ISSN 1831-9424

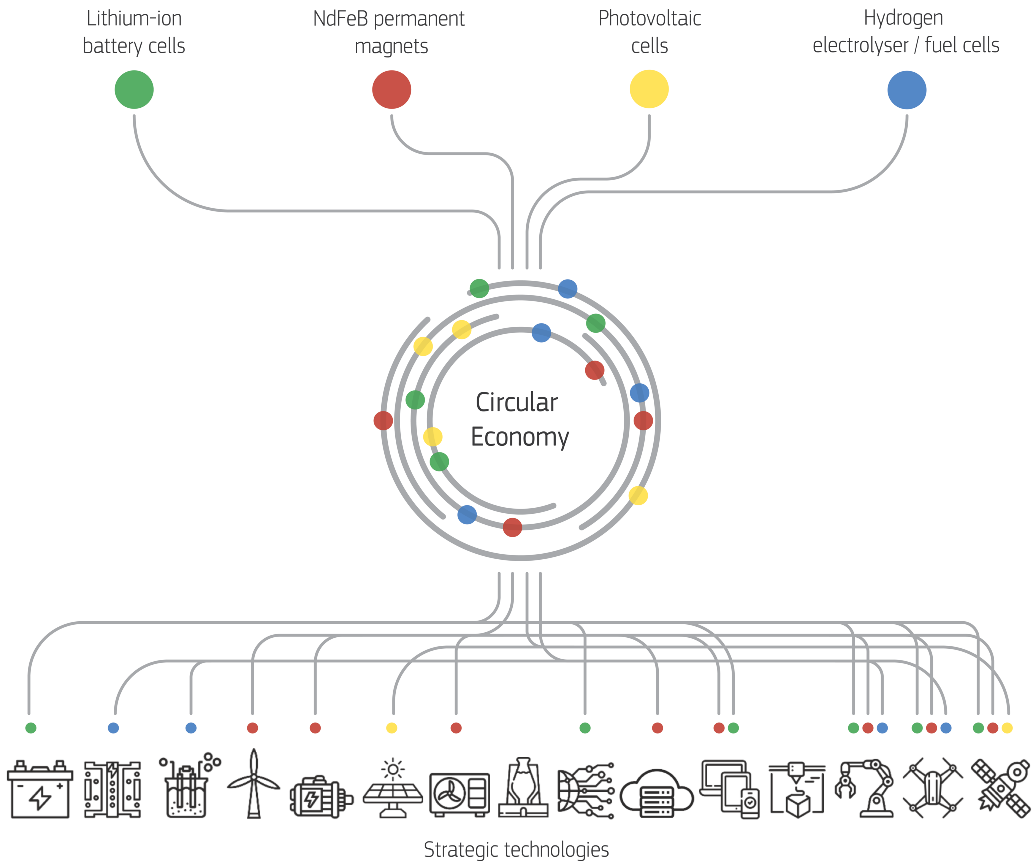
European Commission

JRC SCIENCE FOR POLICY REPORT

Analysis of Circular Economy Research and Innovation (R&I) intensity for critical products in the supply chains of strategic technologies

Baldassarre, B., Buesa, A., Albizzati, P. F., Jakimów, M., Saveyn, H. G. M., Carrara, S.

2023



Joint Research Centre

EUR 31657 EN

Contact information
Name: Brian Baldassarre
Email: Brian.Baldassarre@ec.europa.eu

EU Science Hub
https://joint-research-centre.ec.europa.eu

JRC134253

EUR 31657 EN

PDF ISBN 978-92-68-07529-6 ISSN 1831-9424 doi:10.2760/582527 KJ-NA-31-657-EN-N

Luxembourg: Publications Office of the European Union, 2023

How to cite this report: Baldassarre, B., Buesa, A., Albizzati, P. F., Jakimów, M., Saveyn, H. G. M., Carrara, S., *Analysis of Circular Economy Research and Innovation (R&I) intensity for critical products in the supply chains of strategic technologies*, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/582527, JRC134253.

Contents

Abstract

To develop renewable energy, digital, space and defence technologies, the European Union (EU) needs access to critical raw materials of which a large share is currently imported from third countries. To mitigate the risk of supply disruptions, the Critical Raw Materials Act proposes to diversify sources of imports, while increasing domestic extraction, processing, and recycling. The circular economy is therefore positioned as a key element of the EU strategy to deploy strategic technologies for navigating the sustainability transition in a complex geopolitical landscape. In line with this position, the present study analyses the intensity of circular economy research and innovation (R&I) in the supply chains of strategic technologies. The focus is placed on four critical products containing raw materials having high supply risks: lithium-ion battery cells; neodymium-iron-boron permanent magnets; photovoltaic cells; hydrogen electrolysers and fuel-cells. The R&I analysis is based on the identification of scientific articles, patents, and innovation projects on the subject, with a global scope, in the period between 2014 and 2022. The analysis is enriched by connecting to parallel work on the subject, conducted by Joint Research Centre (JRC) as well as academic institutions, industry, and policy stakeholders. This is functional to provide insight into: where circularity efforts R&I have been placed in terms of different products and supply chains; which countries are undertaking these efforts; how the EU is positioned and how much funding was deployed so far; what are the current gaps and trends going forward. Main insights include the following: 1) circularity R&I for critical products is not balanced, with a prominent focus placed on Li-ion cells on a global level 2) the EU has followed this trend in terms of number of innovation projects and public spending; 3) Next to EU efforts, China and the USA focus intensely on circular economy R&I as well. This study contributes with evidence to advance scientific research and policymaking on the role of a circular economy to achieve open strategic autonomy and climate neutrality in the EU.

Acknowledgements

This report was developed as part of the BounCE4ward project of the Centre for Advanced Studies (CAS) of DG JRC Unit S.4 (Scientific Development Programmes), in collaboration with Unit B.5 (Circular Economy and Sustainable Industry) and Unit C.7 (Energy, Mobility and Climate, Energy Transition Insights for Policy), and in consultation with DG GROW Unit I.1 (Energy Intensive Industries, Raw Materials, Hydrogen).

The authors of the report would like to thank colleagues from DG GROW, especially Constanze Veeh and Milan Grohol for their valuable inputs and discussions during the preparation of this report; Silvia Bobba, Fabrice Mathieux and colleagues from DG JRC Unit D.3 (Land Resources and Supply Chain Assessment), for their valuable and constructive inputs to enrich the report content and improve its contextualization within ongoing policy and research developments; Alessandro Cavalli for his ideas and support in the conceptualization and development of the study; the PNO group for technical support in the execution phase.

Authors

Baldassarre, Brian[1]

Buesa, Alejandro[1]

Albizzati, Paola Federica[1]

Jakimów, Małgorzata[1]

Saveyn, Hans[2]

Carrara, Samuel[3]

[1]European Commission, Joint Research Centre, Directorate S – Innovation in Science and Policymaking, Scientific Development Programmes unit (S.4)

[2]European Commission, Joint Research Centre, Directorate B – Fair and Sustainable Economy, Circular Economy and Sustainable Industry unit (B.5)

[3]European Commission, Joint Research Centre, Directorate C – Energy, Mobility and Climate, Energy Transition Insights for Policy unit (C.7)

Executive summary

Policy context

To develop renewable energy, digital, space and defence technologies, the European Union (EU) needs access to critical raw materials. Yet, a large share of these materials is currently imported from third countries.

To mitigate the risk of supply disruptions, the Critical Raw Materials Act (European Commission, 2023a), proposes to set the following benchmarks to be achieved by 2030 along the strategic raw materials supply chain:

- At least 10% of the EU’s annual consumption for extraction
- At least 40% of the EU’s annual consumption for processing
- At least 15% of the EU’s annual consumption for recycling
- No more than 65% of the EU’s annual consumption from a single third country

The proposal is supported by a study performed by DG GROW on critical raw materials (European Commission, 2023b), and by a DG JRC foresight study assessing supply chain dependencies and forecasting material demand until 2050 in the EU (Carrara et al., 2023).

In the context of the Critical Raw Materials Act – calling for increased recycling – the circular economy (i.e., reducing, reusing, and recycling) is positioned as a key element to achieve open strategic autonomy and climate neutrality in the EU.

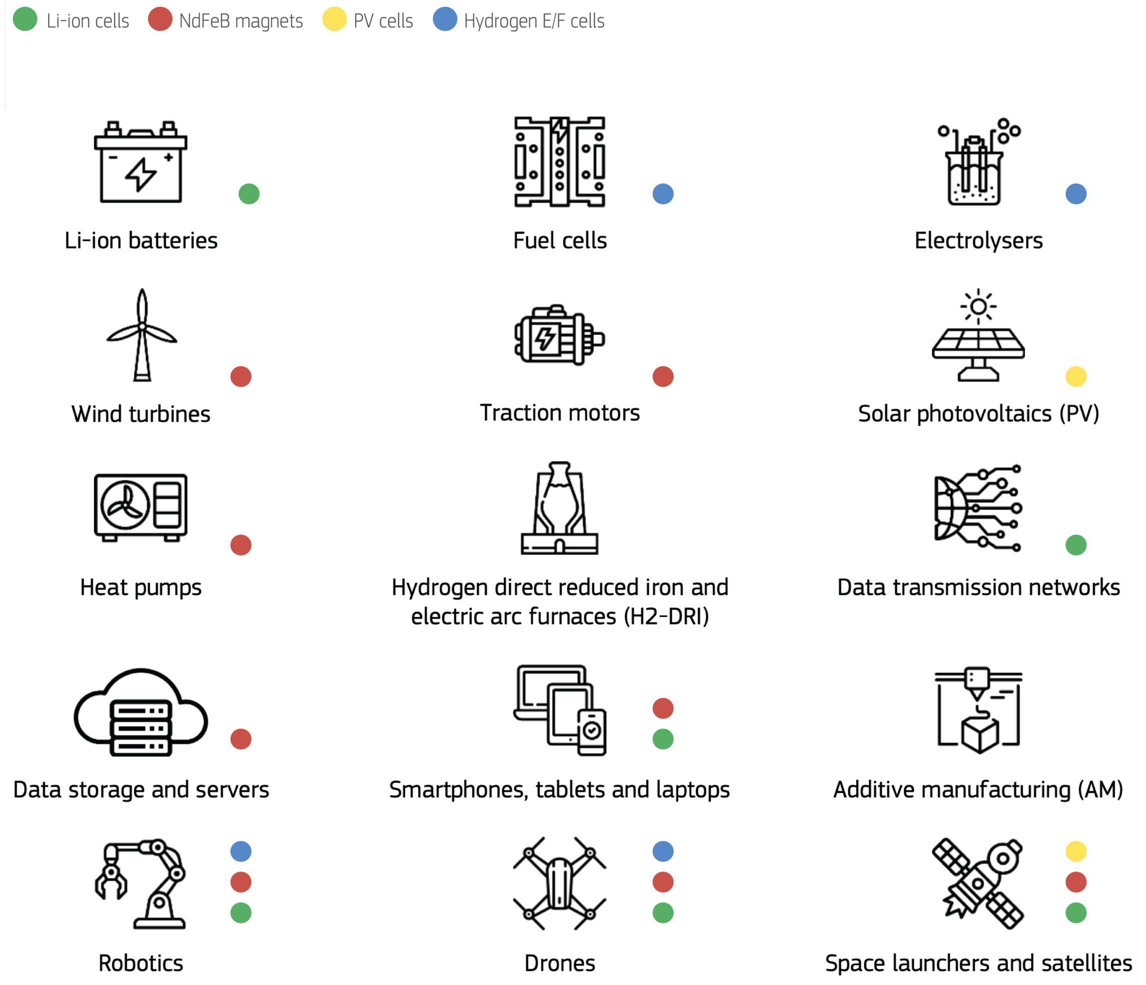
In line with this position and building on former work performed by DG GROW and DG JRC, the present study encompasses an analysis of the circular economy research and innovation (R&I) intensity in the supply chains of strategic technologies.

Circular economy R&I intensity for critical products in the supply chains of strategic technologies

The foresight study of Carrara et al. (2023) assesses potential vulnerabilities and dependencies, and develops forecast scenarios, in the supply chains of fifteen strategic technologies: lithium-ion batteries; fuel cells; electrolysers; wind turbines; traction motors; solar photovoltaics (PV); heat pumps; hydrogen direct reduced iron and electric arc furnaces (H2-DRI); data transmission networks; data storage and servers; smartphones, tablets and laptops; additive manufacturing; robotics; drones; space launchers and satellites. The foresight study is complemented by the current analysis, which is focused on circular economy.

The analysis of the circular economy R&I intensity carried out in this study focuses on four critical products (i.e., components or assemblies), namely: lithium-ion battery cells (Li-ion cells); neodymium-iron-boron permanent magnets (NdFeB magnets); crystalline silicon and compound photovoltaic cells (PV cells); solid-oxide, proton-exchange-membrane, and alkali electrolysers and fuel-cells for hydrogen production and use (Hydrogen E/F cells). These products are selected because they are characterized by high supply risk and are relevant in terms of circularity potential, according to expert judgment and former JRC assessments (Carrara et al., 2023). Further, the abovementioned products are needed to manufacture several of the strategic technologies, as identified in the same report (Carrara et al., 2023). A visualisation of where the four products can be found within the fifteen strategic technologies is presented in Figure I.

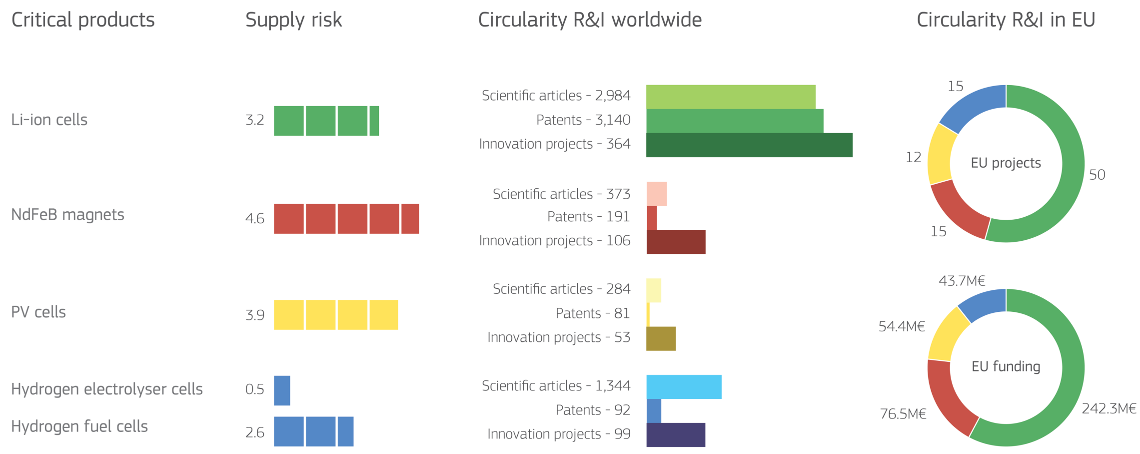
Figure I. Critical products in strategic technologies covered by this study.



Source: JRC analysis; elaboration based on flaticon.com. Strategic technologies list from Carrara et al. (2023).

