LOW-CARBON TECHNOLOGIES AND RUSSIAN IMPORTS

How far can recycling reduce the EU's raw materials dependency?

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Abstract

The term 'strategic autonomy' denotes the political goal of building a self-reliant EU economy with limited exposure to supply disruptions, like those stemming from the Covid-19 crisis. Securing access to the non-energy minerals required for building a new industrial ecosystem consistent with the EU's decarbonisation objectives is important to achieving this goal. Rising demand for these materials has created an arena for geopolitical competition. Moreover, the war in Ukraine has brought forward the need to take a closer look at the external supply of minerals, including from Russia, and potential risks involved.

This Policy Insight first provides a brief overview of EU import dependency on raw materials and Russia's share among EU sources of key supplies for low-carbon technologies. It then looks at prospects for meeting future material demands though circularity for three technologies, namely lithium-ion batteries, wind turbines and fuel cell electric vehicles. The analysis is based on two scenarios with different levels of ambition. They aim to give an indication of the scale of potential benefits that can be achieved through circularity and recycling approaches for components and materials used in these technologies. The estimates suggest that establishing collection and recycling facilities in the EU, through the appropriate policy frameworks in place, can contribute to meeting future EU material demands for them and reduce import dependency.

Still, recycling alone will not suffice to cover the increasing material requirements. Other options will therefore need to be considered, including developing strategic partnerships and joint projects with resource-rich countries (also in light of efforts to cut economic ties with Russia). The EU will further need to source from its own mining reserves, seek improvements in material efficiency and foster material substitution options where possible.

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Introduction

The EU accounts for only a small share of global raw material production and is a large net importer of materials required for a number of key technologies European Commission (2020a). Securing access to raw materials that are critical for the competitiveness of the EU economy has over the years become a top policy priority. In 2008, the European Commission published the European raw materials initiative, its first integrated strategy aimed at supporting access to non-energy minerals. An outcome of the strategy was the establishment of a list[1] of critical raw materials (CRMs) that are important for the European economy and which can be vulnerable to supply disruptions.

More recently, the European Green Deal elevated the topic of access to resources to a 'strategic security' question and emphasised the importance of securing a sustainable supply of the raw materials required for a green and digital transition. The Green Deal was followed by the new industrial strategy for Europe, which held that Europe's strategic autonomy depends inter alia on access to raw materials and led to the preparation of an action plan on CRMs. Among the main steps envisaged in the action plan, published in September 2020, was the launch of a European Raw Materials Alliance bringing together industry, policy and institutional actors. It also called for the preparation of an inventory of potential sources of CRMs that could be retrieved from waste streams and available EU stocks, and the development of strategic partnerships in support of the EU's objectives to diversify its supply of materials.

At the same time, the supply chain disruptions and impacts of the Covid-19 crisis provided further impetus to the EU's strategic autonomy goals (Montanino et al., 2022). As recognised by the revised EU industrial strategy adopted in May 2021 and reflected in the lessons learnt from the crisis, the disruptions due to the pandemic (of which some were unexpected) highlight the need to better understand the EU's strategic dependencies and how they could further evolve in the coming years. While EU manufacturers are still dealing with shortages and other effects caused by the crisis (Szczepański, 2021), the Russian invasion of Ukraine raises new questions and concerns about the EU's future supply-chain vulnerabilities.

A changing global policy landscape

The EU has had a dedicated strategy to support access to non-energy minerals since 2008, yet other major industrial players have also taken steps in this direction. A key reference point for these developments was the decision by China – which dominates global production of rare earth elements (Zhou et al., 2017) – to introduce export restrictions of these metals to Japan in 2010 following an incident near the disputed Senkaku islands (Kalantzakos, 2020). This led to soaring prices of rare earth elements and eventually resulted in a joint complaint to the WTO by the EU, Japan and the US[2]. In the wake of this crisis, Japan adopted a dedicated strategy on

[1] The list is reviewed every three years and currently includes 30 materials.

[2] The case was eventually settled in 2014, see: https://www.wto.org/english/tratop_e/dispu_e/cases_e/ds431_e.htm

securing access to CRMs. It envisaged actions such as diversifying Japan's supply of rare earths through diplomacy, trade agreements and joint exploration activities with other countries. It further involved financial support for recycling projects and technologies, and accumulating stockpiles of critical minerals to minimise future supply risks (Barteková & Kemp, 2016). More recently, the country introduced a legal obligation for companies to request government approval for foreign investments in activities related to 34 critical materials, including rare earths, cobalt and lithium.

