EERA
European Energy Research Alliance

Policy analysis

Securing sustainable critical raw material supply for clean energy in Europe

Context overview and role of research and innovation in solar PV, wind, hydrogen, batteries and power electronics

About EERA

The European Energy Research Alliance (EERA) is the association of European public research centres and universities active in low-carbon energy research. EERA pursues the mission of catalysing European energy research for a climate-neutral society by 2050. Bringing together more than 250 organisations from 30 countries, EERA is Europe's largest energy research community. EERA coordinates its research activities through 18 Joint Programmes and is a key player in the European Union's Strategic Energy Technology (SET) Plan.

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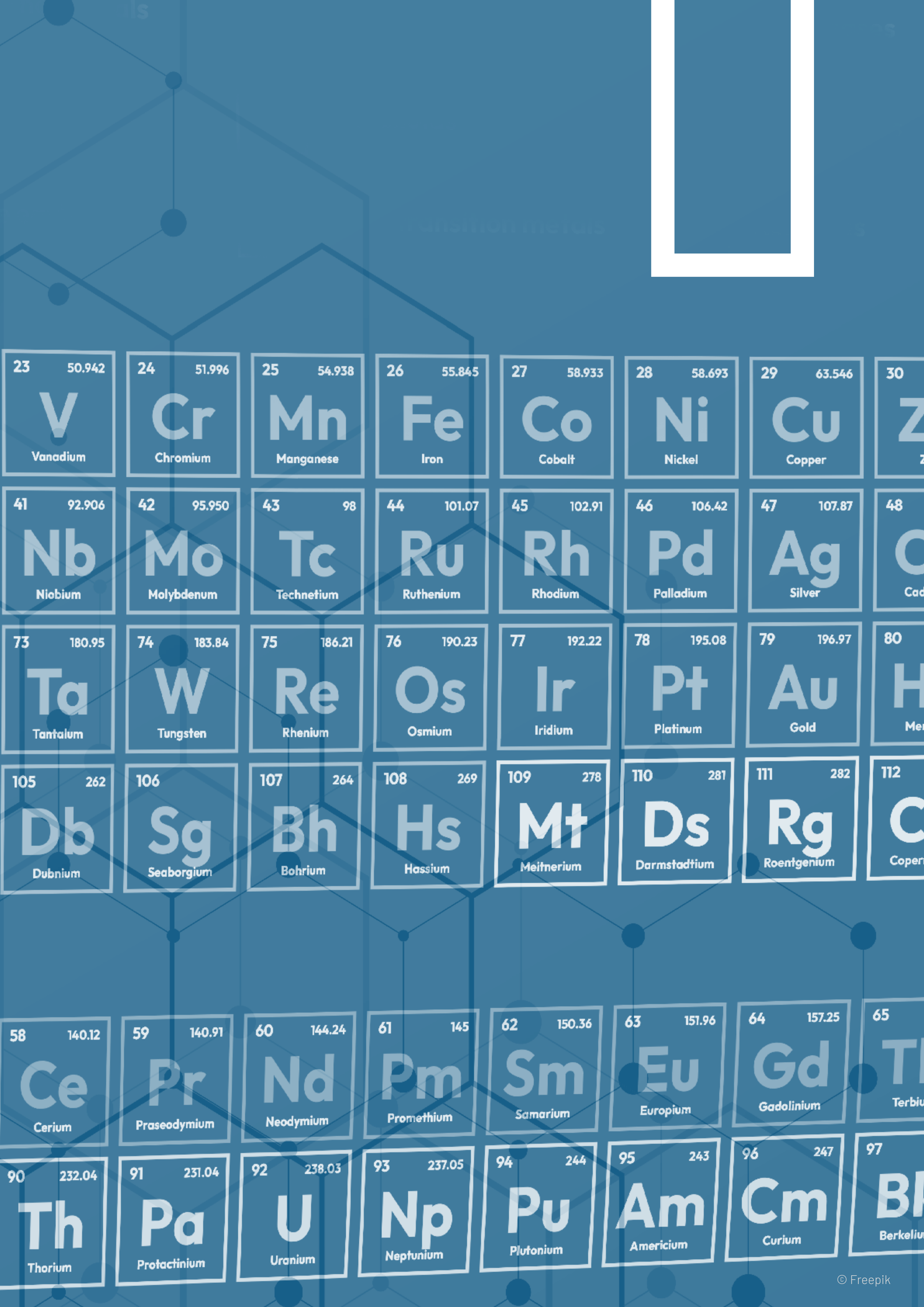
23 50.942 V Vanadium
24 51.996 Cr Chromium
25 54.938 Mn Manganese
26 55.845 Fe Iron
27 58.933 Co Cobalt
28 58.693 Ni Nickel
29 63.546 Cu Copper
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41 92.906 Nb Niobium
42 95.950 Mo Molybdenum
43 98 Tc Technetium
44 101.07 Ru Ruthenium
45 102.91 Rh Rhodium
46 106.42 Pd Palladium
47 107.87 Ag Silver
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73 180.95 Ta Tantalum
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75 186.21 Re Rhenium
76 190.23 Os Osmium
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78 195.08 Pt Platinum
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105 262 Db Dubnium
106 Sg Seaborgium
107 264 Bh Bohrium
108 269 Hs Hassium
109 278 Mt Meitnerium
110 281 Ds Darmstadtium
111 282 Rg Roentgenium
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58 140.12 Ce Cerium
59 140.91 Pr Praseodymium
60 144.24 Nd Neodymium
61 145 Pm Promethium
62 150.36 Sm Samarium
63 151.96 Eu Europium
64 157.25 Gd Gadolinium
65
90 232.04 Th Thorium
91 231.04 Pa Protactinium
92 238.03 U Uranium
93 237.05 Np Neptunium
94 244 Pu Plutonium
95 243 Am Americium
96 247 Cm Curium
97