To gain insight into the circular economy R&I intensity for critical products, the cumulative number of scientific articles, innovation projects and patents is used as a proxy (Czarnitziki et al., 2014; de Rassenfosse & van Pottelsberghe de la Potterie, 2009). To this end, a keyword search was set up to retrieve relevant documents across multiple databases, with a global geographical scope, for the period 2014-2022. Data in the last 3 years of the time series, however, might be affected by delays in database updates and by the COVID-19 crisis, a phenomenon beyond the scope of this analysis. Furthermore, despite the search for innovation projects had a global scope as well, data was in this case only retrieved for the EU, individual Member States, the United Kingdom, Switzerland, Norway, the United States (USA), Canada and Australia. The results of the analysis indicate that, on a global level, circular economy R&I intensity is high for Li-ion cells, medium for NdFeB magnets and Hydrogen E/F cells, and low for PV cells. Even though Li-ion cells are not characterized by the highest supply risk, the number of scientific articles, patents and innovation projects related to their circularity is significantly higher compared to the other products. Mirroring the global situation, between 2014 and 2022, the EU has funded 50 innovation projects focusing on Li-ion cell circularity, for a total amount of EUR 243.3 million. The number of projects and the amount of funding deployed for circularity R&I upon NdFeB magnets, PV cells, and Hydrogen E/F cells is three to five times lower, despite the material demand to manufacture these products is expected to grow in parallel with the demand for Li-ion cells. Figure II visually summarises the high-level results of the analysis.

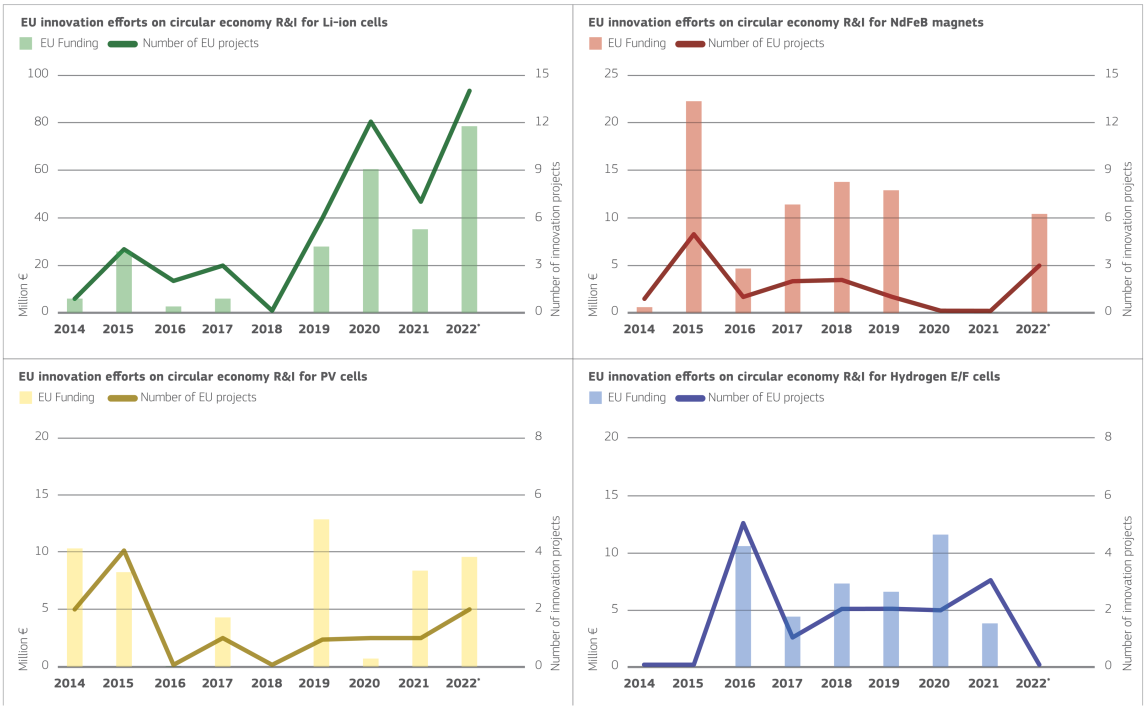
Figure II. Summary of the analysis on circular economy R&I for critical products in strategic technologies.



Source: JRC analysis. Supply risk is based on Carrara et al. (2023).

Focusing on the circular economy R&I efforts in the EU, the number of innovation projects and funding related to Li-ion cells presents an increasing trend as shown in Figure III, while the same cannot be observed for NdFeB magnets, PV cells, and Hydrogen E/F cells. This might be problematic, in view of the ambitions and targets set by REPowerEU (European Commission, 2022d, 2022e), the EU strategy on offshore renewable energy (European Commission, 2020c), the EU solar energy strategy (European Commission, 2022a), and the EU Hydrogen strategy (European Commission, 2020b). To meet these targets, the circular economy R&I enabling new circular economy policies to increase material efficiency will be essential. In the case of Li-ion batteries, the circular economy R&I intensity seems to be going hand in hand with the maturity of policy developments, as exemplified by the upcoming battery regulation, which includes mandatory collection and recycling targets (European Parliament, 2022).

Figure III. Trends for circular economy R&I intensity in the EU for the four products analysed in the study.



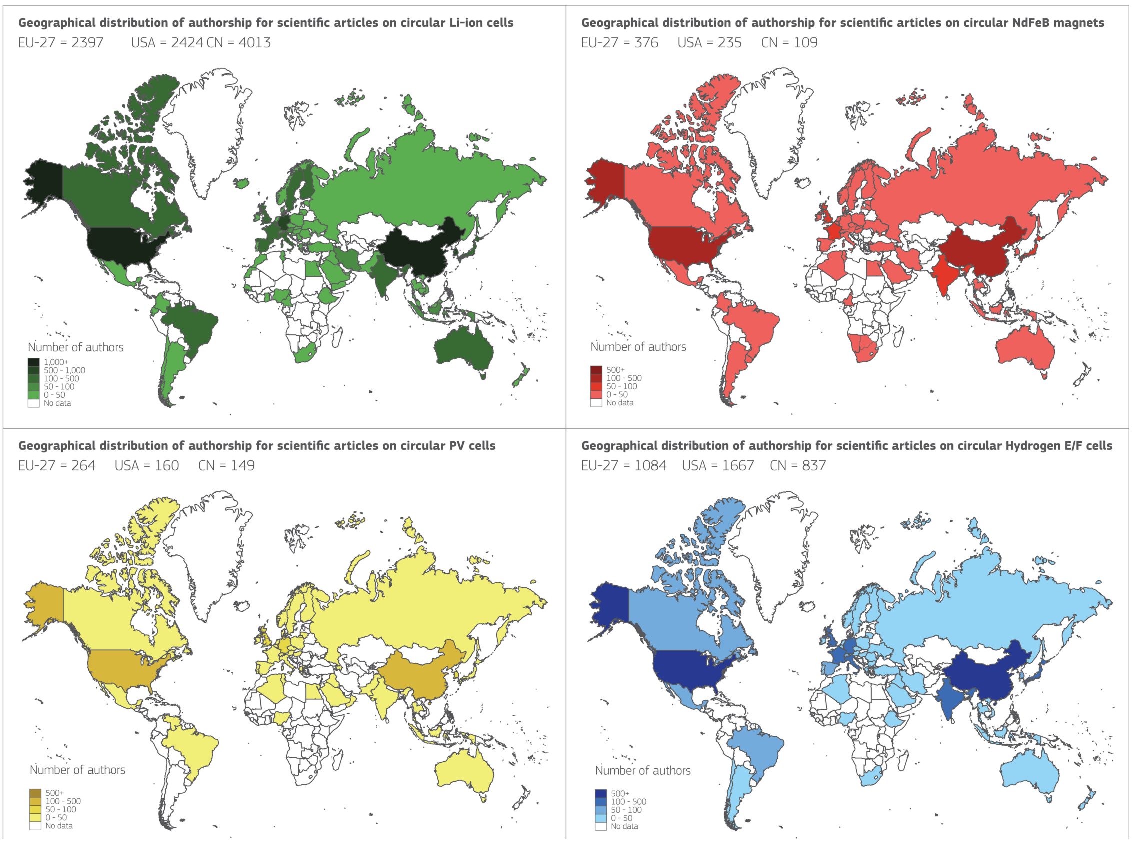
Source: JRC analysis.

However, aside from Li-ion batteries and beyond the recycling policy discussions, few actions have been taken (Baldassarre & Saveyn, 2023; Clean Hydrogen Joint Undertaking, 2022; European Raw Materials Alliance, 2021). Among the actions that have been taken, the EU solar strategy is paving the way, with the upcoming Eco-design requirements for PV panels, which are expected to include durability and information requirements that might play a key role in reducing demand and fostering reparability (European Commission, 2021a, 2022a; Nyffenegger et al., 2023). In the future, it will be important to accelerate both R&I and policymaking in this direction, ensuring the industry alignment and focusing on circularity strategies beyond recycling to reduce primary material demand, by developing circular business models for repairing and remanufacturing of critical products in strategic technologies (Carrara et al., 2023).

In terms of geographical distribution of circular economy R&I efforts, the results of the study are summarized in Figure IV. For all the critical products taken into consideration within this analysis, most scientific articles related to circularity were produced by research institutions based either in the EU, in the USA or in China. Whereas for Li-ion cells circularity research China is clearly in the lead, the EU is slightly ahead of both the USA and China for the other products. The results also reveal greater number of third-country collaborations among the researchers from the EU and the USA than from China. Both the EU and the USA develop collaborations with entities located in Central and South America and the Middle East, and the EU is the preferred partner for

Africa. Conversely, fewer collaborations take place with Asian countries, which attract most of the Chinese collaborations.

Figure IV. Geographical distribution of authorship for scientific articles on circularity of critical products in strategic technologies.



Source: JRC analysis.

Concerning patents, the situation seems quite different. A rapid scan of patent databases shows that China, followed by the Unites States, is strongly in the lead with regards to the production of circularity patents for critical products. Since innovation projects carried out in China fall outside the boundaries of this analysis, a comparison in this sense cannot be made for the time being. However, results also show that the EU has so far supported more projects and invested significantly more public funding than the USA, suggesting that the latter has been more successful in mobilising the private sector, also in view of the higher number of patents.

Main insights

- **First insight:** global circular economy R&I related to strategic technologies has focused primarily on Li-ion cells, with less attention dedicated to other critical products needed for the digital, renewable energy and sustainability transition.
- **Second insight:** the EU has so far invested approximatively three-to-five times more public funding in circularity R&I related to Li-ion cells, in comparison with NdFeB magnets, PV cells, hydrogen electrolysers and fuel cells.
- **Third insight:** next to the EU, China and the USA play a key role in global circular economy R&I efforts related to critical products in strategic technologies, with international collaboration on scientific research being more limited on the Chinese side.

Policy recommendations

- **First policy recommendation:** recalibrating EU focus and future public investments for circularity R&I related to strategic technologies, to target more prominently NdFeB magnets, PV cells and Hydrogen electrolysers and fuel cells, while keeping momentum for Li-ion cells.
- **Second policy recommendation:** Ensuring that the industry stakeholders and emerging alliances working on the R&I of strategic technologies keep circularity aspects in focus, not only for Li-ion cells but for all critical products, especially Hydrogen electrolysers and fuel cells.
- **Third policy recommendation:** ensuring that both public innovation projects and private industry alliances keep a circularity R&I focus beyond recycling, also considering how to reduce primary material demand by developing circular business models for repairing and remanufacturing of critical components in strategic technologies.
- **Fourth policy recommendation:** monitoring circularity R&I efforts in the USA and China, and how they partner in this regard with other countries in East Asia, Middle East, Africa, Central and South America.

Future research

Building upon this study, future research should be carried out to advance policymaking and industry action in this space.

More in-depth analysis into the content of circular R&I outputs (scientific articles, patents and innovation projects) per critical product (Li-ion cells, NdFeB magnets, PV cells and Hydrogen E/F cells) is recommended to gain deeper insight into, for instance, the types of materials in focus and the most promising strategies (reducing vs. reusing vs. recycling) to simultaneously optimize economic and environmental performance. A relevant example in this sense is provided by recent analysis and development of methodological approaches to advance circularity of rare earth elements in e-vehicle motors (e.g., Bobba et al., 2023; Tazi et al., 2023).

Follow up-studies might also focus on deeper supply chain analyses leveraging a multidisciplinary approach (e.g., engineering, industrial design, business and economics, political science) based on a mix of quantitative and qualitative methods, geared towards:

- A detailed mapping of linear and circular processes, business models and stakeholder categories across different stages of the global supply chain.
- Identifying geopolitical, cultural, regulatory, economic, and technical drivers and barriers to circularity in the EU as well as in other countries.
- Integrating qualitative information with quantitative trade flow and micro-economic data to develop future circularity scenarios, assessed in terms of their economic and environmental impacts.

1 Introduction

1.1 Rationale and objective of the analysis

The European Union (EU) faces problematic import dependencies from third countries in terms of critical raw materials and products within and across several strategic supply chains, including those of renewable energy and digital technologies, defence and space applications, and electric mobility amongst others (European Commission, 2021c). For example, the global supply of cobalt – needed to manufacture lithium-ion batteries and, in turn, essential for electrifying mobility and for energy storage – is largely controlled by few non-EU countries (European Commission, 2020f, 2023; European Environment Agency, 2021). The same applies to Neodymium-Iron-Boron permanent magnets, containing rare earth metals needed for wind energy generation and electric mobility. The EU imports 98% of permanent magnets from China alone (European Raw Materials Alliance, 2021).

Since 2011, on a three-year basis, the European Commission (DG GROW) has been publishing a list of Critical Raw Materials (CRMs) which are crucial for the EU economy and industry. The list of CRMs has grown over time, from 14 in 2011 to 34 in 2023, highlighting the growing potential vulnerabilities of the EU industrial ecosystem. In recent years, the perspective has been widened to the whole supply chains, ranging from raw materials to final products. This new approach stems from the consideration that the EU is often dependent on third countries not only for raw materials, but also for intermediate, processed products in many, if not all, of the other parts of the supply chain. This has led to developing a foresight report aimed at exploring the potential vulnerabilities and dependencies and developing future material demand scenarios for strategic technologies and sectors in the EU economy: the first version was published in 2020 (European Commission, 2020d) along with the 2020 CRM study (European Commission, 2020f), while an updated version has recently been published (Carrara et al., 2023), again, jointly, with the latest version of the CRM study (European Commission, 2023b).

In parallel with monitoring, in the most recent years, the need for policy actions has progressively become more and more pressing, especially considering the lessons learnt from the recent disruptions in the global supply chains. These notably refer to the COVID-19 pandemic and the 2022 Russia's aggression on Ukraine, which significantly decreased the imports via the global supply chains from China and Russia, as well as increased challenges on the waste management side. In March 2022, the Versailles declaration (European Council, 2022) called for enhancing the EU defence capabilities, reducing energy dependencies, and building a more robust economic base. The following September, the President of the European Commission, Ursula Von der Leyen, in her State of the European Union Address, announced a forthcoming policy initiative on CRMs. Eventually, the Critical Raw Materials Act was published on 16 March 2023 along with the Net-Zero Industry Act (European Commission, 2023a). The 2023 foresight report and CRM study underpinned this policy initiative by providing scientific evidence on critical raw materials and supply chains. Complementing the CRM list, the CRM Act introduces a list of Strategic Raw Materials, which are crucial for strategic technologies used for the green, digital, defence and space applications.