In a similar vein, the US Department of the Interior identified in 2018 a list of 35 critical minerals deemed very important for the country's economic development and national security. This was followed by the 'Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals'. It aimed at supporting the development of supply chains for critical minerals through, inter alia, R&D investments in mining, recycling and material substitution activities, as well as trade and collaboration agreements with resource-rich countries. Efforts in this domain have intensified with the Biden administration, which has published a comprehensive report identifying specific supply-chain vulnerabilities and announced a number of major investments to enhance the country's capacities in sourcing critical minerals. More recently and in light of the situation in Ukraine, the Biden administration has also announced its intention of using the Defense Production Act to further enhance domestic production and processing of crucial minerals required for low-carbon technologies.

While the global policy landscape around critical minerals is rapidly evolving, the Russian invasion of Ukraine could prove to be another reference point in the global race to secure access to critical resources. As explained below, Russia is an important world supplier of materials that have been identified as critical in the EU's assessment, including palladium and platinum but also aluminium, nickel and copper. The country appears to hold significant reserves of rare earth elements, although to date they remain largely unexploited (Cherepovitsyn & Solovyova, 2022). The EU's efforts to cut economic ties with Russia[3] along with Russia's decision to ban exports of raw materials could put additional pressure on raw material supply chains that are still recovering from the Covid-19 crisis. Furthermore, the financial reverberations of the war are starting to become visible; for example, the price of nickel – a vital material for lithium-ion batteries – has seen an increase of 26 %[4] since the beginning of Russia's invasion[5].

[3] For a list of EU sanctions against Russia, see: https://ec.europa.eu/info/strategy/priorities-2019-2024/stronger-europe-world/eu-solidarity-ukraine/eu-sanctions-against-russia-following-invasion-ukraine_en

[4] The percentage change refers to the period 24 February to 12 April.

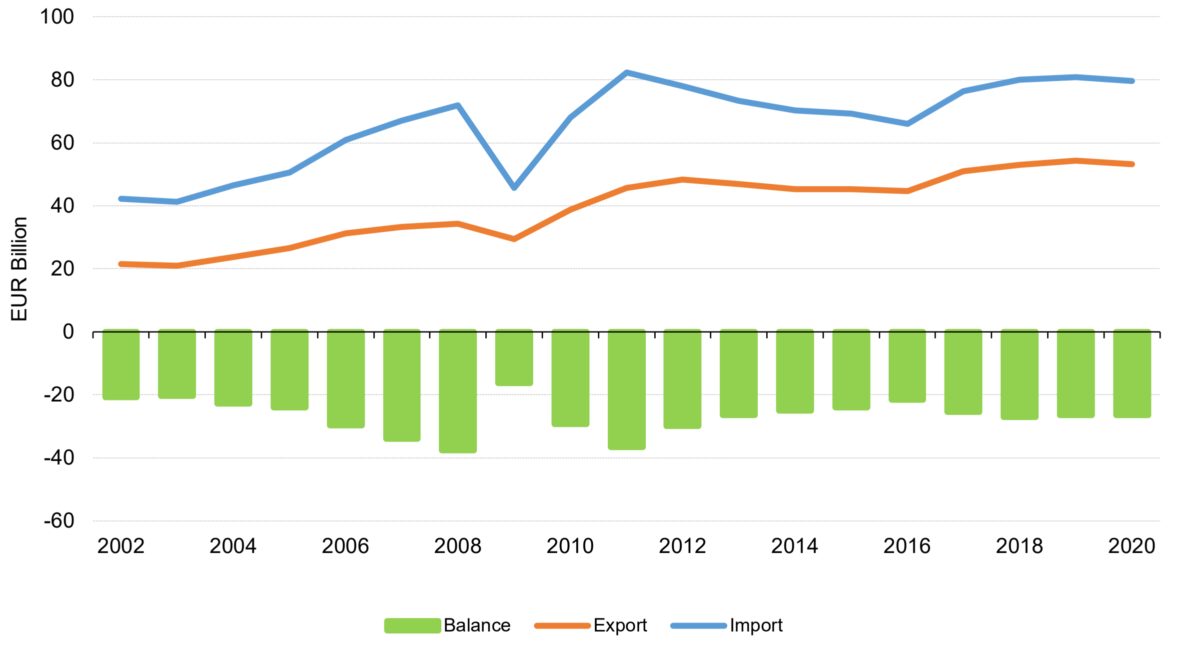
[5] Nickel trades at the London Metal Exchange had to be suspended for the first time in history due to extreme price volatility, after a record 250 % price increase in just one day on 8 March 2022.

