although much of the academic literature calls for a more transformative application of EPR, most stakeholders interviewed for this report consider the scope of EPR as limited to products' end-of-life stage. They point to complementary policy interventions (e.g. eco-design requirements) as the tools for stimulating sustainable changes at earlier phases of a product's lifecycle, and to the European Commission as the best venue for policymaking for the three technologies of interest. The revised EU Waste Framework Directive itself enables a broader scope of EPR, as it allows producers' obligations to include 'a responsibility to contribute to waste prevention and to the reusability and recyclability of products' (Directive (EU) 2018/851 2018). However, expanding the EPR scope to the use stage of a product would imply moving beyond the minimum EPR requirements set at the EU level, and stakeholders seem reluctant to make unilateral steps in this direction. One factor that may have contributed to this reluctance is that monitoring product reuse and repair is, for many products, currently practically infeasible. However, for the three energy transition technologies studied here, monitoring reuse (including export) seems much more feasible in the immediate future than for smaller products that frequently change hands. Monitoring of such flows will also be facilitated by a wider implementation of digital product passports.

Instruments stimulating the use of secondary materials in the manufacturing of new products complement EPR in promoting material recovery

Complementary supply-side policy instruments are fundamental for increasing the effectiveness of EPR in promoting the recovery and reuse of CRMs and other materials of environmental relevance. All stakeholders pointed to the need for secondary materials markets in Europe, driven by strategic industrial ecosystems, to encourage high-value material recycling and closed loop product systems. Currently, low volumes of end-of-life products, due to long lifetimes, works against the business case for high-value material recycling processes. There are also many uncertainties inherent to these product groups, such as changing technologies and lifetimes of products that are not yet fully known. Stakeholders view policy interventions as a potential remedy. For example, recycled content requirements in new products, are essential for nurturing EPR effectiveness by stimulating demand for secondary materials and fostering strategic, EU-based industrial ecosystems.

The road to more effective EPR policy goes through the expansion of its scope and its better alignment with circular economy goals

EPR policy design would benefit from the use of collection targets taking product lifetime into account, the consideration of reuse and repair activities, material recovery targets, and greater oversight of recycling processes to reverse the norm of downcycling. The effectiveness of EPR in achieving CE goals can be further reinforced by leveraging synergies with policies promoting the use of secondary materials in the production of new products, such as recycled content requirements. By adopting such strategies, the Netherlands, as well as the EU, can foster resource efficiency for EV batteries, solar panels, and wind turbines, contributing to the transition towards a greener future. Future research could further assess the feasibility and desirability of these suggestions.

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Appendices

Appendix 1: Definitions of material security, environmental and economic indicators

Table A 1

Definitions of material security, environmental, and economic indicators

Analysis lens	*Index definition*	*Notes*
Material Security	**Supply risk index** – reflects the risk of a disruption in the EU supply of the material. Higher values denote larger risks. Values in the latest EU study range from a high of 5.6 to a low of 0.1 (Carrara et al. 2023).	These indices are specific to a European context and were developed under the request of the European Commission.
Environmental	**End-of-life recycling input rate** – measures recycling's contribution to materials demand in the EU per type of material. The indicator measures, for a given material, how much of its input into the production system comes from the recycling of 'old scrap' (or 'end-of-life scrap') i.e. scrap and waste derived from the treatment of products at their end-of-life (Eurostat 2023).	A universal environmental impact indicator is not available. The end-of-life recycling input rate serves as an indicator of the existing level of circularity in material recycling processes, thereby indicating where further technological advancements are required.
Importance to Energy	**Importance to Energy, medium-term (2025-2035)** – captures the importance of materials and the technologies that use them to the future of energy. The score reflects energy demand (70% of score weight) and substitutability limitations (30% of score weight). Values range from a low of 0 to a high of 4 (Bauer et al. 2023).	Calculated by the U.S. Department of Energy in the Critical Materials Assessment 2023.
Economic	**Primary material price 2018-2022 ($/kg)** – a measure of the price in USD per kg of material. All prices come from the Mineral Commodity Summary 2023 developed by the U.S. Geological Survey, though the underlying sources differ per material – some are from the London Metal Stock Exchange, while others are annual average producer prices (U.S. Geological Survey 2023).	In the absence of a comprehensive price database for secondary material prices, primary material prices from a consistent source were used. When primary material prices are high, and recycling costs are relatively low, there is a stronger market potential for secondary materials.