Among other measures, the CRM Act sets the following benchmarks to be achieved by 2030 along the strategic raw materials supply chain:

- At least 10% of the EU's annual consumption for extraction
- At least 40% of the EU's annual consumption for processing
- At least 15% of the EU's annual consumption for recycling
- No more than 65% of the EU's annual consumption from a single third country

The target on recycling demonstrates that circular economy is at the heart of the CRM Act, which testifies the clear policy relevance of this topic.

In the wake of the CRM Act, this study develops a deep dive into circularity for a set of products identified as crucial in the strategic technologies assessed in the recent foresight report (Carrara et al., 2023). Section 1.2 provides more details on the choice of the focused products, based on the foresight report.

The circular economy is a techno-economic model to use resources more efficiently, while promoting economic resilience and environmental sustainability (Ellen MacArthur Foundation, 2013; European Commission, 2020a). This can be achieved through different strategies, such as sustainable manufacturing, reusing products in line with eco-design practices, and / or by recycling materials. Circular economy strategies (i.e., reducing, reusing, recycling) can be applied to increase resource-efficiency inside the EU, thus reducing imports and mitigating dependencies from overseas, in line with the goals of the CRM act and the New Industrial Strategy (European Commission, 2021c; Gislev & Grohol, 2018; Mathieux et al., 2017).

A relevant example in this regard is provided by the recent battery regulation. The former batteries directive already included mandatory collection and recycling targets. On top of these, the new regulation: sets new and more ambitious targets; includes recycling rates targets also for some critical raw materials; mentions and supports circular economy strategies other than recycling, with the aim of addressing import dependencies and environmental objectives simultaneously (European Parliament, 2023b). This regulation builds on the European Battery Alliance (EBA), launched in 2017 aiming at promoting competitive and sustainable domestic battery cell manufacturing supply chains in the EU. This was followed in 2020 by the European Raw Materials Alliance (ERMA), which recently called for a similar regulation for magnets in motors for electric vehicles (European Raw Materials Alliance, 2021). Another example is the European Chips Act, proposed by the European Commission in 2022, and aiming at fostering the semiconductor production in the EU.

This brief overview shows how similar initiatives to strengthen the EU supply chains are progressively being promoted. In this context, knowledge on Circular Economy R&I is needed to provide scientific evidence to support such initiatives. Nevertheless, contributions are still quite scattered and a systematic analysis providing a comprehensive overview on the subject across different supply chains is, to date, missing.

In this context, the objective of this report is to crystallise knowledge on the *status quo* of circular economy R&I efforts within and across some of the most important supply chains. The analysis illustrates where efforts have been placed, to what extent different countries are involved, and, importantly, how much funding the EU has deployed so far. The analysis flows into three main insights, which are leveraged to inform potential policy recommendations and future research in this space.

1.2 Method of the analysis

This report builds on the recent foresight report on strategic supply chains published by the JRC (Carrara et al., 2023). As anticipated in Section 1.1, the foresight study assesses the potential vulnerabilities and dependencies, and develops forecast scenarios for fifteen technologies in five strategic sectors for the EU economy. These technologies are: Li-ion batteries; fuel cells; electrolysers; wind turbines; traction motors; solar photovoltaics (PV); heat pumps; hydrogen direct reduced iron and electric arc furnaces (H2-DRI); data transmission networks; data storage and servers; smartphones, tablets and laptops; additive manufacturing; robotics; drones; space launchers and satellites. These technologies fall within five strategic sectors for the EU economy: renewable energy, electric mobility (e-mobility), energy-intensive industry, information & communications technology (ICT), and aerospace and defence.

Although with inevitable limitations, these technologies cover a considerable spectrum of the EU industry. The analysis on the intensity of circularity R&I carried out in this study focuses on four critical products (i.e., components or assemblies, according to the classification as in Carrara et al., 2023) needed to develop several of those fifteen technologies: lithium-ion battery cells (Li-ion cells); neodymium-iron-boron permanent magnets (NdFeB magnets); crystalline silicon and compound photovoltaic cells (PV cells); solid-oxide, proton-exchange-membrane, and alkali electrolysers and fuel-cells, and anion exchange membrane electrolyzers for hydrogen production and use (Hydrogen E/F cells). The selection of these products departs from the consideration that they are embedded in most of the technologies analysed by Carrara et al. (2023), while they key relevance in terms for circularity next to strategic autonomy has been validated with expert judgement, through the consultation of experts in the JRC.

These products are characterised by high Supply Risk (SR), according to the assessment carried out in Carrara et al. (2023). The SR depends on several factors: global supply, EU sourcing, import reliance, trade conditions, recycling input rate, substitutability. The SR can theoretically range from 0 to 20, but the highest value appearing in Carrara et al. (2023) is around 6. An element is defined as critical if SR ≥ 1, while it is non-critical if SR < 1. Table 1 shows the SRs calculated for the four investigated products. The results reported in Table 1 show that electrolysers (Hydrogen E) have a non-critical SR. Still, these products have been considered in this work as they are part of the hydrogen supply which includes fuel cells, which do show a critical SR, instead. For simplicity, the products considered in this work will be labelled as critical throughout the text without further elaborating on the specific condition of electrolysers. Table 2 provides an overview of which of the technologies contain the critical products within the scope of this analysis.

Table 1. Critical products in strategic technologies analysed in this study on circular economy R&I.

Critical product	Supply risk (1)
Li-ion cells	3.2
NdFeB magnets	4.6
PV cells	3.9 (2)
Hydrogen E/F cells	0.5 (3) / 2.6 (4)

(1) JRC-computed value for products based on Supply Risk (SR) values (scale from 0 to 20; ≥1 is critical) from Carrara et al., 2023.
(2) Value applies to c-Si technology.
(3) Average value for the four types of electrolysers analysed.
(4) Value for fuel cells.

To gain insight into the intensity of R&I efforts related to the circularity of the critical products in strategic technologies, the cumulative number of scientific articles, innovation projects and patents is used as a proxy. All three outputs can indeed be taken as a metric for R&I intensity, and a similar approach has already been adopted by previous research on related subjects (Czarnitziki et al., 2014; de Rassenfosse & van Pottelsberghe de la Potterie, 2009; Lanjouw & Schankerman, 2004; Liping, 2011). Notably, the Clean Energy Technology Observatory (CETO) of the JRC recently conducted a similar R&I analysis based on scientific articles, innovation projects and patents, although not with a specific focus on circularity (Bielewski et al., 2022; Chatzipanagi et al., 2022; Dolci et al., 2022; Georgakaki et al., 2022; Telsnig et al., 2022) with the notable presence of the computation of a circularity indicator solely based on the number of patents related to recycling and secondary raw materials (Georgakaki & Mountraki, 2022).

Quantitative data about the amount and features of scientific articles, innovation projects and patents related to selected units of analysis was collected with a dedicated software platform. The software was used to search for these documents systematically across multiple databases (e.g., The Lens for scientific articles, EU CORDIS for innovation projects, European Patent Office for patents, amongst several others). Geographical boundaries for the search were set to global, encompassing the worldwide body of scientific articles and patents. Despite the search for innovation projects had a global scope as well, data was in this case only retrieved for the EU, individual Member States, the United Kingdom, Switzerland, Norway, the United States, Canada and Australia.

Table 2. Applications of critical products in strategic technologies covered by this study.

		Critical products			
		Li-ion Cells	NdFeB magnets	PV cells	Hydrogen E/F cells
Strategic technologies	Batteries	X			
	Fuel cells (*plant*)				X
	Electrolysers (*plant*)				X
	Wind turbines		X		
	Traction motors		X		
	Solar PV			X	
	Heat pumps		X		
	H2-DRI				
	Data transmission networks	X			
	Data storage and servers		X		
	Smartphones, tablets, laptops	X	X		
	Additive manufacturing				
	Robotics	X	X		X (fuel cells)
	Drones	X	X		X (fuel cells)
	Space launchers and satellites	X	X	X	

Source: Carrara et al., 2023.

The analysis covers the period 2014-2022. This was meant to set a reference of global R&I efforts against EU efforts throughout the Horizon 2020 funding programme, as well as during the first two years of Horizon Europe; however, historical data for 2021 and 2022 may be partially incomplete due to possible delays in database updates. In this vein, the last three years of the time series might have also been affected by the

COVID-19 crisis - e.g., in 2020 values, with a negative impact on the number of projects starting in 2021-, a phenomenon beyond the scope of this analysis.

The systematic search of documents was conducted using a subject-action-object semantic approach, which is suitable for the purpose at hand and has already been employed to collect data on technology development trends (Guo et al., 2016; Wang et al., 2015). As part of this approach, a search query based on the Boolean combination of three keyword categories has been defined for each unit of analysis:

- The first keyword category relates to the object (i.e. the critical product and the critical raw materials within).
- The second category relates to the subject (i.e. the technology containing the products, as well as its applications).
- The third category contains keywords related to the action (i.e., different circularity strategies).

For example, in the case of NdFeB magnets the search query was structured as follows:

("ndfeb" OR "neodymium" OR "rare earth" OR …) AND ("electric motor" OR "hdd" OR "wind" OR …) AND ("circular economy" OR "recycling" OR "additive manufacturing" OR …)

Keyword selection was performed by the JRC in collaboration with industry and academic experts. The process involved several iterations in the software until a final, reliable search query was defined. To limit the results to those sources primarily about the investigated subject, the query was set to search only in the title, abstract and keywords of the scientific articles, innovation projects and patents.

Data output consisted in several spreadsheets containing all the retrieved documents, specifying for each one of them several features including the type of document (i.e., article, project, patent), date, author, country, institution (for the articles), applicants (for the patents), funding (for the projects), etc. This raw data output was consequently clustered and analysed thematically to derive graphic and written results. The first set of research outputs is a comparison of circularity R&I intensity across the selected units of analysis (i.e., critical products needed to manufacture strategic technologies). To this end, a unified indicator was defined as an equally weighted combination of the number of innovation projects, patents, and scientific articles per year.

For each unit of analysis, the level of R&I intensity was derived as a Z-score which represents the number of standard deviations by which the value for one product is above or below the mean value for all products. It is calculated by subtracting the population mean from an individual score and then dividing the difference by the standard deviation. This is indeed a commonly used method by research in various scientific fields (e.g. Agarwal & Taffler, 2007; Wu, et al., 2023). For instance, if technology X has a value of 100 and technologies Y and Z have values of 50 and 175, the z-score for technology X will be [100 – (1/3 * (50+175+100)] / 51.4 = -0.13, where 51.4 is the standard deviation of the values of all three technologies. For instance, if technology X has a value of 100 and technologies Y and Z have values of 50 and 175, the z-score for technology X will be [100 – (1/3 * (50+175+100)] / 51.4 = -0.13, where 51.4 is the standard deviation of the values of all three technologies. The value for each product is computed as the arithmetic average of articles, patents, and projects. Besides, insights are also provided in terms of the disaggregated number of scientific articles, innovation projects and patents present for each unit of analysis; the cumulative number of EU projects; and funding associated to the latter.

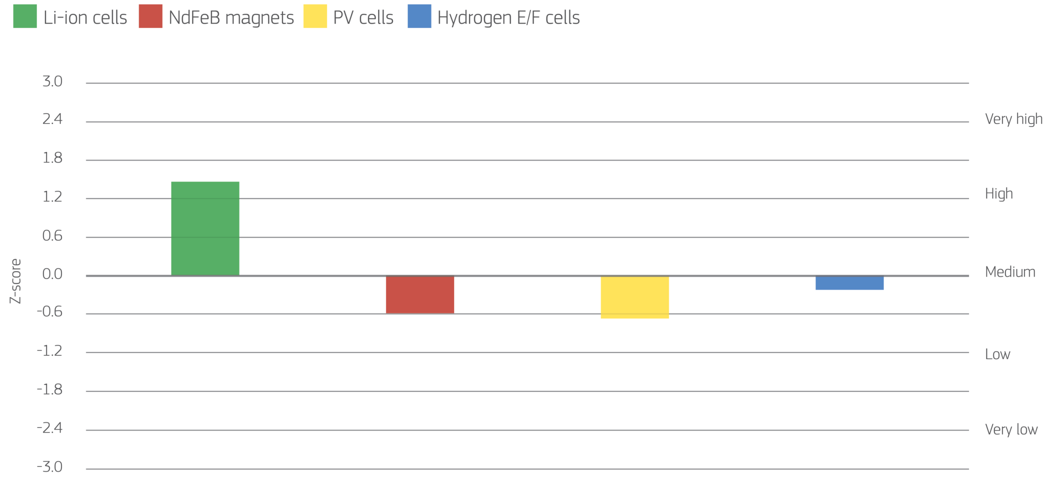
The next section presents the results of this analysis. After providing an overview of R&I efforts across units of analysis, further detail for each product is provided in terms of trends in R&I intensity, the number of EU projects and associated funding, and the geographical location of the institutions producing the scientific articles.

2 Circular economy R&I intensity for critical products in the supply chains of strategic technologies

2.1 Comparison of R&I intensity across critical products

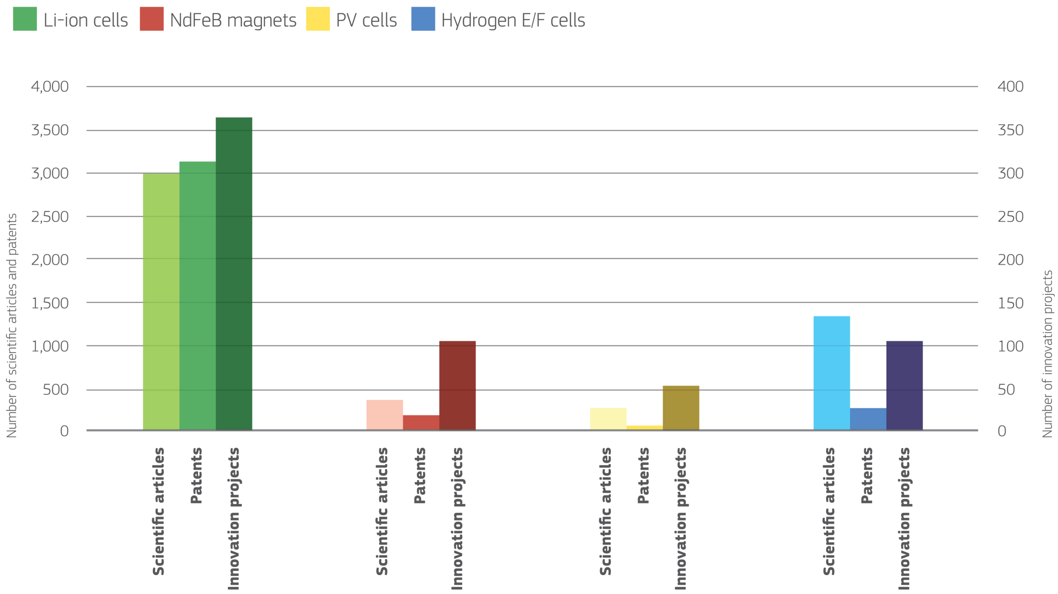
The results of the analysis show that the global level of circular economy R&I intensity is high for Li-ion cells, medium for NdFeB magnets and Hydrogen E/F cells, and low for PV cells (Figure 1). This overall insight is reflected into the global number of scientific articles, patents and innovation projects for each product. For Li-ion cells, there are 2,984 scientific articles, 3,140 patents and 364 innovation projects. For NdFeB magnets, there are 373 scientific articles, 191 patents and 106 innovation projects. For PV cells there are 284 scientific articles, 81 patents and 53 innovation projects. For Hydrogen E/F cells there are 1,344 scientific articles, 92 patents and 99 innovation projects (Figure 2).