EU import dependency in numbers and the role of Russia

The EU is heavily reliant on imports to meet its raw materials needs. According to Eurostat, in 2020 the EU exported EUR 53.2 billion and imported EUR 79.6 billion's worth of raw materials[6], marking a EUR 26.6 billion deficit in its raw materials trade balance. Notably, after a period of decline in the five years leading to 2016, when it reached EUR 21.5 billion, the deficit has since been increasing (see Figure 1).

Among different commodities, EU import dependency is particularly high for materials within the metal, minerals and rubber product category, which accounted for 51 % of the entire value of raw material imports (EUR 40.5 billion) and 82 % of the raw materials trade deficit (EUR 21.8 billion) in 2020. Falling within this category are materials of strategic importance for the EU green and digital technological transition. For instance, lithium, cobalt and nickel are extensively used in lithium-ion batteries, which are crucial components of electric vehicles. Platinum, palladium and iridium are used in fuel cells and electrolysers, essential technologies in the hydrogen economy. Rare earth elements are used for permanent magnets, fundamental for electric vehicle traction motors and wind turbine generators. Renewable energy technologies, like wind turbines and solar panels, also make large use of materials such as aluminium, copper and silicon metals, among others.

Figure 1. EU trade in raw materials, 2002-2020



Source: Eurostat (2022a).

[6] The figures provided on raw materials include non-manufactured goods like oilseeds, cork, wood, pulp, textile fibres, ores and other minerals as well as animal and vegetable oils. They do not include energy products (Eurostat, 2022a).

As shown in Figures 2 and 3, Russia is among the larger suppliers of raw materials to the EU, with EU net imports from it significantly increasing over the last few years. Although the country receives much attention for its predominant role in the global oil and gas market, it is also a key world supplier of metals and mineral ores. Russia is in fact among the largest world suppliers of palladium (40 % of world supply), the second largest for platinum (13 %) and nickel (12 %), and a key supplier of aluminium and copper, among others. Moreover, due to vast (but still largely unexploited) reserves of rare earth elements (USGS, 2022), the country holds the potential become a key player in the rare earths market in the future (Cherepovitsyn & Solovyova, 2022).

Figure 2. EU main trade partners in raw materials by import share in monetary terms, 2020

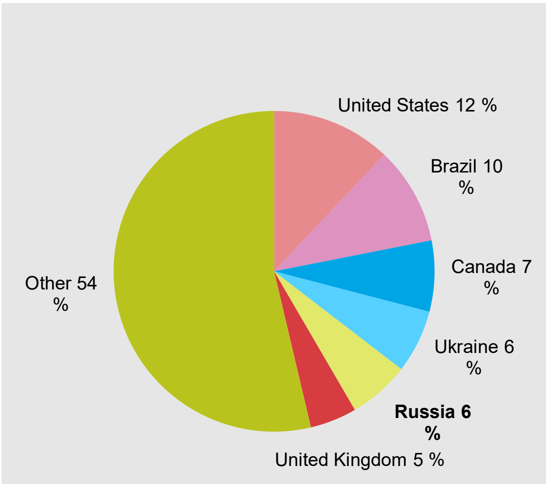
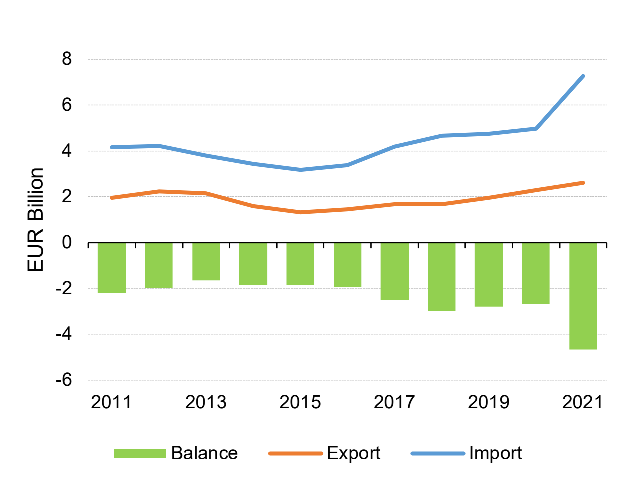


Figure 3. EU trade of raw materials with Russia, 2011-2021



Source: Eurostat (2022a; 2022b).