Appendix 2: Material-at-a-glance Factsheets

COPPER

Critical Raw Material, Strategic Raw Material

(European Commission 2023)

Supply Risk Index (2023) = 0.1

Reflects the risk of a disruption in the EU supply of the material. Values range from a low of 0.1 to a high of 5.6 (Carrara et al. 2023).

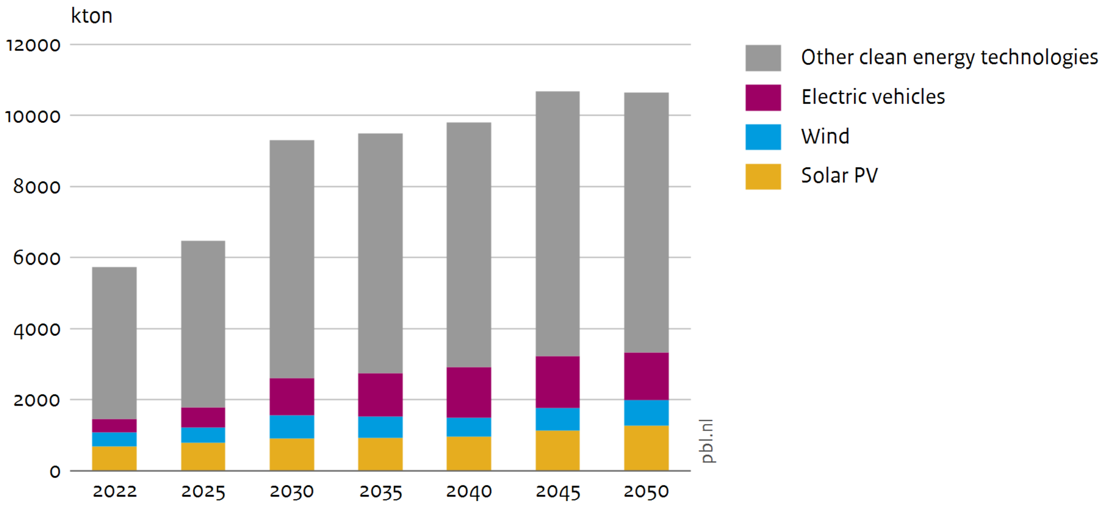
End-of-life recycling input rate (2022) = 55%

Contribution of recycled materials to raw materials demand in the EU (Eurostat 2023).

Importance to Energy, medium-term (2025-2035) = 3.0

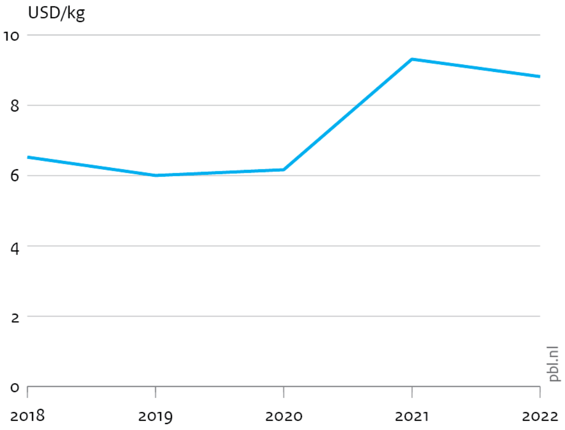
Captures the importance of materials and the technologies that use them to the future of energy. The score reflects energy demand (70% of score weight) and substitutability limitations (30% of score weight). Values range from a low of 0 to a high of 4 (Bauer et al. 2023).

Copper demand for clean technologies



Source: International Energy Agency, 2023

Annual average London Metal Exchange copper prices, grade A, cash



Source: U.S. Geological Survey, 2023

NICKEL

Critical Raw Material, Strategic Raw Material

(European Commission 2023)

Supply Risk Index (2023) = 0.5

Reflects the risk of a disruption in the EU supply of the material. Values range from a low of 0.1 to a high of 5.6 (Carrara et al. 2023).