Figure 1. Global circular economy R&I intensity for critical products in strategic technologies.



Source: JRC analysis.

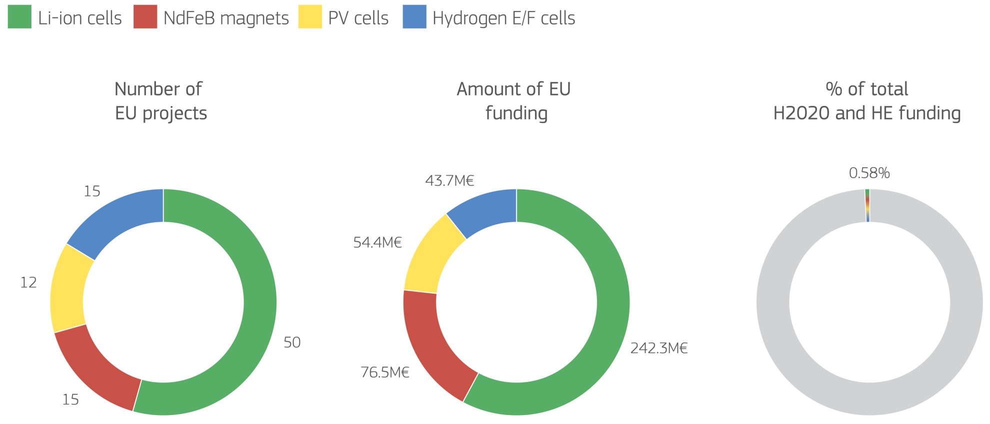
Figure 2. Global number of scientific articles, innovation projects and patents related to circular economy R&I for selected critical products in strategic technologies.



Source: JRC analysis.

The global picture appearing from the results in Figures 1 and 2 is also reflected in the innovation efforts carried out in the EU. In the period between 2014 and 2022, the EU has funded 50 innovation projects focusing on Li-ion cell circularity, for a total amount of EUR 243.3 million, which corresponds to 0.33% of the total Horizon 2020 and Horizon Europe funding. In the same period, 15 projects related to NdFeB magnets were funded, for an amount of EUR 75.5 million (i.e., 0.11% of the total Horizon 2020 and Horizon Europe funding). 12 projects related to PV cells were funded with EUR 54.5 million, corresponding to 0.08% of the total Horizon 2020 and Horizon Europe funding. Projects related to Hydrogen E/F cells amounted to 15, funded with EUR 43.7 million, which corresponds to 0.06% of the total Horizon 2020 and Horizon Europe funding. When making a comparison of the funding spent by the EU on the circularity R&I across critical products in strategic technologies, a strong imbalance is present in favour of Li-ion cell projects, which absorbed 57% of it. By contrast, the amount spent on PV cells and Hydrogen E/F cells was the most limited, amounting to 13% and 10%, respectively, of the cumulative amount. Expenditure on NdFeB magnet circularity R&I was slightly superior (18%). The results are displayed in Figure 3.

Figure 3. EU investment in circular economy R&I for critical products in strategic technologies, for the period 2014-2022.

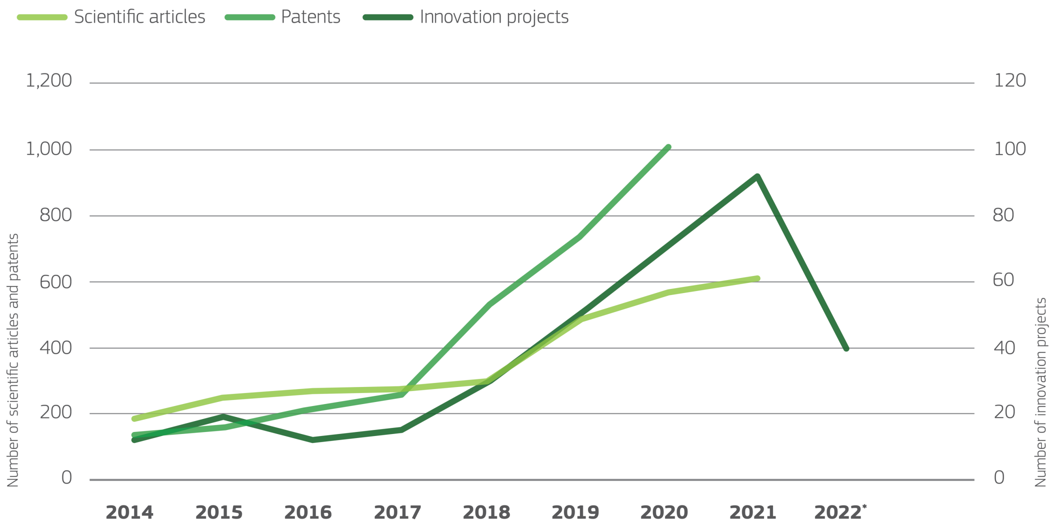


Source: JRC analysis. H2020: Horizon 2020; HE: Horizon Europe.

2.2 Circular economy R&I intensity for Li-ion cells

The results of the analysis related to circular economy R&I intensity for Li-ion cells show a growing trend since 2014. The number of scientific articles increased steadily from 184 in 2014 to 610 in 2021. The number of projects also increased at moderate rate between 2014 and 2017, from 12 to 15, and then faster in the following three years, reaching 92 in 2021. The same trend applies to patents, which increased from 135 to 215 between 2014 and 2017, sharply increasing to 1009 in 2020. See Figure 4.

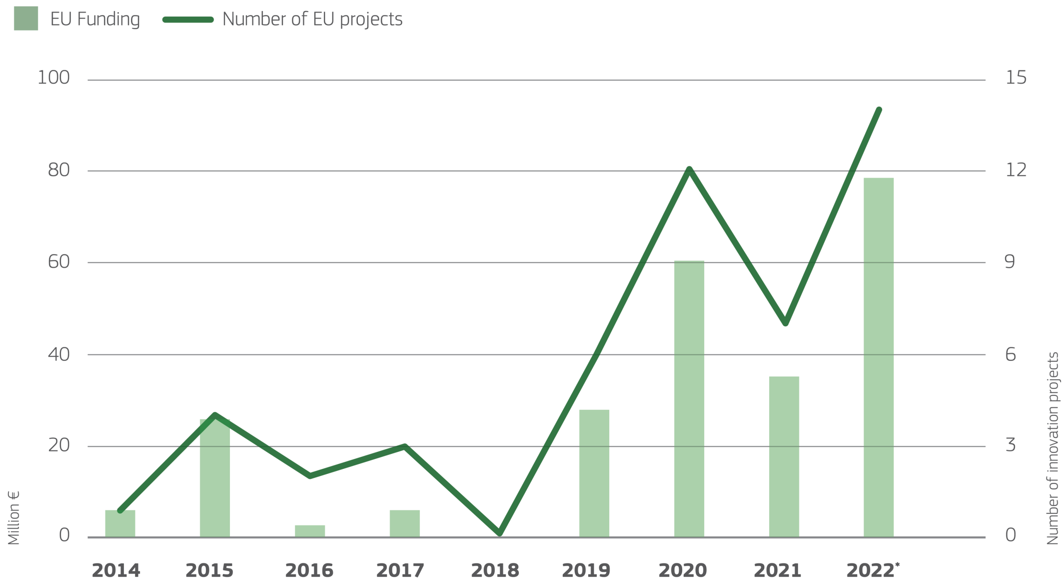
Figure 4. Trends in global circular economy R&I intensity for Li-ion cells for the period 2014-2022.



Source: JRC analysis.

Narrowing down the focus to innovation projects funded by the EU, the results show a similar trend. The number of projects increased from 1 in 2014, associated to a budget of EUR 5.9 million, to 14 in 2022, associated to a budget of EUR 78.6 million. Within this growth, few variations (2016, 2017, 2021) and gaps (2018) are observed, as shown in Figure 5.

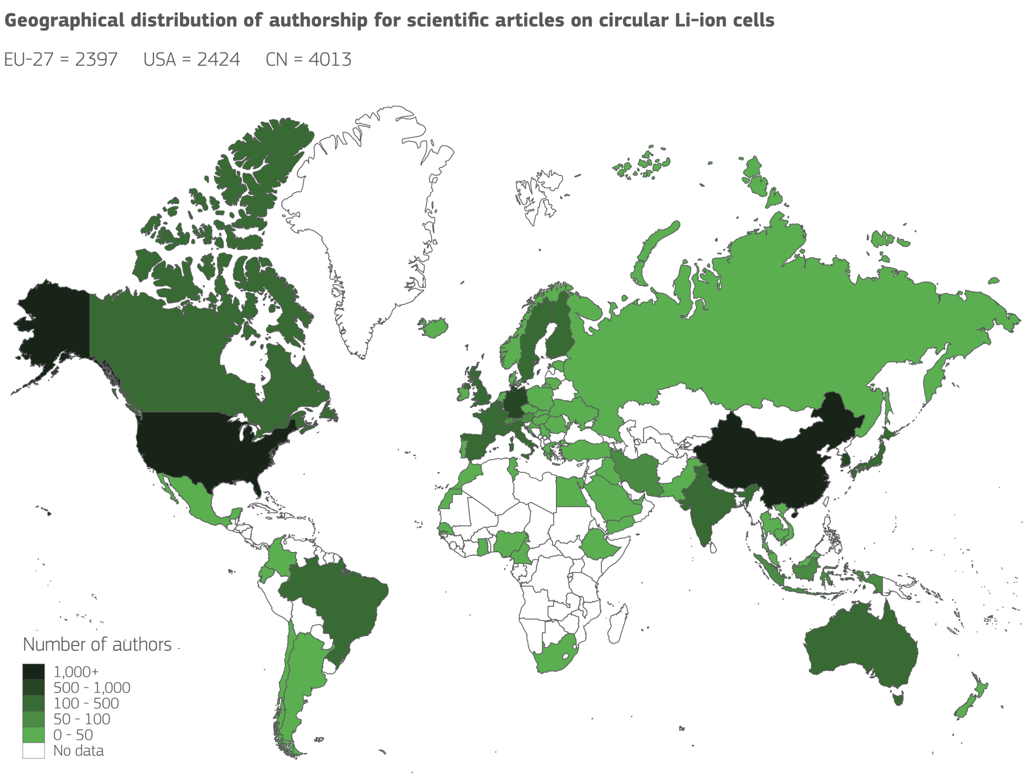
Figure 5. EU innovation efforts on circular economy R&I for Li-ion cells, for the period 2014-2022.



Source: JRC analysis.

Concerning the geographical distribution of R&I efforts, the results show that the largest number of researchers producing scientific articles on Li-ion cells circularity (over 4,000) are based in China (Figure 6). The other two research powerhouses are the USA and the EU, gathering circa 2,400 scholars each (Figure 6).

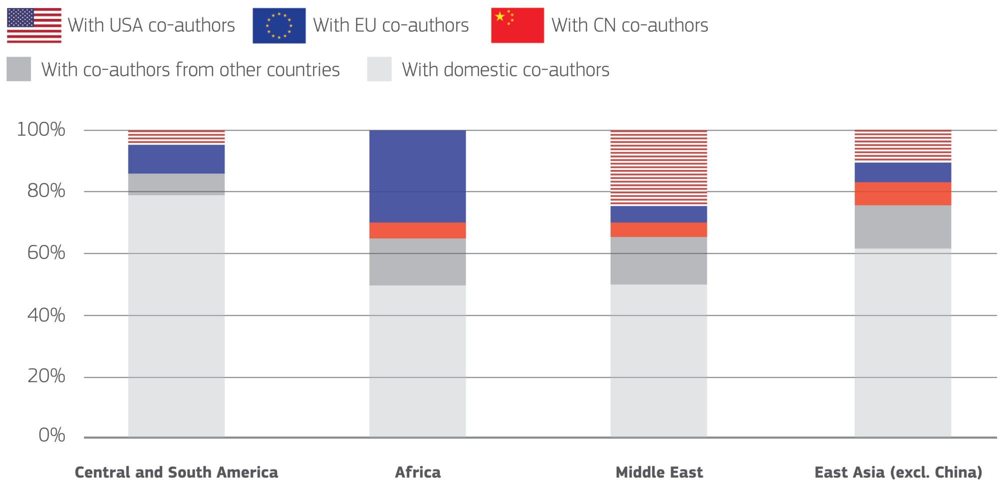
Figure 6. Geographical affiliation of researchers producing scientific articles on Li-ion cells circularity.



Source: JRC analysis.

A deeper analysis of the structure of cross-country collaboration in research articles is also performed, using the geographical distribution of co-authors in multiple-authored publications. EU, China and the USA are isolated as major research partners for all other countries clustered into four geographical regions, consisting to a large extent of emerging economies. For articles on Li-ion cells circularity, researchers from African countries tend to collaborate more visibly with co-authors from the EU, while academics from the Middle East collaborate more intensely with USA affiliates. For Central and South America, as well as East Asia, the degree of cross-region co-authorship is somewhat smaller and more heterogeneous. See Figure 7.

Figure 7. Co-authorship across countries for scientific articles on the circularity of Li-ion cells.



Source: JRC analysis.

It is relevant to observe how the results of this Li-ion cells circularity R&I analysis compare with those of a recent JRC analysis carried out by the Clean Energy Technology Observatory (CETO). This work contains an R&I analysis not focusing specifically on reducing, reusing, and recycling strategies for Li-ion cells, but rather on batteries and Li-ion technology at a higher level (Bielewski et al., 2022).

Between 2014 and 2021, the EU has supported 145 projects related to Li-ion battery technology, with a total investment of EUR 424.6 million. In comparison the EU innovation projects related to Li-ion cell circularity were 50 between 2014 and 2022, for a total of EUR 242.3 million. These figures indicate that 34% of the number projects and 57% of the underlying funding allocated to Li-ion R&I was, at least to a certain extent touching upon circularity aspects. Furthermore, the amount of EU project and related funding for Li-ion cells circularity has been growing by approximately one order of magnitude between 2014 and 2021. The size of the figures suggest that circularity has become and will increasingly be an integral and important part of the overall R&I efforts for Li-ion batteries in the EU, which is in line with the maturity of circular policymaking and supporting scientific work in this space (European Parliament, 2023; Matos et al., 2020).