In more detail, Table 1 shows the EU's import reliance and the Russian share of EU sourcing[7] for a selection of materials required for five prime decarbonisation technologies: lithium-ion batteries, wind turbines, solar PV, fuel cells and traction motors[8]. As shown in the table, among others Russia accounts for a sizeable share of EU sourcing of aluminium (17 %) and nickel (17 %), for which it represents the largest EU supplier, as well as molybdenum (9 %) and copper (7 %). Moreover, Russia covers a significant share of EU sourcing for a number of CRMs, including palladium (41 %), platinum (16 %), cobalt (5 %) and lithium (4 %).

[7] EU sourcing is defined as the sum of domestic production and imports (European Commission, 2020b).

[8] These are among the key technologies identified by the European Commission (2020a).

Table 1. EU import reliance for key materials and the Russian share of EU sourcing

Material	EU import reliance (%)	Russian share of EU sourcing (%)		Technologies				
		Stage 1	Stage 2	Lithium-ion batteries	Fuel cells	Wind turbines	Solar PV	Traction motors
Aluminium	59	-	17	✓		✓	✓	✓
Borate*	100	-	1			✓	✓	✓
Cadmium	0	-	4				✓	
Chromium	66	-	5			✓		✓
Cobalt*	86	5	2	✓	✓			
Copper	44	-	7	✓	✓	✓	✓	✓
Dysprosium	100	5	-			✓		✓
Gallium*	31	-	1				✓	
Germanium*	31	-	10				✓	
Indium*	0	-	1				✓	
Iron ore	72	5	2			✓	✓	✓
Lithium*	100	-	4	✓				
Manganese	90	-	1	✓		✓		
Magnesium*	100	-	1					
Molybdenum	100	-	9			✓	✓	✓
Natural graphite*	98	2	-	✓	✓			
Neodymium*	100	-	-			✓		✓
Nickel	28	-	17	✓	✓		✓	
Niobium*	100	-	1	✓		✓		
Palladium*	93	**41	-		✓			
Platinum*	98	-	**16		✓			
Praseodymium*	100	-	-			✓		✓
Selenium	9	-	6				✓	
Silicon metal*	63	-	4	✓			✓	✓
Tellurium	0	-	5				✓	
Terbium*	100	-	-				✓	
Titanium*	100	-	1	✓	✓			

Sources: European Commission (2020a; 2020b); **own calculations based on World Integrated Trade Solution (n.d./a; n.d./b).
Notes: import reliance is calculated as the ratio between net imports (imports minus exports) and EU sourcing (for net exports, import reliance is equal to zero); EU sourcing is calculated as the sum of domestic production and imports; Stage 1 and 2 refer to the life-cycle stages of the material (ore supply (stage 1) and refined material supply (stage 2)); *CRMs.

Reducing dependency through the circular economy and recycling

As shown above, the EU exhibits high levels of dependency for various materials required for major decarbonisation technologies, while demand for these materials is expected to increase in the future to meet ambitious climate-neutrality objectives by 2050. In light of this challenge, developing recycling capacities in Europe for components and materials used in decarbonisation technologies is considered to be among the main solutions for mitigating EU import dependency.

In this section, we develop different scenarios for the years 2030 and 2040 for three case studies on decarbonisation technologies, namely lithium-ion batteries for electric mobility, wind turbines and fuel cells. We assess the amount of material that could potentially be recovered through the development of recycling capacities in Europe for these technologies. Then, by comparing these figures with estimates of the material demand originating from the same technologies in 2030 and 2040, we approximate the share of future demand that might be covered by recycling. The scenarios are based on two variables – collection rates and recycling efficiency rates – and on a set of assumptions about the material requirements and future market growth of technologies. More information about the methodology and sources is presented in the Appendix.