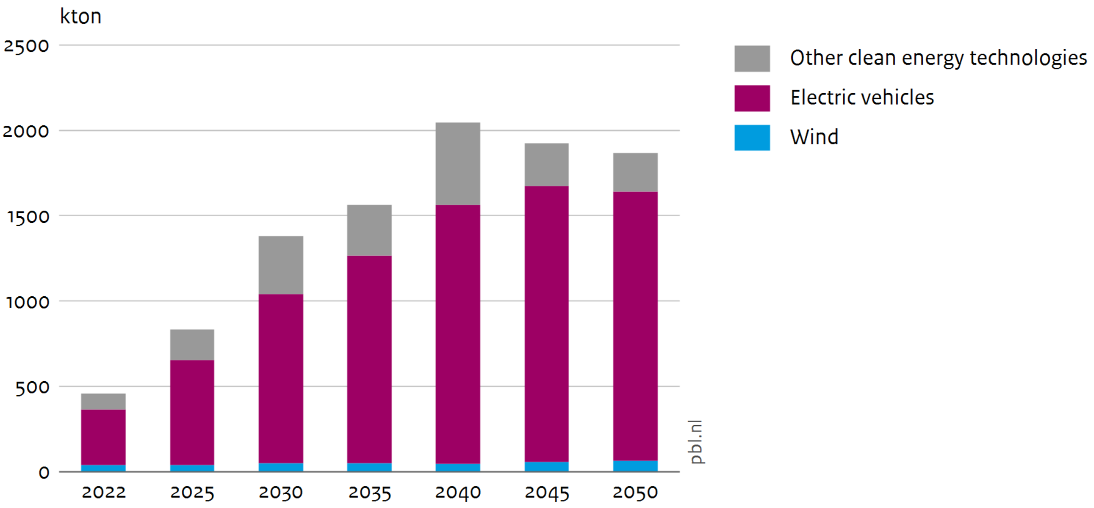
End-of-life recycling input rate (2022) = 16%

Contribution of recycled materials to raw materials demand in the EU (Eurostat 2023).

Importance to Energy, medium-term (2025-2035) = 3.7

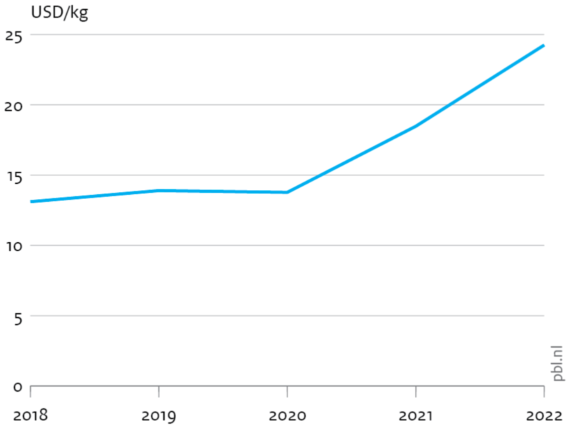
Captures the importance of materials and the technologies that use them to the future of energy. The score reflects energy demand (70% of score weight) and substitutability limitations (30% of score weight). Values range from a low of 0 to a high of 4 (Bauer et al. 2023).

Nickel demand for clean technologies



Source: International Energy Agency, 2023

Annual average London Metal Exchange nickel prices (cash)



Source: U.S. Geological Survey, 2023

SILICON

Critical Raw Material, Strategic Raw Material

(European Commission 2023)