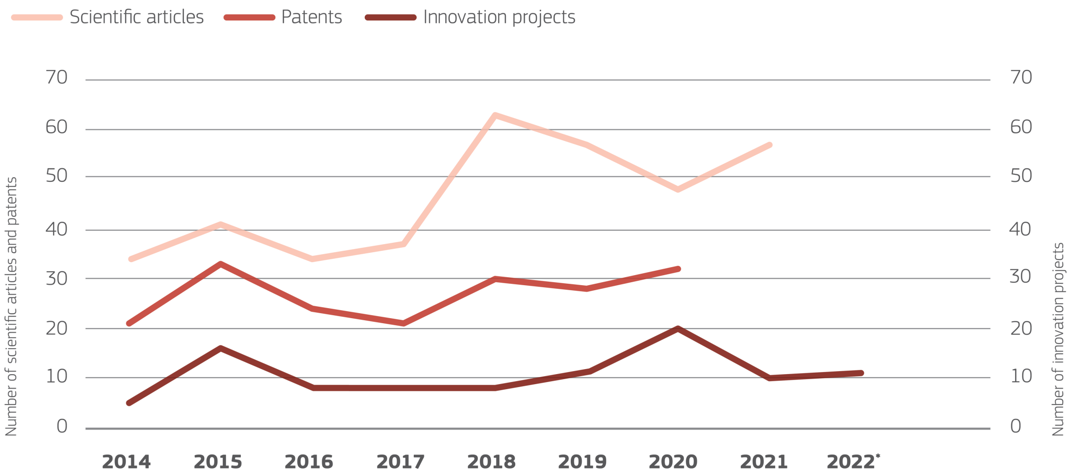
Concerning patenting activity, the high level R&I analysis on batteries did not isolate Li-ion technology, providing only aggregated insight. According to this analysis, most battery patents between 2017 and 2019 were developed in China (51%), followed by Japan (20%), Korea (13%) and EU (8%). The trend in the production of high value patents produced globally indicates sustained growth of 166%, from approximately 1500 patents in 2009 to approximately 4000 in 2019. On the other hand, Li-ion cell circularity patents grew sharply by 647% for from 135 in 2014 to 1009 in 2020, indicating the increasing importance of material efficiency.

Concerning the number of scientific articles produced globally on Li-ion batteries grew by 433%, from approximately 300 in 2010 to approximately 1600 in 2021. In comparison, the number of scientific articles focusing Li-ion cells circularity specifically amounts to fair share of the total, with a more limited yet significant growth of 231%, from 184 articles in 2014 to 610 articles in 2021. These figures reflect those related to the number of projects, suggesting that also on the scientific research, circularity is an important aspect often considered when conducting R&I on Li-ion batteries.

2.3 Circular economy R&I related to NdFeB magnets

For NdFeB magnets, growth of R&I intensity linked to circular economy aspects has been more modest since 2014, particularly in terms of innovation projects and patents. For scientific articles, however, the number of outputs has nearly doubled following an acceleration in 2017-18. Besides, all three categories exhibit a similar pattern, including a spike in 2015 which might be explained by the initiation of long-term research projects. See Figure 8.

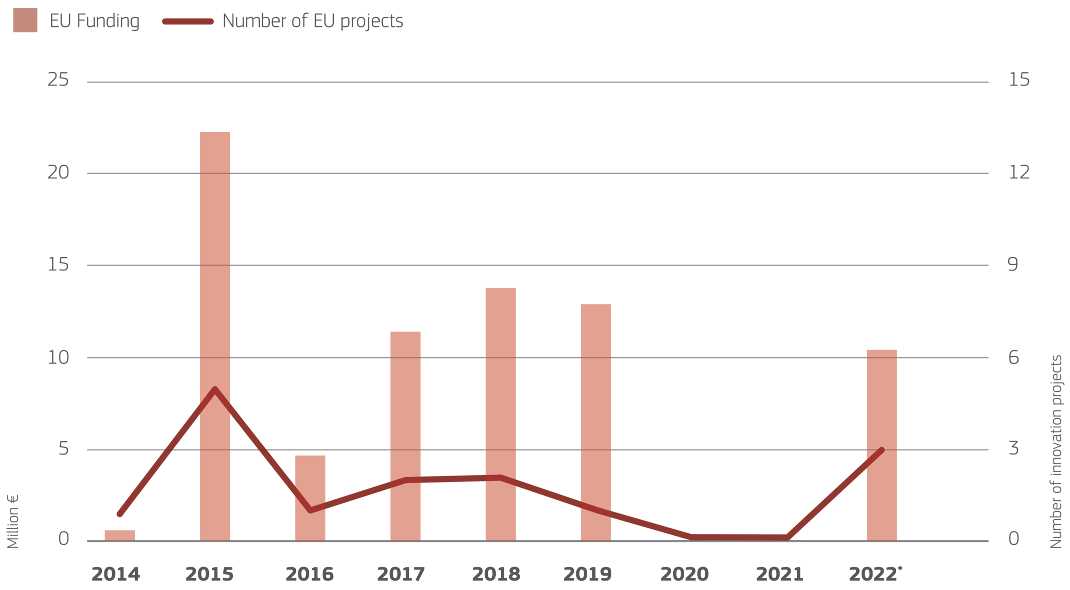
Figure 8. Trends in global circular economy R&I intensity for NdFeB magnets, for the period 2014-2022.



Source: JRC analysis.

With regards to EU-wide innovation projects, the largest disbursements took place in 2015 for circa EUR 22.5 million, distributed across 5 projects, also the highest figure for the period. Since then, there was a window of relatively stable advancement between 2016 and 2019 with 1-2 projects a year and EUR 10.5 million on average. After two years of inactivity in 2020-21, which might be related to the COVID-19 pandemic, 3 projects started in 2022 with similar total funding. See Figure 9.

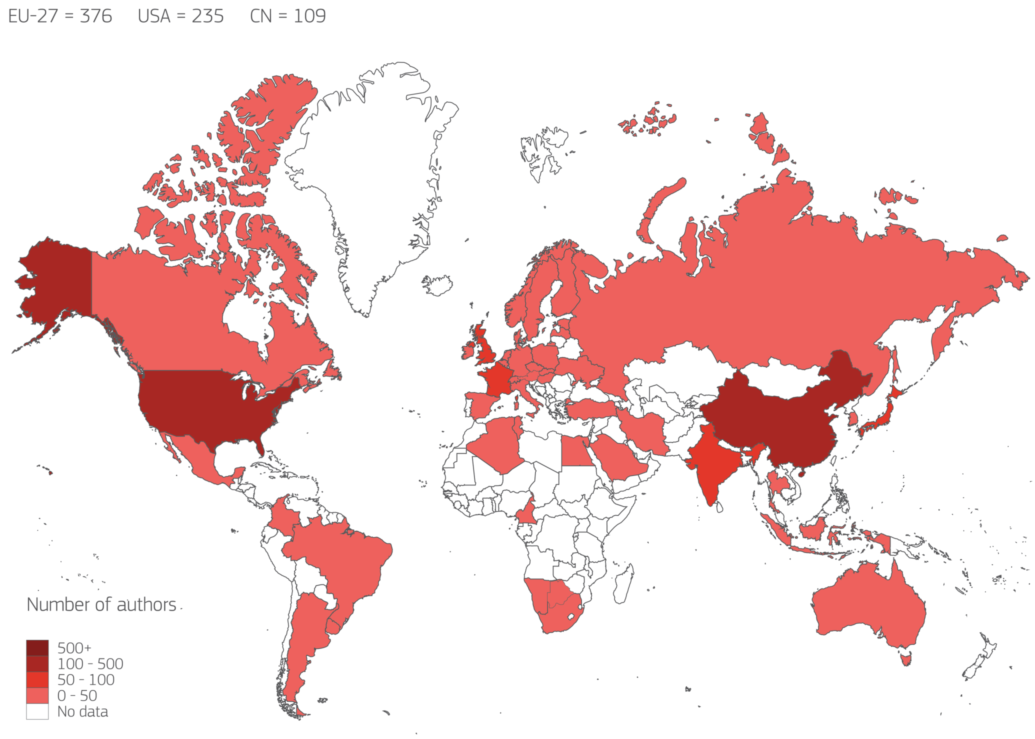
Figure 9. EU innovation efforts on circular economy R&I for NdFeB magnets, for the period 2014-2022.



Source: JRC analysis.

In geographical terms, the EU concentrates the largest number of authors producing research articles on circularity for NdFeB magnets (376) - with Germany and France standing out among Member States - followed by the USA (235) and China (109). See Figure 10.

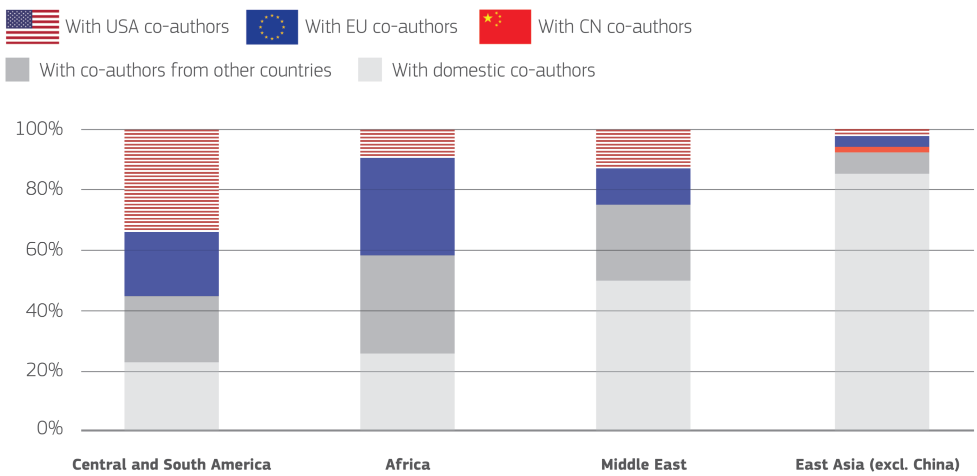
Figure 10. Geographical affiliation of researchers producing scientific articles on NdFeB magnets circularity.



Source: JRC analysis.

In terms of cross-country co-authorship of publications, researchers in Central and South American countries engage with peers outside their region for most publications, co-authoring 30% of all articles in the area with the USA-based scholars, followed by 20% with the EU-based scholars and another 20% with scholars from other locations. This also appears to be the case for African researchers, though the degree of collaboration with the EU is much larger than with the USA. For the Middle East, cross-region authorship is much less frequent, and it is negligible in East Asian countries; in the latter two, the role of the USA, the EU and China is also less prominent. See Figure 11.

Figure 11. Co-authorship across countries for scientific articles on the circularity of NdFeB magnets.



Source: JRC analysis.

It is relevant to observe how the results of this NdFeB magnets circularity R&I analysis compare with those of a recent JRC analysis carried out by the Clean Energy Technology Observatory (CETO). This work contains an R&I analysis not focusing specifically on reducing, reusing, and recycling strategies for NdFeB magnets, but rather on wind energy (as one of the main applications of NdFeB magnets in the EU) at a higher level (Telsnig et al., 2022).

Between 2014 and 2021, the EU has invested EUR 883 million of public funding for wind energy R&I, compared to the EUR 76.5 million spent on NdFeB circularity. In terms of trend, wind energy R&I is based on a stable yearly investment with relatively small fluctuations, while NdFeB magnets circularity R&I encompasses significant fluctuations, whit 2 gap years (2020-2021) where no funding was deployed. Furthermore, it is noted that out of all the 34 most relevant circularity-related public and private EU innovation projects identified by the wind energy R&I analysis, only 3 focused NdFeB magnets, while 21 focused on turbine blades. These numbers suggest that the circularity of composite materials has so far received significantly more R&I attention than the circularity of critical rare earth elements in the EU.

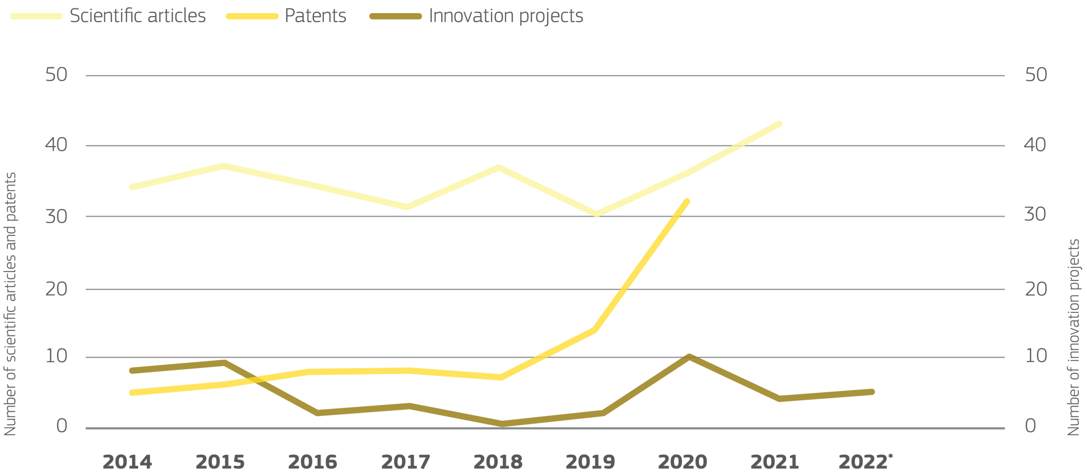
In terms of patenting activities for wind energy R&I, the trend does not encompass significant yearly increases or decreases, which is comparable to NdFeB circularity patenting. While in the case of overall wind energy patenting China is in the lead, for high value patents the EU is in the lead, whit an average patent production of approximately 375 patents per year between 2014 and 2019. It is noted that most of the high value patents produced in the EU originated from Denmark and Germany.

Concerning the number of scientific articles produced globally on wind energy, the number has grown steadily by 511%, from 427 publications in 2010 to 2607 publications in 2021. When looking at the number of scientific articles related to specific components of wind turbines, a growth of 381% is recorded, from 199 publications in 2010 to 958 in 2011. In comparison, the number of scientific articles focusing on the circularity of NdFeB magnets, which is the most relevant component of a wind turbine in terms of criticality, only grew by 67%, from 34 in 2014 to 57 in 2021. Most of the articles on wind energy components originate in China, the EU and the USA. The same applies to articles on NdFeB magnets circularity.

2.4 Circular economy R&I intensity for PV cells

In the case of PV cells, the number of scientific articles globally remained stable at 30-35 per year until 2019, when it increased reaching 43. Patent generation was relatively flat at around 7 per year but boosted significantly to 14 in 2019 and 32 in 2020. Muted growth is also apparent for innovation projects until 2019, with mixed signals ever since; noticeably, their order of magnitude is smaller than for Li-ion cells, similarly to what was seen for NdFeB magnets. See Figure 12.

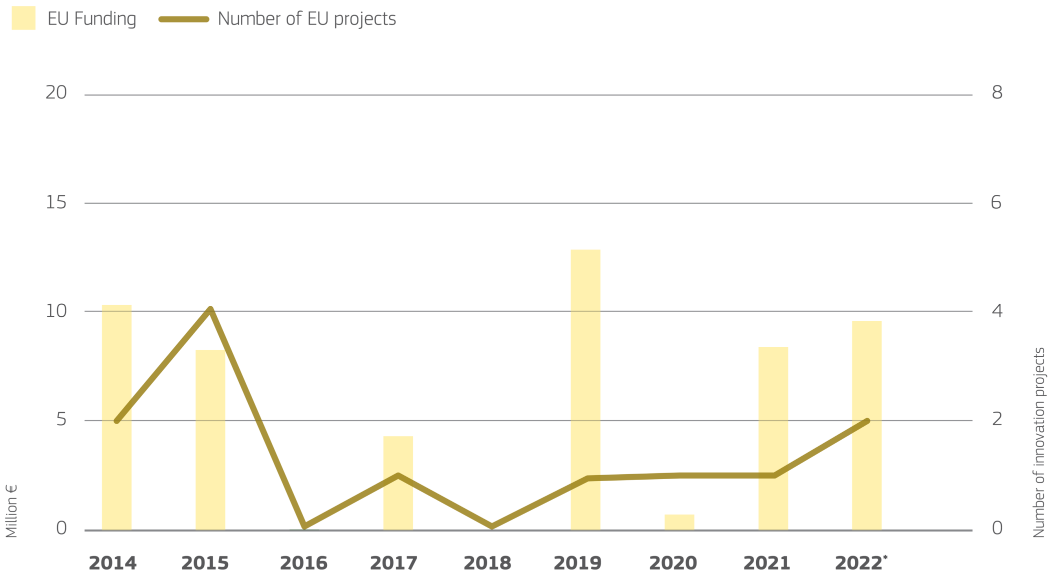
Figure 12. Trends in global circular economy R&I intensity for PV cells for the period 2014-2022.