Lithium-ion batteries for electric mobility

Production of lithium-ion batteries (LIBs) is expected to grow significantly in the coming years, mainly driven by the rapid expansion of the electric vehicle (EV) market. As a result, the demand for necessary materials used in LIB production, such as lithium, nickel and cobalt, is expected to substantially increase as well. Although available projections for the future development of the European EV fleet can differ quite widely[9], they generally show a growth trajectory, with annual sales rapidly rising until the late 2030s or early 2040s, and slowing down afterwards. Such a market trend will inevitably lead to a large number of batteries being available for recycling at some point in time. Still, given the swift increase in battery production it will only be possible to cover a relatively low share of material demand through recycling in the early years of market development, even assuming relatively high collection and recycling efficiency rates. However, the share will likely be higher starting approximately in 2040, when the growth of material demand is expected to slow down due to a decrease in the growth of the EV market.

The scenarios presented in Table 2 largely reflect the above considerations. Assuming an average EV lifetime of 10 years[10] and an EV market trend based on an average of estimates available in the literature[11], the amount of material potentially recovered through recycling in 2030 ranges between 9 and 24 % of the requirements for LIB production that year, depending on the specific material and the scenario considered. In 2040, the bandwidths span from 25 to 52 %. The shares in the most ambitious scenarios are generally twice as high as the lower ones, with the variation mostly caused by the difference in collection rate assumptions between the two scenarios (50 % in scenario 1 vs 90 % in scenario 2). Among the materials assessed, lower shares are reported for nickel due to the assumption of increasing use per battery unit over time[12]. On the other hand, higher figures for aluminium and copper reflect decreasing consumption in the future due to technology evolution, while lithium use is expected to remain relatively stable. All results are reported in Table 2.

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[9] EV sales in the EU are expected to increase from the current 1.3 million units per year (European Environmental Agency, 2021) to between 6.5 million (Wood Mackenzie, n.d.) and 11.9 million (IEA, 2021) units per year in 2040.

[10] According to Abdelbaky et al. (2021), two thirds of the LIBs are modelled to end their lifetime within that of the EV in which they are incorporated, which ranges between 10 and 15 years. Recent estimates of the lifetime of EV batteries are between 8 (Drabik & Rizos, 2018) and 12 (Ellingsen et al., 2016) years. For more details on the methodology employed, see the Appendix.

[11] In order to develop the scenarios, we assume annual EV sales to increase from the current 1.3 million units per year (European Environmental Agency, 2021) to 5.4 million in 2030 and 9.4 million in 2040 (own calculations based on Wood Mackenzie, n.d. and IEA, 2021).

[12] According to the NCX scenario of Xu et al. (2020), the average nickel content in LIBs is expected to increase from 27 kg per LIB in 2020 to 41 kg in 2040.

Table 2. Potential for covering material demand for EV lithium-ion batteries through recycling

	2030				2040			
	Material recovered (thousand tonnes)		Demand covered by recycling (%)		Material recovered (thousand tonnes)		Demand covered by recycling (%)	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2
Lithium*	4	9	11	21	18	36	26	52
Nickel	16	31	7	14	94	189	25	49
Cobalt*	4	8	9	18	21	43	29	58
Aluminium	53	107	12	24	197	395	26	52
Copper	29	58	11	22	113	228	25	50

Source: own calculations.
Notes: for the methodology and the assumptions, see the Appendix; *CRM.

Wind turbines

The growth of wind power capacity in Europe has been rather constant over recent years, with the quantity of annual new installations rising by 35 % between 2012 and 2021[13]. But even if relatively constant growth is maintained in the future, the share of demand in 2030 and 2040 covered by recycled materials from end-of-life wind turbines is unlikely to be very high. This is due to the long lifetime of the technology (over 20 years), which will lead to a small number of wind turbines reaching the end-of-life stage compared with projected demand. It should be noted, though, that moving beyond 2040 with more wind turbines reaching the end-of-life stage, higher quantities of materials would be available for recycling.

The scenarios presented in Table 3 show the quantity of selected materials that could potentially be recovered from the recycling of wind turbines reaching their end of life in 2030 and 2040, compared with the estimated material demand from wind turbine production of the same years. The scenarios are built on the assumption that onshore wind turbines have a lifetime of 25 years and employ a gearbox type of generator, whereas offshore turbines last for 30 years and use a direct drive type of generator[14]. The results indicate that the share of material demand covered through recycling ranges from 3 to 25 % in 2030 (depending on the material and scenario considered), with only a marginal increase in 2040 (7 to 27 %), due to the gradual growth in production. Notably, shares vary quite significantly among materials, with copper and rare earth elements (neodymium, dysprosium and praseodymium) presenting the lowest shares. As explained above, this is the result of relatively faster growth of offshore wind power capacity with respect to onshore wind, which requires the largest amount of such materials.