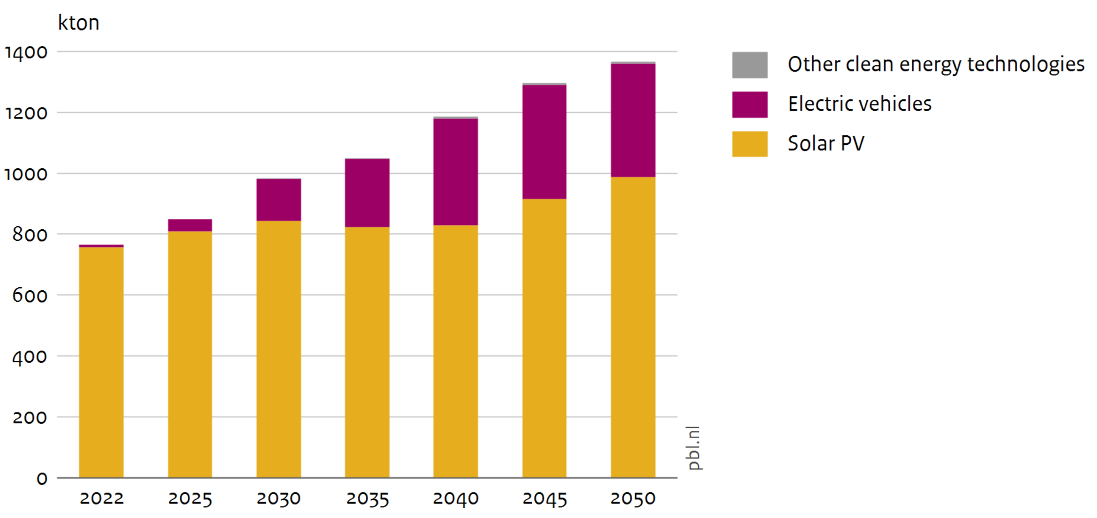
Supply Risk Index (2023) = 1.4

Reflects the risk of a disruption in the EU supply of the material. Values range from a low of 0.1 to a high of 5.6 (Carrara et al. 2023).

Importance to Energy, medium-term (2025-2035) = 3.0

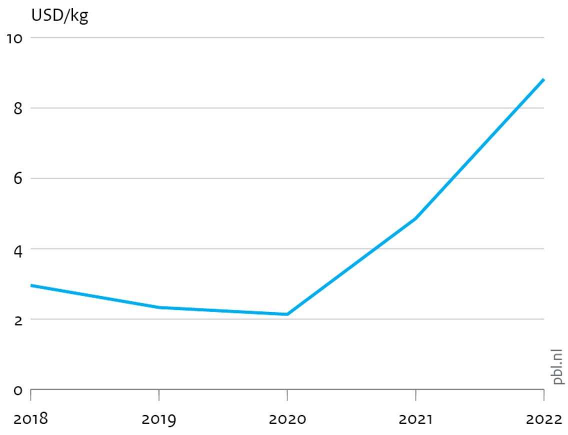
Captures the importance of materials and the technologies that use them to the future of energy. The score reflects energy demand (70% of score weight) and substitutability limitations (30% of score weight). Values range from a low of 0 to a high of 4 (Bauer et al. 2023).

Silicon demand for clean technologies



Source: International Energy Agency, 2023

Average prices of silicon metal



Source: U.S. Geological Survey, 2023

MANGANESE

Critical Raw Material, Strategic Raw Material

(European Commission 2023)