Source: JRC analysis.

In terms of the European funding for innovation in the PV cells circularity, the pattern appears irregular. Within each of the periods 2014-16, 2017-19 and 2020-22, there are two years where projects are funded more significantly, in such a way that aggregate funding in all three of them is almost equal (EUR 18 million on average). However, more projects were initiated during the earlier period (2014-16) while more recently (since 2019) the funds have been distributed among fewer projects. All in all, there is no visible acceleration in both the number and the value of projects in 2021-22. See Figure 13.

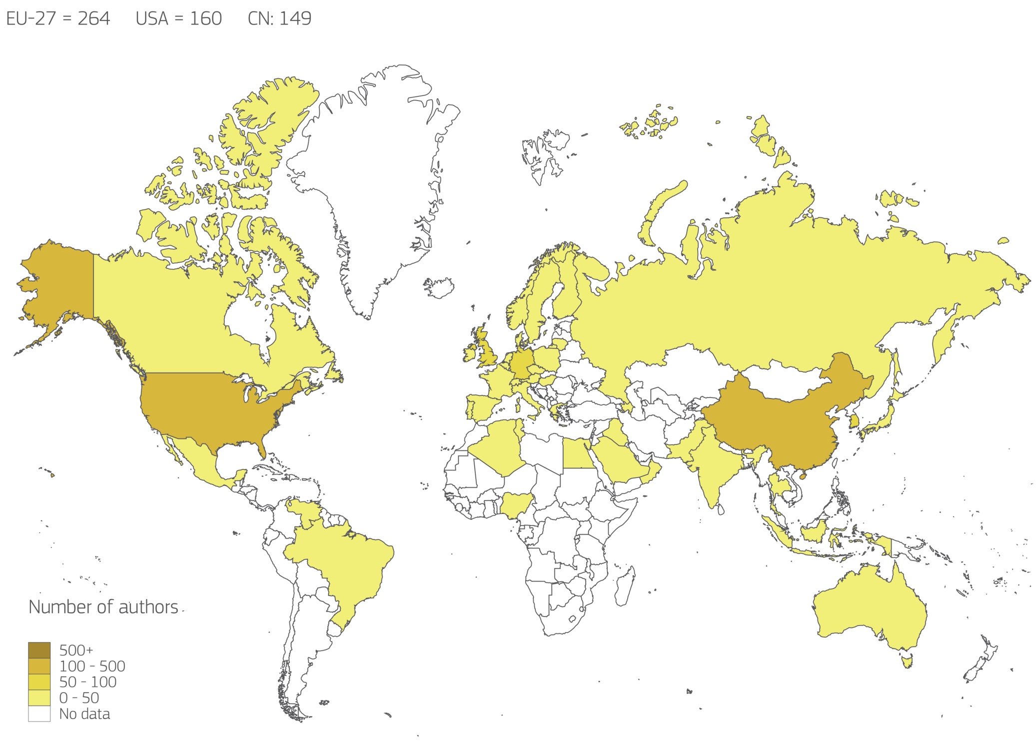
Figure 13. EU innovation efforts on circular economy R&I for PV cells, for the period 2014-2022.



Source: JRC analysis.

Similar to the case of the NdFeB magnets, the largest number of authors of scientific articles on PV cells circularity are affiliated to institutions in the EU (264) - with Germany in the lead among Member States-, followed by the USA (160) and China (149). See Figure 14.

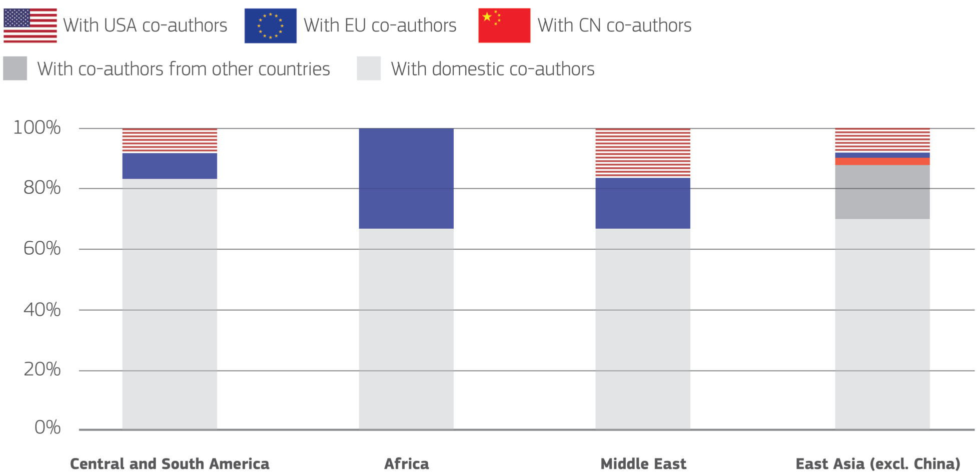
Figure 14. Geographical affiliation of researchers producing scientific articles on PV cells circularity.



Source: JRC analysis.

Compared to the two products discussed above, the degree of cross-regional collaboration in research articles is noticeably smaller for PV cells. At most, 30% of publications in our four areas of interest feature co-authors from a different region. The EU stands out as the partner of choice for African researchers, while collaboration in Central and Southern America and the Middle East are more evenly split between the EU and the USA. Lastly, Eastern Asian researchers seem to collaborate more with third countries. See Figure 15.

Figure 15. Co-authorship across countries for scientific articles on the circularity of PV cells.



Source: JRC analysis.

It is relevant to observe how the results of this PV cells circularity R&I analysis compare with those of a recent JRC analysis carried out by the Clean Energy Technology Observatory (CETO). This work contains an R&I analysis not focusing specifically on reducing, reusing, and recycling strategies for PV cells, but rather on PV technologies in general (Chatzipanagi et al., 2022).

Between 2014 and 2021, the EU has supported 140 projects related to PV technology, with a total investment of EUR 455 million. In comparison the EU innovation projects related to PV cell circularity were 12 between 2014 and 2022, for a total of EUR 54.4 million. These figures indicate that only 8% of the number projects and 12% of the underlying funding allocated to Li-ion R&I was considering circularity aspects. According to these figures, circularity is part of PV R&I to a limited extent. In terms of trend, EU PV R&I is based on a stable yearly investment with relatively small fluctuations in the past decade, while PV cell circularity R&I encompasses significant fluctuations, whit 2 gap years (2015 - 2018) where no funding was deployed.

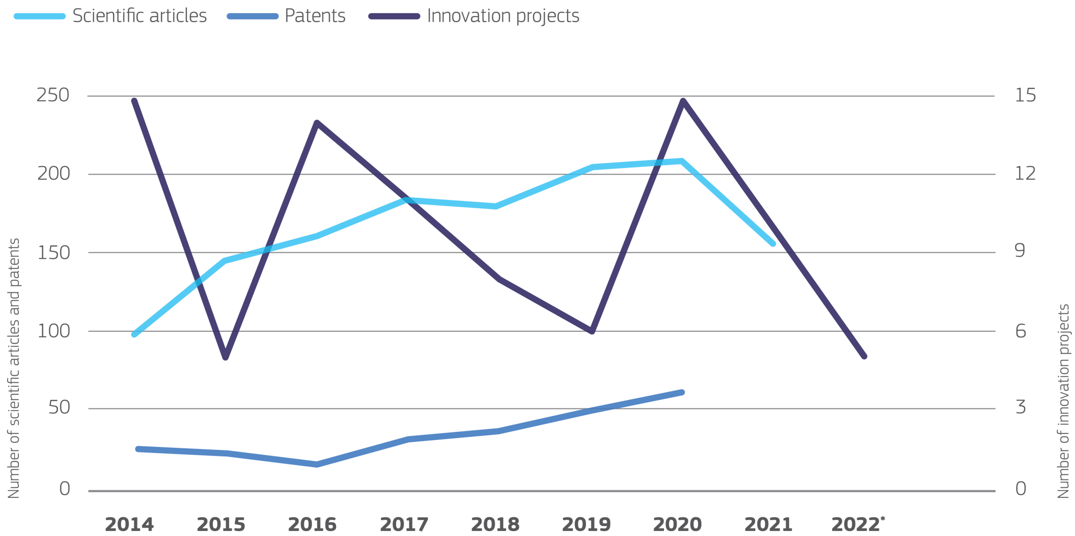
Concerning patenting activity, the high level R&I analysis on PV technology shows that between 2017 and 2019 China has been in the lead for the total number of patents. The trend in the production of high value patents produced globally on PV points to stability with an average production between 100 and 300 patents per year between 2009 and 2019. On the other hand, PV cell circularity patents, although significantly less abundant in terms of absolute numbers, grew by 540% for from 5 in 2014 to 32 in 202, with a sharp positive inflection point in 2018.

Concerning the production of scientific articles, the R&I analysis on PV technology restricted the focus to the EU, while in this circularity R&I analysis the focus is global, making it difficult to trace a comparison. Nevertheless, it is relevant to highlight that the number of scientific articles produced on PV in the EU alone is significantly superior than the total number of articles on circularity produced globally, which, as shown in Figure 12, does not follow a steady increase trend.

2.5 Circular economy R&I intensity for Hydrogen E/F cells

Scientific articles and patents on circularity of hydrogen electrolyser and fuel cells have been on the rise since 2014, with both doubling in the analysed time span. Though no complete information is available for the last two years, the upward trend appears robust. As regards innovation projects, their number has been oscillating between 5 and 15 with no clear pattern. See Figure 16.

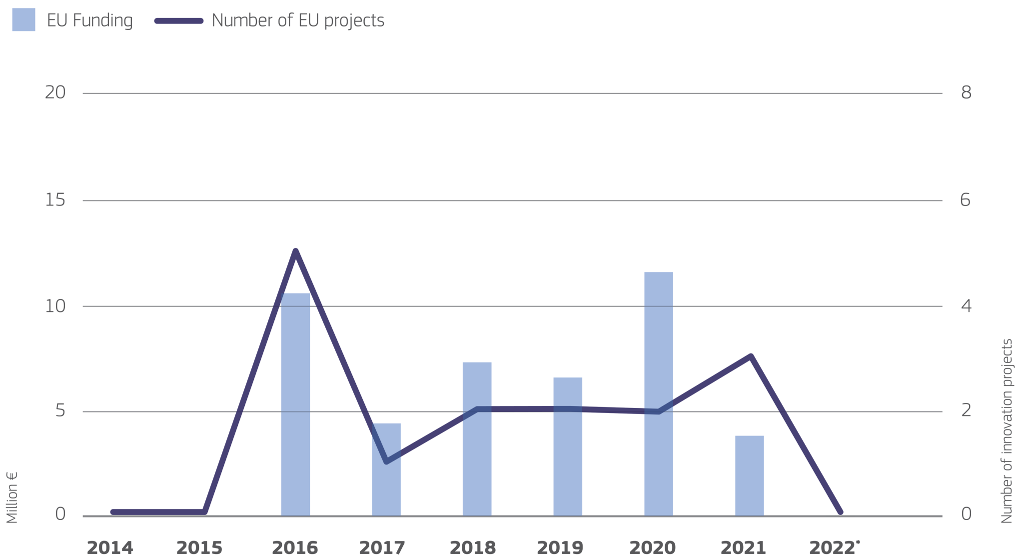
Figure 16. Trends in global circular economy R&I intensity for Hydrogen E/F cells for the period 2014-2022.



Source: JRC analysis.

At the EU level, no innovation project was initiated in 2014 and 2015, in stark contrast with the following year where 5 projects were funded with a total amount of EUR 10 million. Since 2017, both the number of innovation projects and the allocated funding have been on an upward trend until 2022, though incomplete information at the end of the sample probably reflects recent developments only partially (Figure 17).

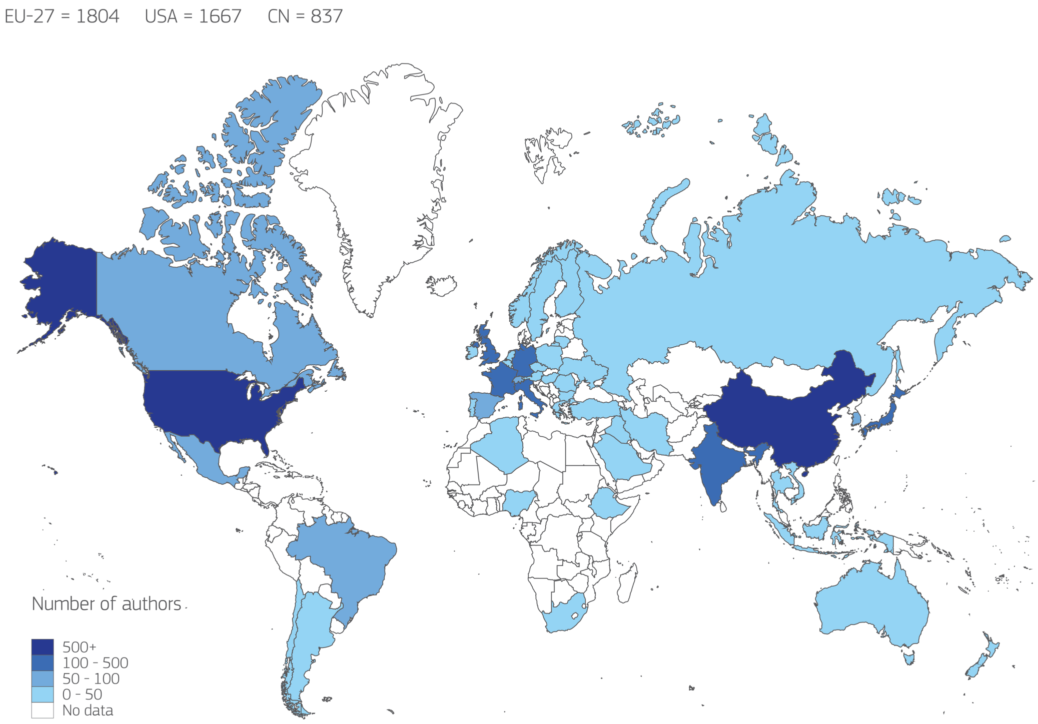
Figure 17. EU innovation efforts on circular economy R&I for Hydrogen E/F cells, for the period 2014-2022.



Source: JRC analysis.

In geographical terms, the USA hosts the largest number of authors producing research on circularity for this product, followed by the EU and China (Figure 18).