[13] According to WindEurope (2022), total annual new installations in Europe grew from 12.9 GW in 2012 to 17.4 GW in 2021. Over the same period new offshore ones almost tripled, moving from 1.2 GW to 3.3 GW.

[14] For more details on the material intensity of each type of technology, see the Appendix.

Table 3. Potential for covering material demand for wind turbines through recycling

	2030				2040			
	Material recovered (thousand tonnes)		Demand covered by recycling (%)		Material recovered (thousand tonnes)		Demand covered by recycling (%)	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2
Aluminium	5	10	13	25	9	16	15	27
Copper	3	6	6	10	6	11	4	14
Nickel	1	3	12	22	2	4	11	24
Molybdenum	0.4	0.8	11	20	0.7	1.3	10	22
Praseodymium*	0.01	0.03	3	5	0.04	0.07	7	9
Dysprosium*	0.02	0.04	6	11	0.04	0.1	13	15
Neodymium*	0.2	0.3	5	10	0.3	0.6	12	13

Source: own calculations.
Notes: for the methodology and the assumptions, see the Appendix; *CRM.

Fuel cells for electric mobility

Although their market share is still very limited, fuel cell electric vehicles (FCEVs) are expected to play a relevant role in future transport decarbonisation, and their market penetration is expected to increase in the medium to long term. In fact, although only about 2300 new FCEVs were registered in 2020, according to the European Commission (2020a) the overall FCEV fleet is expected to reach 20 million units in 2040 in a medium-demand scenario, and well over 40 million in a high-demand scenario. Irrespective of the actual trajectory, the expected growth leads to concerns about the availability of several raw materials used for fuel cell production, primarily platinum (Hydrogen Council, 2021).

Table 4 presents the scenarios on platinum recovered from end-of-life FCEVs in 2030 and 2040, as well as the relative share of platinum demand for FCEV production covered by recycled material. In order to build the scenarios, we assumed that FCEV market growth will follow the mid-demand scenario of the European Commission (2020a), with a constant annual growth rate of 48 % from now until 2040. Also, based on a number of sources, we assumed the amount of platinum used in fuel cells for electric mobility to decrease from the current 30 grams to 5 grams in 2040. Finally, we assumed FCEVs to have an average lifetime of 10 years. As a result, according to our scenarios no significant platinum will likely be recovered from end-of-life FCEVs in 2030, irrespective of the collection and recycling rates assumed, as only a very limited number of vehicles will have reached the end-of-life stage by that year. What is more, since the estimated market size in 2030 will be more than 50 times larger than 2020 levels, the share of material demand covered by recycling will be very low (less than 1 % in both scenarios). Yet, as the market penetration of FCEVs is expected to increase much faster from the early 2030s onwards, a larger amount of platinum will be available for recycling in 2040 and beyond. Indeed, in 2040 our estimates report the share of platinum demand covered by recycling to range between 6 % (scenario 1) and 11 % (scenario 2).

Table 4. Potential for covering material demand for fuel cells for FCEVs through recycling

	2030				2040			
	Material recovered (tonnes)		Demand covered by recycling (%)		Material recovered (tonnes)		Demand covered by recycling (%)	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2
Platinum*	0.029	0.06	0.35	0.59	1.6	3.15	5	11

Source: own calculations.
Notes: for the methodology and the assumptions, see the Appendix; *CRM.

Outlook

The EU's efforts to transform its industrial landscape at the speed required for meeting EU climate-neutrality objectives are interwoven with access to critical materials. While the EU has adopted dedicated strategies and actions to reduce its dependency on imports of these materials, Russia's invasion of Ukraine brings forward new challenges to consider in the global race for resources. Russia is an important EU supplier of a number of necessary materials, like aluminium, nickel and copper. It is also a source of CRMs, such as palladium, platinum, cobalt and lithium. With the unfolding economic sanctions and ongoing efforts to cut economic ties with Russia, options for further diversifying sources of these materials will need to be identified.