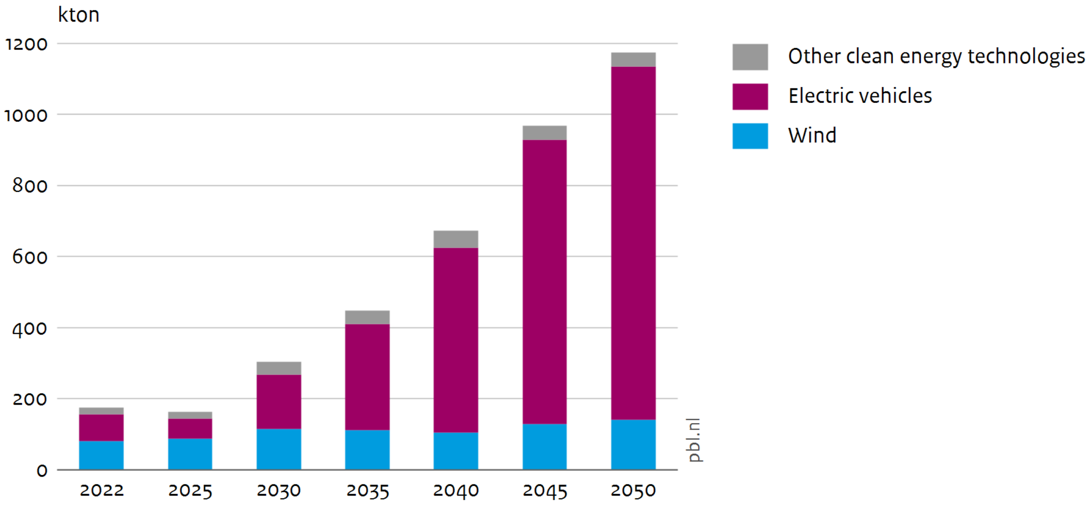
Supply Risk Index (2023) = 1.2

Reflects the risk of a disruption in the EU supply of the material. Values range from a low of 0.1 to a high of 5.6 (Carrara et al. 2023)

Importance to Energy, medium-term (2025-2035) = 2.3

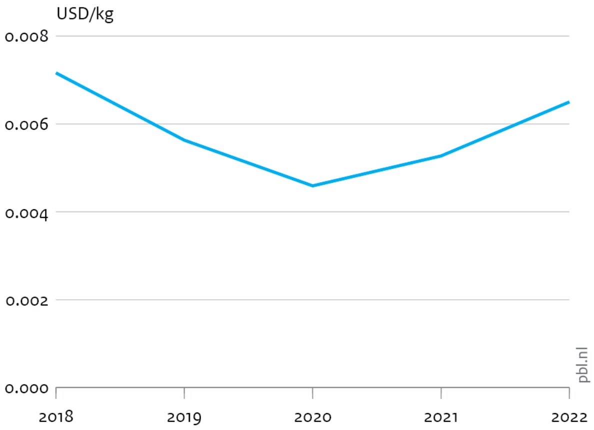
Captures the importance of materials and the technologies that use them to the future of energy. The score reflects energy demand (70% of score weight) and substitutability limitations (30% of score weight). Values range from a low of 0 to a high of 4 (Bauer et al. 2023).

Manganese demand for clean technologies



Source: International Energy Agency, 2023

Average prices of manganese content, cost, insurance and freight, China



Source: U.S. Geological Survey, 2023

LITHIUM

Critical Raw Material, Strategic Raw Material

(European Commission 2023)

Supply Risk Index (2023) = 1.9

Reflects the risk of a disruption in the EU supply of the material. Values range from a low of 0.1 to a high of 5.6 (Carrara et al. 2023).

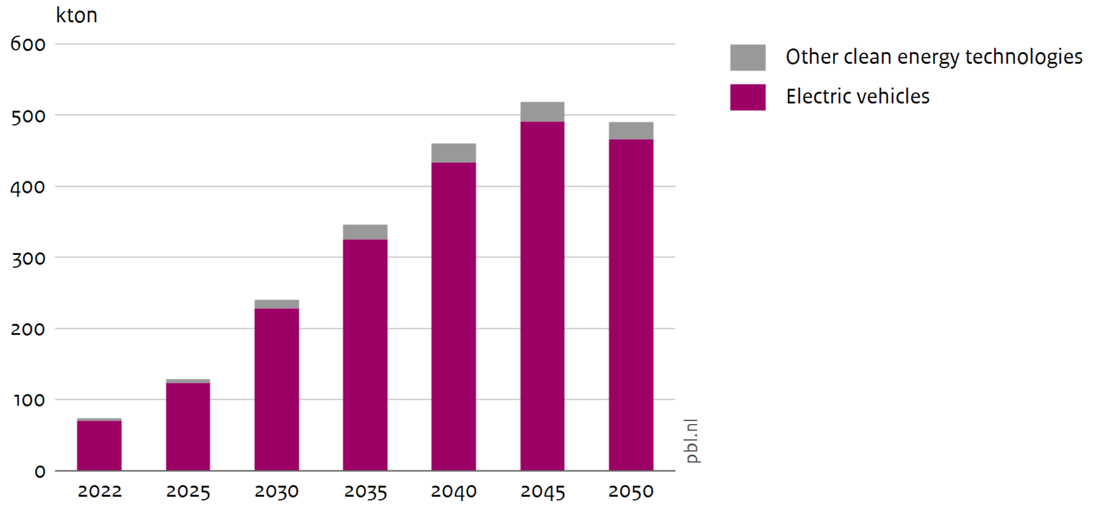
End-of-life recycling input rate (2022) = 0%

Contribution of recycled materials to raw materials demand in the EU (Eurostat 2023).