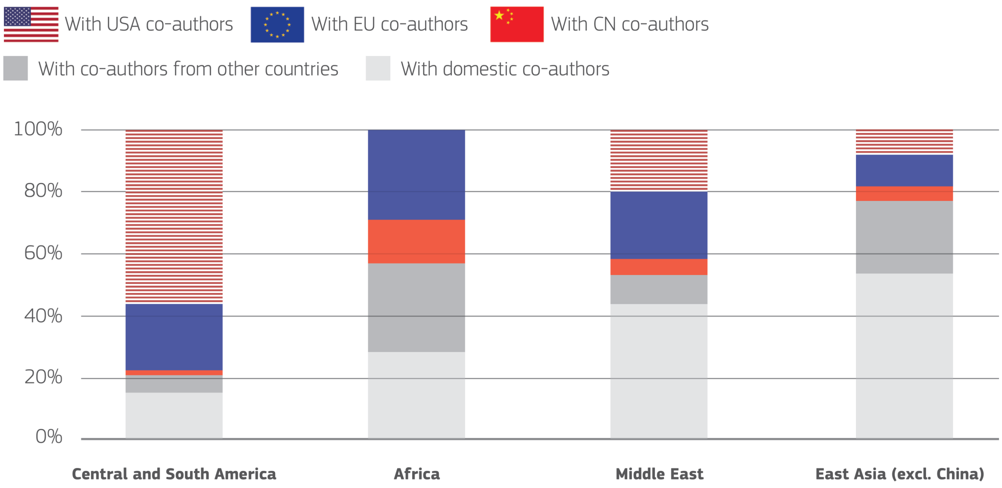
Figure 18. Geographical affiliation of researchers producing scientific articles on Hydrogen E/F cells circularity.



Source: JRC analysis.

Hydrogen E/F cells exhibit the most heterogeneous pattern of cross-regional co-authorship out of the four products considered in this report, in terms of both the degree of penetration and the choice of external partners. The first noticeable feature is the more visible presence of Chinese co-authors. Besides, more than 80% of articles by authors in Central and South American countries are co-authored with researchers from other regions, frequently from the USA (>50%) but also from the EU (20%). Africa-based researchers tend to co-author with researchers from the EU and third countries, although Chinese researchers make up for their largest share in this study (~10%). In the Middle East, foreign co-authorship is split between the USA and the EU, as was the case with PV cells. Finally, East Asian researchers tend to partner with third countries more than researchers located in the other three locations, and this feature is consistent across all four products. See Figure 19.

Figure 19. Co-authorship across countries for scientific articles on the circularity of Hydrogen E/F cells.



Source: JRC analysis.

It is relevant to observe how the results of this Hydrogen E/F cells circularity R&I analysis compare with those of a recent JRC analysis carried out by the Clean Energy Technology Observatory (CETO). This work contains an R&I analysis not focusing specifically on reducing, reusing, and recycling strategies for these critical products, but rather on electrolysis and hydrogen production in general (Dolci et al., 2022).

The EU has made available a massive amount of public funding for hydrogen technologies R&I, via different channels. Between 2014 and 2020, through Horizon2020 programme is injected over EUR 130 million of funding for different technologies for water electrolysis. On top of this, since 2008, EUR 150.5 million of funding came from the Clean Hydrogen Joint Undertaking and its predecessors. Additional EU support came through the ETS innovation, for an amount equal to EUR 240 million in 2020 alone. By contrast, funding related to the circularity of hydrogen technologies was 43.7 between 2014 and 2022, spent over 15 projects. This is not associated to a stable growth trend, but characterized by rather wide oscillations.

Concerning patenting activity, the high level R&I analysis on electrolysis and hydrogen production in general shows that numbers grew by 893%, from 190 in 2005 to 1888 patents filed globally in 2020. This sharp increase trend is not mirrored by circularity related patents, which are much more limited in absolute terms and declined from 24 in 2014 to 15 in 2016, when they started to grow again up to 61 in 2020.

Concerning the production of scientific articles, the R&I analysis on electrolysis and hydrogen technologies restricted the focus to the EU, while in this circularity R&I analysis the focus is global, making it difficult to trace a comparison. Nevertheless, it is relevant to highlight a moderate increase in numbers in both cases.

3 Conclusions

This study encompasses an analysis of the level of circular economy R&I intensity related to a selection of critical products embedded in strategic technologies. These products are Li-ion cells, NdFeB magnets, PV cells, Hydrogen E/F cells. Table 3 provides a high-level overview of the overall results of the analysis, showing for each products the supply risk, level of global circularity R&I and the EU investment.

Table 3: Summary on the analysis on circular economy R&I for critical products in the supply chain of strategic technologies.

Critical product	Supply risk (1)	Global circularity R&I (5)	EU investment (6)
Li-ion cells	3.2	High	*242.3 M€* (0.33%)
NdFeB magnets	4.6	Medium	*76.5 M€* (0.11%)
PV cells	3.9 (2)	Low	*54.4 M€* (0.08%)
Hydrogen E/F cells	0.5 (3) / 2.6 (4)	Medium	*43.7 M€* (0.06%)

Source: Carrara et al., 2023 and JRC analysis.

(1) JRC-computed value for products based on Supply Risk (SR) values (scale from 0 to 20; ≥1 is critical) from Carrara et al. (2023).

(2) Value applies to c-Si technology.

(3) Average value for the four types of electrolysers analysed.

(4) Value for fuel cells

(5) JRC-computed value derived as a Z-score based on the number of scientific articles, patents and innovation projects.

(6) % of Horizon 2020 and Horizon Europe total funding.

3.1 Main insights

The results of the analysis point toward three main insights, presented in the following paragraphs.

First insight: Global circular economy R&I related to strategic technologies has focused primarily on Li-ion cells, with less attention dedicated to other critical products needed for the digital, renewable energy and sustainability transition.

The analysis shows that the level of circularity R&I intensity for Li-ion cells is high, considering an average of the total number of scientific articles, innovation projects, and patents on the subject. Between 2014 and 2017, this number grew steadily. From 2017 onwards the trend accelerated significantly. The same cannot be said of the other critical products that were analysed. The level of circularity R&I intensity is 90% lower for NdFeB magnets, 94% lower for PV cells, and 74% lower for Hydrogen E/F cells. For these other critical products, the total number of scientific articles, innovation projects, and patents is much more limited, with growth patterns not comparable to those of Li-ion cells. Despite being still relatively limited, the yearly number of articles related to NdFeB magnets and Hydrogen E/F cells grew moderately since 2014, while the number of patents related to PV cells started to rise quickly since 2018. Overall, there is an uneven distribution of circular economy R&I efforts and the related strategic technologies globally.

Second insight: *The EU has so far invested approximatively three to five times more public funding in circularity R&I related to Li-ion cells, in comparison with NdFeB magnets, PV cells, hydrogen electrolysers and fuel cells.*

Since 2014, the EU has consistently funded several innovation projects related to critical products in strategic supply chains, with some gaps observed in 2020 and 2021, arguably due to the delay effects caused by COVID-19. For Li-ion cells, 50 innovation projects focusing on circularity were funded, for a total amount of EUR 243.3 million. However, EU public investment was 68% lower for NdFeB magnets, 77% lower for PV cells, and 82% lower for Hydrogen E/F cells. Furthermore, the number of yearly projects and funds associated to Li-ion cell circularity grew from 1 project (EUR 5.9 million) in 2014 to 14 (EUR 78.6 million) in 2022. Cumulatively, 34% of the number of EU projects related to Li-ion technology, and 57% of the underlying funding allocated was, at least to a certain extent, touching upon circularity aspects, making reduce, reuse and recycling strategies an important integrate part of EU R&I efforts in this space. The same cannot be said for the other products. The yearly number of projects related to NdFeB magnets circularity between 2014 and 2022 has remained relatively stable at around 1.6 with an average yearly budget of EUR 8.5 million. The yearly number of projects related to PV cells circularity between 2014 and 2022 remained relatively stable at around 1.3 with an average yearly budget of EUR 6 million. The yearly number of projects related to Hydrogen E/F cells circularity between 2014 and 2022 has remained relatively stable at around 1.6 with an average yearly budget of EUR 4.9 million. Overall, there is a strong imbalance in terms of publicly funded R&I efforts related to the circularity of strategic technologies in the EU.

While this trend might lead to mitigating the current import dependency of Li-ion battery cells from China, it is also likely to leave unsolved or aggravate future dependencies related to other key technologies that are equally essential for EU's open strategic autonomy (European Commission, 2021c, 2021b, 2022b). This is problematic given the geopolitical issues surrounding critical raw material supply, especially in the light of the lessons learnt from the recent disruptions on the global supply chains, notably those related to the COVID-19 pandemic and the 2022 Russia's aggression on Ukraine, which significantly decreased the imports via the global supply chains from China and Russia, as well as increased challenges related to the waste management (European Environment Agency, 2021; Leiden Delft Erasmus Centre for Sustainability, 2022).

Third insight: *Next to the EU, China and the USA play a key role in global circular economy R&I efforts related to critical products in strategic technologies, with international collaboration on scientific research being more limited on the Chinese side.*

For all the critical products taken into consideration within this analysis, most scientific articles related to circularity were produced by research institutions based either in the EU, in the USA or in China. While, for Li-ion circularity research China is clearly in the lead, for the other products, the EU seems to be slightly ahead of both the USA and China. Our analysis also reveals greater number of third-country collaborations among the researchers from the EU and the USA than from China. Both the EU and the USA develop collaborations with entities located in Central and South America and the Middle East. The EU is the preferred partner for Africa. Fewer collaborations take place with East Asian countries, which attract most of the Chinese collaborations (except for Hydrogen E/F cells with Africa, where Chinese collaborations are marked).

This trend may have two possible explanations. The first reason stems from the political conditions in China, which may lead to a more stringent governmental control on the research related to strategic technologies. The second reason relates to the different approach to circularity in China as compared to the Western countries (EU and the USA). After all, China is the main producer of products considered in this study, as well as the main supplier of the CRMs contained therein. Therefore, whereas circularity is a geopolitical and industrial imperative for the EU and the USA, this is not the case for China.

However, the situation might be quite different for patents. A rapid scan of patent databases shows that China, followed by the USA, is strongly in the lead with regards to the production of circularity patents for critical products. Since innovation projects carried out in China fall outside the boundaries of this analysis, a comparison in this sense cannot be made for the time being. However, results also show that the EU has so far supported more projects and invested significantly more public funding than the USA, suggesting that the latter has been more successful in mobilising the private sector, also in view of the higher number of patents. These insights must be confirmed by further analysis. Overall, despite the ambitions of the EU Circular Economy Action Plan and explicit mentions of the relevance of circularity approaches within the New Industrial Strategy, substantial R&I work is still needed at the EU level for it to assume an autonomous, leading position in this space (Carrara et al., 2023; European Commission, 2020a, 2021c).

These insights are closely related to the outcomes of former work already carried out by the JRC. In particular, the foresight study, on which this report directly builds on Carrara et al. (2023), already highlights the need for more R&I, mentioning as well relevant circularity aspects to consider for different strategic technologies. For example, in line with the CRM act, it calls for enhanced circularity, eco-design and data availability along the whole Li-ion battery value chain, to decrease demand for primary materials. Similar considerations are made for technologies containing NdFeB magnets, as well as for PV panels and Hydrogen E/F technologies. Parallel considerations are made also by the R&I studies carried out by CETO (Bielewski et al., 2022; Chatzipanagi et al., 2022; Dolci et al., 2022; Georgakaki et al., 2022; Telsnig et al., 2022), which mention at times the importance of circularity, despite not focusing on it specifically either. The present R&I analysis therefore complements these former works with a more in depth and specific focus on circularity. As a result, it provides quantitative evidence showing that despite good intentions: 1) circularity R&I for critical products is not yet balanced across critical products on a global level, with a prominent attention dedicated to Li-ion possibly in comparison to equally or more critical technologies; 2) the EU has followed this trend in terms of number of innovation projects and public funding; 3) other countries, and in particular China and the USA are focusing intensely on circularity R&I as well. This situation is in line with circular policy developments in the EU, which are indeed more mature for Li-ion batteries than for other strategic technologies (European Parliament, 2023). In this sense, this R&I analysis aims to draw attention to this important aspect, in conjunction with parallel and related JRC work (e.g., Tazi et al., 2023), to contribute to the ongoing incorporation of circular economy considerations, traditionally grounded in waste management policy, in the wider EU strategic autonomy agenda, as called by the +15% recycling target put forward by the CRM act (European Commission, 2023a). To this end, in the following sections 3.2 and 3.3 policy recommendations are provided, along with future research needs, connecting the three insights mentioned above with relevant scientific, policy and industry developments.

3.2 Policy recommendations

Upon the three key insights, four policy recommendations are proposed.

First policy recommendation: *Recalibrating the EU focus and future public investments for circularity R&I related to strategic technologies, to target more prominently NdFeB magnets, PV cells and Hydrogen electrolysers and fuel cells, while keeping momentum for Li-ion cells.*

Currently, most efforts for circularity R&I are concentrated on Li-ion cells. This area has reached a good level of maturity, generating more scientific research, more innovation projects, and more patents. The recent

“Regulation (EU) 2023/1542 of the European Parliament and of the Council of 12 July 2023 concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC” contains important circularity guidelines and binding targets (European Commission, 2020e; European Parliament, 2023). Furthermore, in relation to Li-ion batteries work on circularity is continuing at full speed with an increased focus on wider sustainability aspects. For example, the JRC is currently focusing on the definition of the rules to calculate and report both the rate for recycling efficiency and for recovery of materials to model waste batteries recycling processes and to calculate the corresponding carbon footprint, with the scope to increase current knowledge and forecast future recycling processes.

The same cannot be said for NdFeB magnets, PV cells and Hydrogen E/F cells, which indeed (with the exception of hydrogen technologies) show a higher SR than Li-ion cells according to the supply chain analysis developed in Carrara et al. (2023). The New Industrial Strategy and Critical Raw Materials Act call for further policies explicitly targeting circularity aspects in relation to these critical products (European Commission, 2021c, 2022b). While some new policies are already emerging, as exemplified by the upcoming eco-design requirements for PV modules (European Commission, 2021a, 2022g; Polverini et al., 2023), their successful implementation will require the EU financial support, which might be deployed through the Horizon Europe Programme.

Following the European Green Deal targets and related legislation, the coming years and decades will be characterised by a strong expansion of the products, or the technologies containing the products, considered in this study (i.e., batteries, traction motors, wind turbines, solar PV panels, and Hydrogen E/F cells). This implies that dedicated – and increasing – EU funding should be injected into their circularity: firstly, to meet the 15% recycling target fixed in the CRM Act (see Section 1.1), and, more generally, to avoid a substantial waste management problem, which would inevitably appear in the absence of dedicated measures.

In exact terms, according to REPowerEU (European Commission, 2022d, 2022e) and the EU solar energy strategy (European Commission, 2022a) the capacity of solar PV and wind power turbines installed in the EU should grow from 136 GW in 2020 to 592 GW in 2030 and from 177 GW in 2020 to 510 GW in 2030, respectively: a 4-fold and 3-fold expansion, respectively. Focusing specifically on the offshore wind power, with the capacity of around 15 GW in 2020, the EU strategy on offshore renewable energy (European Commission, 2020c) fixes the objective of at least 60 GW of offshore wind by 2030, with a view to reach 300 GW of installed capacity by 2050. This means a 5-fold expansion by 2030 and a 25-fold expansion by 2050. Additionally, the EU Hydrogen strategy (European Commission, 2020b) fixes the objective of reaching 40 GW capacity of renewable hydrogen production by 2030, starting from capacity below 1 GW in 2020.