Building recycling capacities in the EU for materials required by decarbonisation technologies, including from existing product stocks[15], can not only contribute to meeting future EU material demands but also to mitigating our import dependency on other countries, including Russia. Our analysis provides some insights in this regard. For LIBs for electric mobility, for example, recycling end-of-life batteries could – under an ambitious scenario – help meet 21 % of the 2030 demand for lithium for new battery production, 18 % of cobalt and 14 % of nickel (for which Russia accounts for the largest share of EU sourcing). Moving towards 2040, these figures could be higher with more batteries reaching the end-of-life stage and providing higher quantities of materials available for recycling: 52 % for lithium, 49 % for nickel and 58 % for cobalt in the most optimistic scenarios. An important driver of the difference in the figures between the two scenarios is the collection rate for recycling these batteries in the EU (50 % in scenario 1 vs 90 % in scenario 2).

For wind turbines, under an ambitious scenario – that is, assuming fairly high recycling efficiencies and collection rates for recycling in the EU – recycling could help meet 25 % of 2030 aluminium requirements and 22 % of nickel for new turbines. In 2040, the figures would see a small increase: up to 27 % for aluminium and up to 24 % for nickel. Given that wind turbines

[15] For example, a study by Rizos et al. (2019) has calculated that in the EU there is a stock of about 700 million mobile phone devices containing materials such as cobalt, lithium, palladium and copper, which have not been collected for recycling.

have a long life span (over 20 years), beyond 2040 the number of wind turbines installed in previous decades and reaching the end-of-life stage will grow, providing further opportunities for recovering materials. For EV fuel cells and material requirements for platinum (a CRM), the benefits of recycling end-of-life vehicles would be visible in the longer term (11 % of 2040 material demands) since market penetration of these vehicles is expected to increase from 2030 onwards.

Overall, the above estimates indicate that accelerating the establishment of collection and recycling facilities in the EU for the above technologies, through the appropriate policy frameworks in place, can support the EU's strategic autonomy objectives and reduce import dependency on non-EU countries. The EU should therefore intensify its efforts to expand its recycling capacities and further utilise available opportunities for such investments through the Next Generation EU instrument and the ongoing recovery process.

Still, the above figures indicate that efforts in the recycling domain alone will only be able to cover a share of the growing material demands by low-carbon technologies. In addition, the EU will need to seek ways to diversify its supplies as it cuts economic ties with Russia. Other options will need to be considered, including sourcing from its own mining reserves, seeking improvements in material efficiency and fostering material substitution options where possible. Developing strategic partnerships and joint projects with resource-rich countries, such as the partnership with Ukraine established before the war, can also help secure access to non-energy minerals.

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Appendix. Supplementary data and methodological information

Methodology

The scenarios presented in this Policy Insight are built upon a set of variables and assumptions. The variables employed, which determine the difference in outcome between more and less optimistic scenarios, are collection rates and recycling efficiency rates. The collection rate may be defined as the share of units of a product (e.g. electric vehicles) that, after reaching the end-of-life stage, are collected with the intent of being recycled in the EU. Recycling efficiency rates refer to the share of material that is physically recovered through the recycling process out of the total amount of end-of-life material that enters the recycling process.

For each technology, the most optimistic collection-rate scenario (scenario 2) was based on information currently available in the literature. A more pessimistic collection rate for each technology was then determined by subtracting 40 % from the more optimistic one. Similarly, two recycling efficiency rates were considered for each material. In particular, recycling efficiency rates referring to best practices found in the literature were assumed for scenario 2, and lower recycling efficiency rates for the pessimistic scenarios were determined by subtracting 10 % from the best-practice rates. All collection and recycling efficiency rates are reported in Table A1.

Several assumptions on the technologies analysed were also used to construct the scenarios. Such assumptions were based on information and forecasts retrieved from a number of sources and allowed estimation of the quantity of material reaching the end of life in 2030 and 2040 for each technology assessed. Such assumptions referred to a) the material content, b) the lifetime and c) the current and future market size of each technology. In the case the electric vehicles, due to highly divergent projections on the future market size found in the literature, our own estimates based on an average of such projections were considered for the 2040 scenarios (Table A2).