Importance to Energy, medium-term (2025-2035) = 4.0

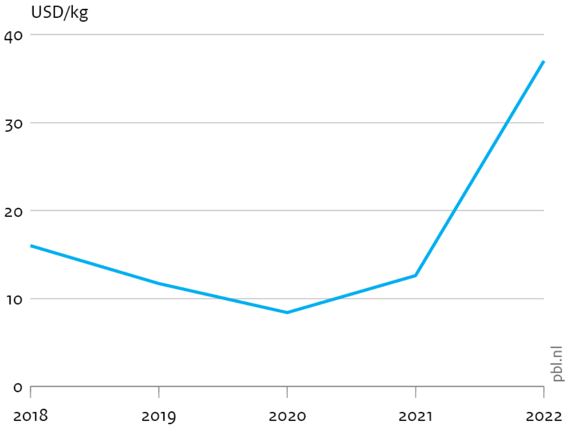
Captures the importance of materials and the technologies that use them to the future of energy. The score reflects energy demand (70% of score weight) and substitutability limitations (30% of score weight). Values range from a low of 0 to a high of 4 (Bauer et al. 2023).

Lithium demand for clean technologies



Source: International Energy Agency, 2023

Annual average price nominal, battery-grade lithium carbonate



Source: U.S. Geological Survey, 2023

COBALT

Critical Raw Material, Strategic Raw Material

(European Commission 2023)

Supply Risk Index (2023) = 1.7

Reflects the risk of a disruption in the EU supply of the material. Values range from a low of 0.1 to a high of 5.6 (Carrara et al. 2023).

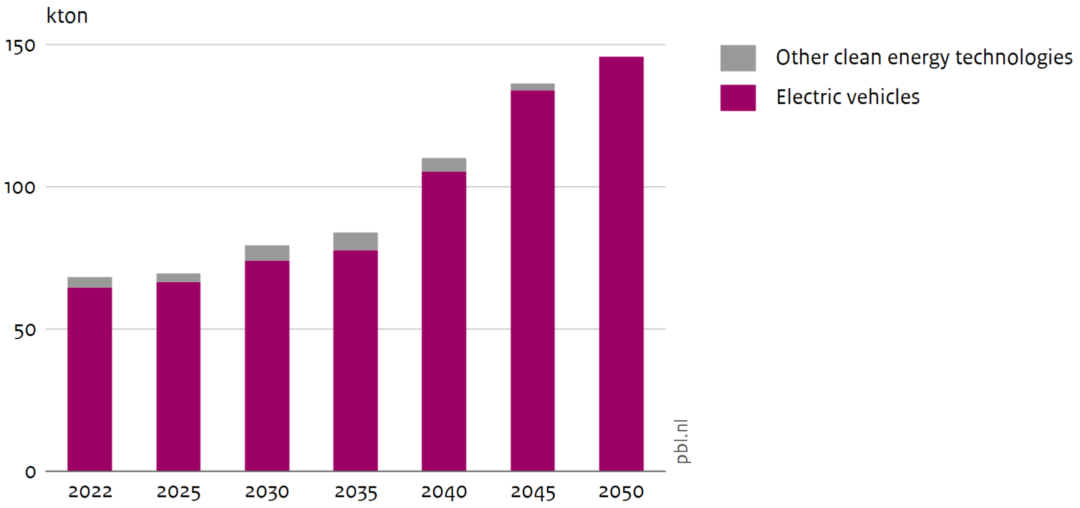
End-of-life recycling input rate (2022) = 22%

Contribution of recycled materials to raw materials demand in the EU (Eurostat 2023).