The consequence of this expansion is an unprecedented increase in material demand. As reported in Carrara et al. (2023), the EU demand for rare earths will increase almost fivefold for permanent magnets required in wind turbines only, while lithium demand for batteries in electric vehicles will also increase by a factor of 11. By 2050, the EU demand (high demand scenario) in all the explored sectors for raw materials such as neodymium, dysprosium (the two main rare earths), nickel, lithium and graphite may increase 6, 7, 16, 21 and 26 times compared with the current values, respectively.

This overview shows that a tremendous growth is expected horizontally in all the technologies under investigation, and not only for Li-ion cells. Therefore, whereas investments in circularity R&I in Li-ion cells remains fundamental, comparable marked investment should be dedicated to NdFeB magnets, PV cells, and hydrogen technologies, possibly even anticipating the capacity growth.

Second policy recommendation: *Ensuring that the industry stakeholders and emerging alliances working on the R&I of strategic technologies keep circularity aspects in focus, not only for Li-ion cells but for all critical products, especially Hydrogen electrolysers and fuel cells.*

The private sector's contribution to accelerating the R&I related to the critical products embedded in strategic technologies is essential for the EU's strategic autonomy. In the case of Li-ion cells, a European Battery alliance was already established in 2017, Since then, efforts have intensified, with stakeholder collaborations, such as BatteriesEurope (https://batterieseurope.eu/) and Battery 2030+ (https://battery2030.eu/), working on the topic, providing insights on trends, roadmaps and key performance indicators to be used by R&I projects in both short- and long-term approaches (Di Persio et al., 2020). In these contexts, recycling is regarded as an important strategy to mitigate critical raw material dependencies (European Commission, 2019). Furthermore, focus has been placed on battery circularity also through the Important Projects of Common European Interests (IPCEI) scheme, involving ambitious circular research and development activities to deliver beyond the state-of-the-art innovation across the value chain, such as the recycling and repurposing of used batteries. Concerning the other critical products, the circularity status quo in terms of industry actions and alliances is not as advanced, despite progress is being made. About PV cells, the European Solar PV Industry Alliance is also being established as part of the EU Solar Energy Strategy, with circular eco-design for recycling and reuse playing an important role going forward (European Commission, 2021a, 2022a). Concerning NdFeB magnets, the European Raw Material Alliance is focusing on the primary and secondary supply of rare earths (European Raw Materials Alliance, 2021). Recycling of rare earths for use in NdFeB magnets is possible and may be economically viable, with several projects and start-ups are setting up pilots for scaling up recycling processes, which are not yet mature enough to be widely deployed (Alves Dias et al., 2020; Telsnig, 2021). On the other hand, the European Clean Hydrogen Alliance is more focused on implementing the hydrogen infrastructure, while circularity aspects do not seem yet to be a core part of the innovation strategy, despite the presence of raw material dependencies in terms of platinum group metals and nickel, and despite the fact that circularity constitutes a pillar of the EU Clean Hydrogen Joint Undertaking (Clean Hydrogen Joint Undertaking, 2022; European Commission, 2022c, 2022f). However, more circularity developments are accelerating also for Hydrogen E/F cells. The JRC is currently already supporting the EU Clean Hydrogen Joint Undertaking in view of the launch of the European Hydrogen Sustainability and Circularity Panel.

In general, apart from rare cases, circular economy does not seem to be of central importance to these various green technologies and CRM alliances. Instead, anticipating the expected increase in demand, the primary material supply tends to be their current priority. However, increasing domestic recycling can secure secondary supply, and should therefore become a priority on the way forward, as indicated in the CRM act. Therefore, it is essential that circularity aspects are first brought to the attention of all stakeholders in the supply chain, and that the key stakeholders are supported in the implementation of the circularity measures.

Third policy recommendation: *Ensuring that both public innovation projects and private industry alliances keep a circularity R&I focus beyond recycling, also considering how to reduce primary material demand by developing circular business models for repairing and remanufacturing critical components of strategic technologies.*

Considering the forecasted increase of material demand to manufacture critical products, to secure supply in an unstable geopolitical landscape, circularity plays an important role, as confirmed by recent works of both JRC and EC (e.g., Carrara et al., 2023; Tazi et al., 2023; European Commission, 2023a). As mentioned by these documents, recycling of critical materials will be crucial going forward, while more efforts will need to be established to consider also other circularity strategies, such as reducing material demand through circular business models for sharing, repairing, remanufacturing and reusing products. Such solutions have a higher potential to optimize environmental and economic performance according to circular economy theory and should therefore be prioritized according to the EU waste hierarchy (Ellen MacArthur Foundation, 2013; European Commission, 2008). While in the long run they might become essential for EU's strategic autonomy, at this stage there is a window of opportunity to put them in place before the infrastructure for renewable energy generation is fully in place. If this is delayed, only ex-post solutions will be available, which leaves few options other than recycling. Recent JRC work also aligns in this sense, arguing for the relevance and potential of remanufacturing to achieve the goals of the Green Deal and Industrial Strategy, for example in the automotive sector (Bobba et al., 2021).

The policy focus beyond recycling is still limited. A recent systematic analysis of all EU publications on the circular economy shows that recycling is still considered significantly more than other circularity strategies (Baldassarre & Saveyn, 2023). This is reflected in policymaking around CE of critical products in strategic technologies. A relevant example in this is provided by the battery regulation. Compared to the former directive, next to updated collection recycling targets, it assumes a life cycle approach mentioning also other circular strategies to foster repairability, supported emerging technology means such as a digital "battery passport". These ambitious steps beyond recycling are very relevant, and on the way forward will require further development to be translated from qualitative strategic guidelines into binding circularity targets as in the case for recycling. Notably, the EU solar strategy is pioneering in this direction, with the upcoming Eco-design requirements for PV panels, which are expected to include durability and information requirements, which might play a key role in reducing demand and fostering repairability (European Commission, 2021a, 2022a; Nyffenegger et al., 2023). Science for policy research is indeed accelerating quickly in this space (Polverini et al., 2023). However, eco-design practices for circular business models for these technologies, are not yet a core part of the circular policymaking discussion, while on the industry side they have not been scaled up yet, despite proactive efforts of sectorial association and frontrunning companies being present. In this sense current and recent JRC analysis and project work is contributing to advance circular policymaking beyond recycling, with a diverse focus including, for example, the collection of portable and lights means of transport batteries (Huisman & Bobba, 2021), potential interventions to foster a second battery life and impacts (Bobba et al., 2019), additional circularity strategies to increase critical raw material efficiency in end-of-life vehicles (Tazi et al., 2023), and development of novel circularity indicators (Bobba et al., 2023) and related methods for carbon footprint calculation (Polverini et al., 2023).

Indeed, circular business models are difficult to design effectively and implement successfully (Baldassarre et al., 2020). A recent consultancy study surveyed more than 500 manufacturing companies with revenues over $1 billion and found that over 90% claimed to be implementing circular business models (Colucci & Vecchi, 2021). However, scientific evidence shows that most circular business model ideas fail to reach the market (Ritala et al., 2018; Tukker, 2015). Implementing circular business models for repairing and remanufacturing renewable energy technologies is perhaps even more challenging than for other product categories due to several factors including the technical complexity, relatively recent installation, long lifetime cycles (e.g., 10 to 30 years for batteries, wind turbines, car motors, PV panels, electrolysers) and current exponential growth in R&I (Carrara et al., 2020; Telsnig, 2021; Tsanakas et al., 2020).

Scientific research shows that these circular business model solutions are, at least in principle and from a technical standpoint, possible. For example; EV batteries can be given a second life in stationary energy storage applications (Bobba et al., 2019); NdFeB magnets embedded in wind turbines and in digital technologies can be re-used (Frost et al., 2021; Telsnig, 2021). PV panels as well, can be provided to customers through product-service-system solutions that extent producer responsibility to the end-of-life, resulting in overall product-life extension as a consequence (Tsanakas et al., 2020; van der Heide et al., 2022). Beyond the technical feasibility, a key common challenge to the implantation of these solutions relates to the business case. To date, purchasing a new PV panel from China is still cheaper than repairing it in the EU. In this sense, EU policy may have key role. Public innovation projects, in collaboration with private industry alliances may explore beyond the ambitious 15% target of the CRM act, to better understand the behavioural and business (model) changes that are needed in this space.

Fourth policy recommendation: *Monitoring circularity R&I efforts in USA and China, and how they partner in this regard with other countries in East Asia, Middle East, Africa, Central and South America.*

As detailed in our insights, the EU is well placed at the global level in relation to circular economy R&I efforts, championing them along with the United States and China. In terms of scientific publications, three of the four critical products analysed, the EU ranks above the USA and China, and is second to them both only in the case of Li-ion batteries, with publication figures very close to the USA's. At any rate, both China and the USA have a consolidated circularity research infrastructure in place: this constitutes a reason for caution and deserves close monitoring to maximise collaboration opportunities and strategically partner with third countries. In the case of patents, although a geographical analysis falls out of the scope of this report, a quick glance at other data sources not specifically related to circularity shows that China often ranks ahead of the EU (depending on the technology and value of the patent) (Bielewski et al., 2022; Chatzipanagi et al., 2022; Dolci et al., 2022; Georgakaki et al., 2022; Telsnig et al., 2022); a quantification of how much research initiated on circularity of critical products (measured by academic publications) results in patents, and what the position of the EU is within, could constitute an interesting follow-up to this study.

Geopolitical blocks are becoming increasingly concerned about securing the supply of CRMs, as illustrated by the publication of critical raw material lists in the USA, the EU as well as in some Member States. The categorisation alone does not solve the problem of import dependencies, but it needs to be combined with circularity strategies. While the findings of this study give a favourable picture of research efforts in this field, the translation to policy actions at the EU level is currently at its inception phase.

Our analysis clearly highlights how the EU scientific community is already collaborating intensively with partners around the world on circularity research. However, our results show that the EU, the USA and China exhibit different preferences towards collaboration with other countries, possibly due to historically different spheres of geopolitical influence. The USA, for instance, have a much stronger presence in Central and Southern America in terms of co-authorship across all four critical products, while Africa is more prone to working with EU co-authors. Other regions such as the Middle East are more evenly split between the EU and the USA in this regard. Concerning the role of China, its co-authoring intensity is smaller, perhaps due to a stronger preference towards the establishment of domestic scientists in institutions abroad. From an EU standpoint, the finalisation of the CRM act can catalyse the development of Strategic Partnerships to exploit these collaborations.

3.3 Future research

Future research building upon this report might be functional to advance policymaking and industry action in this space.

Work may in the first-place focus on addressing the limitations of this analysis, in particular consolidating results with a follow up analysis focusing on the last 3 years of the investigated time series (2014-2022), and on innovation projects in Asia, which are currently not part of this analysis. Importantly, more in-depth analysis into the content of the proposed circular R&I outputs (scientific articles patents and innovation projects) per technology (Li-ion cells, NdFeB Magnets, PV cells and Hydrogen E/F cells) is needed. This analysis would benefit from a multidisciplinary approach integrating views from engineering and industrial design, business and economics, as well as political science and international relations, leveraging in combination quantitative and qualitative methods to prove a holistic and comprehensive picture.

On the qualitative side, future research might focus on systematically reviewing the content of the identified scientific articles, patents and innovation projects. This would allow researchers and policymakers to better understand, for example, to what extent scientific articles focus on different circularity strategies (recycling vs. reusing vs. reducing), which methods are used (e.g. life cycle assessments, 'LCA', material flow analysis, etc.), and to what extent the content of innovation project deliverables and patents are connected to emerging policy priorities. In turn, doing so would allow to adequately understand the diversity and quality of the proposed solutions, and further assess the success of EU-funded Horizon scheme in supporting circularity R&I vis-a-vis the research, patents and projects funded in the USA and China. Moreover, based on the analysis and the current industrial panorama, the developed database on papers/patents/projects could be used to develop an even more in-depth analysis to identify gaps/opportunities for further analysis and projects that can support policies with more quantitative evidence. The in-depth analysis of these outputs could be further complemented by stakeholder consultations (interviews) and fieldwork in the factories/sites where the circular R&I are implemented. Both desk research and fieldwork should focus on the following aspects:

- Identifying circularity drivers and barriers in the supply chains of strategic technologies containing critical raw materials. Such analyses would entail understanding which technical, economic, regulatory, and wider cultural and geopolitical factors might catalyse or hinder circularity in selected supply chains at different levels, in terms of recycling, eco-design practices, and circular business models (Axt et al., 2023; Baldassarre et al., 2022; Baldassarre & Saveyn, 2023; Bobba et al., 2018; Bobba et al., 2021; Buesa et al., 2023). Understanding these aspects would allow to provide targeted policies in support of the circularity R&I for the selected technologies.
- Replicating similar qualitative supply chain studies with a scope beyond the EU and its Member States. Given the global nature of the supply chains at hand, complementary in-depth assessment of the corresponding outputs produced in the USA and China might be essential. Such comparative appraisal would allow to adequately understand the positioning of the EU circularity R&I related to the four critical products isolated in this report.

Building on the insights derived on the qualitative side, a quantitative follow-up exercise would allow to provide more granular insight informing potential industry and policymaking actions. In this sense integrating modelling methods from the domains of applied economics and environmental engineering might prove relevant to better understand the circularity *status quo* and future potential in the supply chains of strategic technologies.

- On the economic modelling front, research on circularity strategies in critical supply chains requires a high level of detail to capture the specific traits of each component and technology; however, most models lack the necessary level of disaggregation. One possible solution is to combine different sources of information: along with qualitative insights, macroeconomic data on trade flows of materials and components (e.g., from EUROSTAT) can be complemented with micro-level datasets (e.g., customs data from DG TAXUD) to attain the required granularity, by splitting country-level information into sectoral or material detail. Subsequently, the merged data can be used to design circularity scenarios solidly grounded in accurate assumptions that can be fed onto economic models, from input-output setups to general equilibrium (Buesa et al., 2023). Such models can quantify the impact of enhanced circularity on output, employment, and industrial value added.

- In parallel, the information collected via supply chain analyses and material flow analyses are functional for performing (either bottom-up or top-down, or a hybridisation of the two) life cycle assessments and life cycle costing (LCC). The former allows quantifying environmental impacts, while the latter socio-economic impacts. LCAs and LCCs can be performed on products/systems from cradle-to-gate or cradle-to-grave, depending on the scope of the study; yet, they disregard macro-economic impacts, i.e. the effect that a change in one system can have on other sectors of the economy. To overcome this, LCAs should be integrated with computational general equilibrium models to capture rebound effects, which is indeed a key aspect to consider (Albizzati et al., 2022; Bobba et al., 2020). Modelling exercises should also facilitate carbon footprint calculations, as shown by recent work (Andreasi Bassi et al., 2023). These methods can be employed to assess policies and/or actions targeted on the different levels of, for example, the waste hierarchy and, therefore, assist in the selection of a cascading tree of actions that should be followed.

All in all, research on the circularity of critical products would greatly benefit from the combination of qualitative and quantitative methods, as previously described, encompassing expert knowledge from a broad range of disciplines, notably social science -with a focus on economics and geopolitics- and engineering sciences.

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List of abbreviations and definitions

CRM	Critical raw material
EBA	European Battery Alliance
ERMA	European Raw Materials Alliance
GW	Gigawatt
H2-DRI	Hydrogen direct reduced iron
ICT	Information and Communications Technology
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
Li-ion	Lithium ion
MFA	Material flow analysis
NdFeB	Neodymium-iron-boron
PV	Photovoltaic
R&I	Research and Innovation
SR	Supply Risk

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