Table A 1. Scenario variables

	Scenario 1	Scenario 2	Source (Scenario 2)
Collection rates (%)			
Electric vehicles	50	90	Abdelbaky et al. (2020)
Wind turbines	60	100	Ciacci et al. (2019)
FC electric vehicles	50	90	Reverdiau et al. (2021)
Recycling efficiency rates (%)			
Aluminium	88	98	OEA (n.d.)
Cobalt	89	99	Lebedeva et al. (2016)
Copper	85	95	Wang et al. (2021)
Dysprosium	88	98	Jönsson et al. (2020)
Lithium	89	99	Lebedeva et. al (2016)
Molybdenum	89	99	Wu et al. (2020)
Neodymium	88	98	Jönsson et al. (2020)
Nickel	87	97	Lebedeva et. al (2016)
Platinum	85	95	Reverdiau et al. (2021)
Praseodymium	88	98	Jönsson et al. (2020)

Table A 2. Scenario assumptions

		Assumption	Source
Lithium-ion batteries			
Lifetime of EVs		10 years	Abdelbaky et al. (2021); Drabik and Rizos, (2018); Ellingsen et al. (2016)
EU EV sales		2020: 1 365 000	European Environmental Agency (2021)
		2030: 5 421 000 2040: 9 385 000	Own calculation based on Wood Mackenzie (n.d.) and IEA (2021)
Material content per EV (kg)			
	Lithium	2020: 7.3 2030: 7.4 2040: 7.3	Own calculations based on Xu et al. (2021)
	Nickel	2020: 26.9 2030: 39.9 2040: 40.7	
	Cobalt	2020: 7.2 2030: 8.8 2040: 7.8	
	Aluminium	2020: 91.2 2030: 82.7 2040: 81.8	
	Copper	2020: 51.4 2030: 49.1 2040: 48.9	
Collection rates		Scenario 1: 50 % Scenario 2: 90 %	Abdelbaky et al. (2020)
Wind turbines			
Lifetime of wind turbines		Onshore: 25 years Offshore: 30 years	European Commission (2020a)
Wind turbines, annual new installations (GW)			
	Onshore	2005: 6.5 2010: 9 2015: 9.8 2030: 22 2040: 31	WindEurope (2017) for 2000-2015 values; Carrara et al. (2020) for 2030-2040 values (medium demand scenario)
	Offshore	2000: 0 2005: 0.1 2010: 0.9 2015: 3 2030: 12 2040: 18	
Material content per GW (t/GW)			
	Aluminium	Onshore: 1 600 Offshore: 500	Carrara et al. (2020) (DD-PMSG turbines offshore, GB-PMSG turbines onshore)
	Chromium	Onshore: 580 Offshore: 525	
	Copper	Onshore: 950 Offshore: 3 000	

Dysprosium	Onshore: 6 Offshore: 17	
Molybdenum	Onshore: 119 Offshore: 109	
Neodymium	Onshore: 51 Offshore: 180	
Nickel	Onshore: 440 Offshore: 240	
Praseodymium	Onshore: 4 Offshore: 35	
Fuel cells		
Lifetime of FCEVs	10 years	Jahromi and Heidary (2021)
FCEV sales	2020: 2 300 2030: 123 000 2040: 6 567 000	Fuel Cells and Hydrogen Observatory (n.d.) Own calculations based on European Commission (2020a)
Material content per FCEV (g)		
Platinum	2020: 30 2030: 18 2040: 5	Hughes et al. (2021) Own calculations based on Hughes et al. (2021) and Harvey (2018) Harvey (2018)

Additional material consumption for technologies

Tables A3 to A5 present our estimates of material demands for the clean technologies assessed in the years 2030 and 2040. These estimates take into account market growth of the assessed technologies and changes in their material intensity (see also the figures and sources in Table A2).

Table A 3. Material demand for lithium-ion batteries for electric mobility (thousand tonnes)

	2030	2040
Lithium	40	69
Nickel	216	382
Cobalt	48	73
Aluminium	448	767
Copper	266	459

Table A4. Material demand for wind turbines (thousand tonnes)

	2030	2040
Aluminium	41	59
Copper	57	84
Dysprosium	0.1	0.3
Molybdenum	1.3	3.9
Neodymium	0.6	3.3
Nickel	4	13
Praseodymium	0.07	0.5

Table A5. Material demand for fuel cells for electric mobility (tonnes)

	2030	2040
Platinum	2.2	33.8

Limitations

This study aims to give an indication of the scale of potential benefits in reducing EU import dependency for the key materials required for decarbonisation technologies through circularity/recycling approaches, yet has some limitations. A first limitation is the recycling efficiency rates. Specifically, due to the availability of data it was not possible to differentiate the recycling efficiency rates by product group; instead, we employed rates that were material-specific. Moreover, results based on available estimates for 2030 and 2040 should be treated with caution, since future advances in collection processes and recycling technologies were not taken into account.