Importance to Energy, medium-term (2025-2035) = 3.4

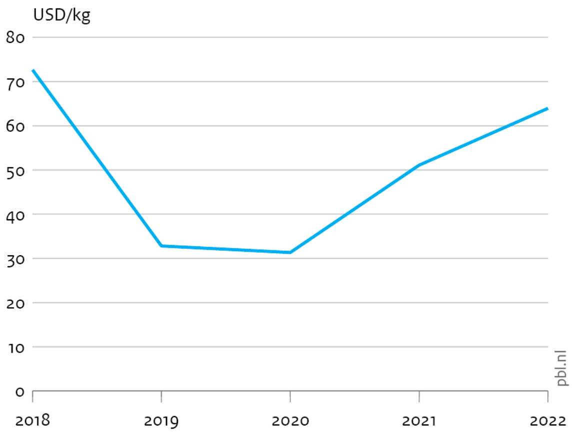
Captures the importance of materials and the technologies that use them to the future of energy. The score reflects energy demand (70% of score weight) and substitutability limitations (30% of score weight). Values range from a low of 0 to a high of 4 (Bauer et al. 2023).

Cobalt demand for clean technologies



Source: International Energy Agency, 2023

Annual average London Metal Exchange cobalt prices (cash)



Source: U.S. Geological Survey, 2023

GRAPHITE

Critical Raw Material, Strategic Raw Material

(European Commission 2023)

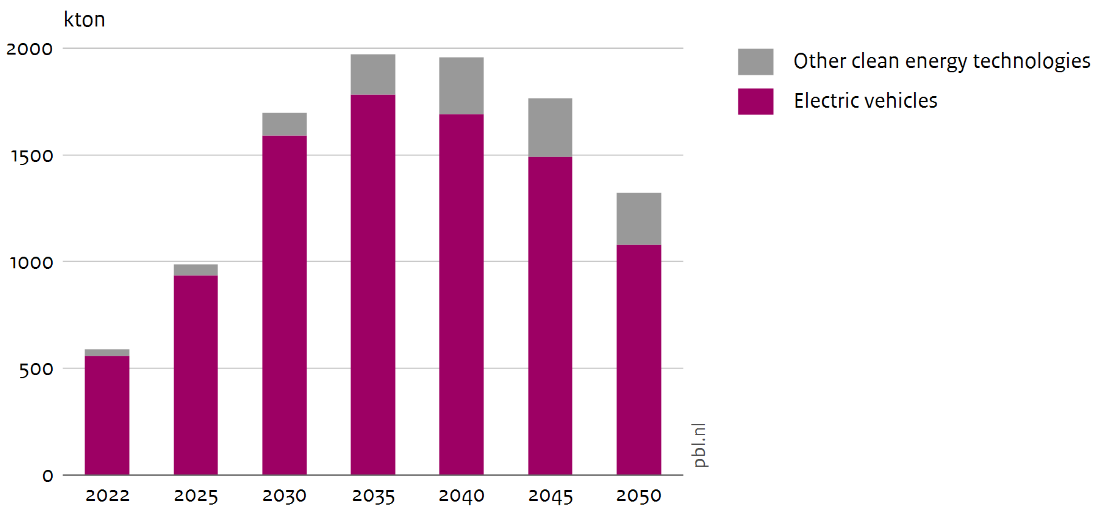
Supply Risk Index (2023) = 1.8

Reflects the risk of a disruption in the EU supply of the material. Values range from a low of 0.1 to a high of 5.6 (Carrara et al. 2023).

Importance to Energy, medium-term (2025-2035) = 3.4

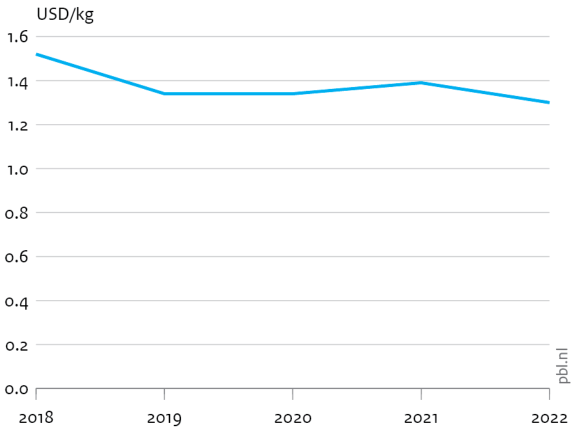
Captures the importance of materials and the technologies that use them to the future of energy. The score reflects energy demand (70% of score weight) and substitutability limitations (30% of score weight). Values range from a low of 0 to a high of 4 (Bauer et al. 2023).

Graphite demand for clean technologies



Source: International Energy Agency, 2023

Flake graphite price, average unit value of imports, dollars per kg at foreign imports



Source: U.S. Geological Survey, 2023

NEODYMIUM

Critical Raw Material, Strategic Raw Material

(European Commission 2023)

Supply Risk Index (2023) = 3.6

Reflects the risk of a disruption in the EU supply of the material. Values range from a low of 0.1 to a high of 5.6 (Carrara et al. 2023).

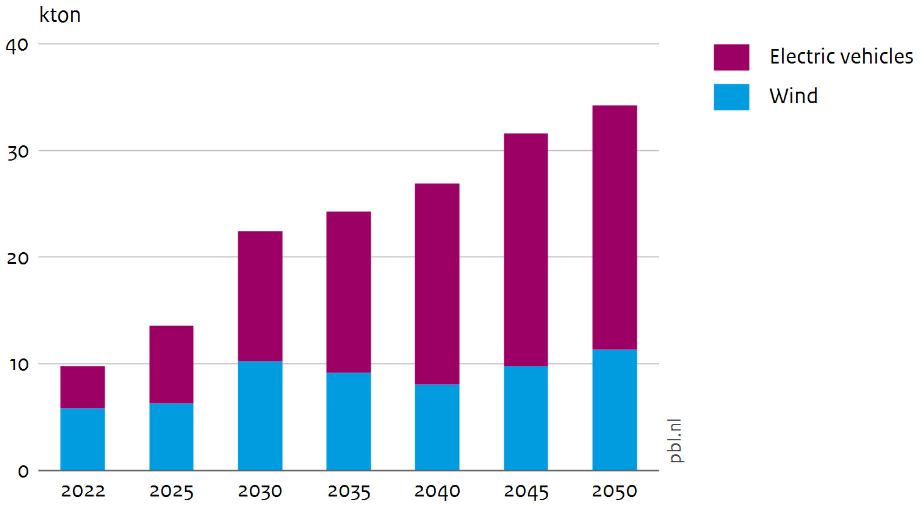
End-of-life recycling input rate (2022) = 1%

Contribution of recycled materials to raw materials demand in the EU (Eurostat 2023).

Importance to Energy, medium-term (2025-2035) = 3.0

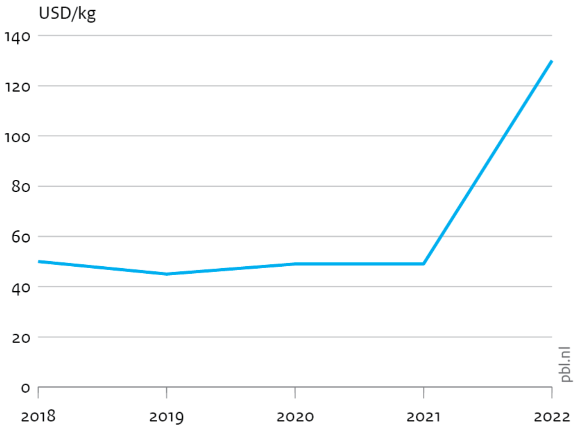
Captures the importance of materials and the technologies that use them to the future of energy. The score reflects energy demand (70% of score weight) and substitutability limitations (30% of score weight). Values range from a low of 0 to a high of 4 (Bauer et al. 2023).

Neodymium demand for clean technologies



Source: International Energy Agency, 2023

Average prices Neodymium



Source: U.S. Geological Survey, 2023