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List of abbreviations and acronyms

AC	Alternating current
AEFC	Alkaline exchange fuel cell
AEWE	Alkaline exchange water electrolysis
AI	Artificial intelligence
CBAM	Carbon Border Adjustment Mechanism
CET	Clean Energy Transition
CIGS	Copper Indium Gallium Selenide
CMMI	Critical Minerals Mapping Initiative
CRMA	Critical Raw Materials Act
CRM	Critical raw material
DC	Direct current
DRC	Democratic Republic of the Congo
EERA	European Energy Research Alliance
ERMA	European Raw Materials Alliance
ESG	Environmental, social and governance
EU	European Union
EIT	European Institute of Innovation and Technology
EV	Electric vehicle
FTA	Free trade agreement
GATT	General Agreement on Tariffs and Trade
GW	Gigawatt
HVDC	High-voltage direct current
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
IRA	Inflation Reduction Act
NGO	Non-governmental organisation
PEFC	Polymer electrolyte fuel cell
PEMEL	Proton exchange membrane electrolyser
PEWE	Polymer electrolyte water electrolyser
PGM	Platinum group metal

PMDD	Permanent magnet direct-drive
PV	Photovoltaic
R&D	Research and development
R&I	Research and innovation
REE	Rare earth element
SDG	Sustainable Development Goal
SRM	Strategic raw material
TCO	Transparent conductive oxides
TRL	Technology readiness level
USA	United States of America
WTO	World Trade Organization
WBG	Wide-bandgap

Executive Summary

The European Energy Research Alliance (EERA) was established 15 years ago as the formal research pillar of the European Strategic Energy Technology Plan (SET Plan). Its mission is to catalyse European energy research for a climate-neutral society by 2050, aligning seamlessly with the EU's long-term climate goals. By coordinating the efforts of about 250 leading energy research organisations across 30 countries, EERA provides the EU with world-class scientific expertise in low-carbon energy technologies and advises the EU on the best energy transition strategies. In consonance with this mission, the current report analyses the strategic significance of critical raw material (CRM) security of supply within the context of Europe's clean energy transition (CET).

Europe's journey towards climate neutrality critically hinges upon the massive deployment of low-carbon technologies, which is expected to generate a dramatic increase in CRM usage. These materials are pivotal in most low-carbon technologies, such as PV modules, wind turbines, batteries and electrolysers, to name but a few. Against this backdrop, one central concern revolves around Europe's profound import dependency on these critical materials, which inherently constitutes a major vulnerability with respect to the execution of the CET.

The race against climate change is known to be paralleled by a race for industrial domination of the clean technology sector. This report is of particular significance at a time of profound reshuffling of the post-Cold War geopolitical order, evidenced by extreme international tensions, the emergence of unexpected new regional political alliances and new economic corridors, and the re-emergence of major protectionist policies and trade barriers, all factors that constitute major risks for CRM supply chains.

Based on a range of studies from authoritative international agencies, research institutions, and think tanks, the report provides a reliable and detailed analysis of the state of play of the collective knowledge base on CRMs. Leveraging the wide-ranging expertise of the EERA scientific community in the field of low-carbon technologies, the analysis provides incremental intelligence on how vulnerabilities of the CRM supply chain could affect the EU's clean technology industry and CET process. A deep dive is provided into five technologies that are central to the CET, namely, solar photovoltaics (PV), wind turbines, batteries, electrolysers and power electronics, analysing how these technologies could potentially be affected by disruption of CRM value chains.

The report concludes with a set of policy recommendations, aimed at addressing both the geopolitical challenge of securing the supply of CRMs as a whole and the specific details of the five technologies analysed. It ultimately emphasises the central role of research in most of the mitigation strategies available to manage the systemic risks posed by CRM supply security.

Introduction

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The transition to a clean energy future in Europe relies heavily on the availability of critical raw materials (CRMs), which are essential for producing clean energy technologies such as solar panels, wind turbines, and electrolysers for hydrogen production, or batteries and electrical motors for electric vehicles (EVs). With a growing emphasis on technological innovation, humanity has increasingly harnessed the properties of elements, particularly metals, to drive progress. Today, numerous key technologies across all industrial sectors continue to rely on the unique physical properties of specific raw materials. However, the concentration of global CRM production in a few countries gives rise to significant geopolitical risks and vulnerabilities in the supply chain. Acknowledging these challenges, the clean energy research community of the European Energy Research Alliance (EERA) aims, through this policy analysis, to expand and enhance the knowledge base on CRMs. The objective is to contribute to developing and implementing strategic measures that address the reliance on limited CRM sources while ensuring a sustainable and secure supply for the clean energy sector in line with the European Union's ambitious 2030 and 2050 neutrality goals.

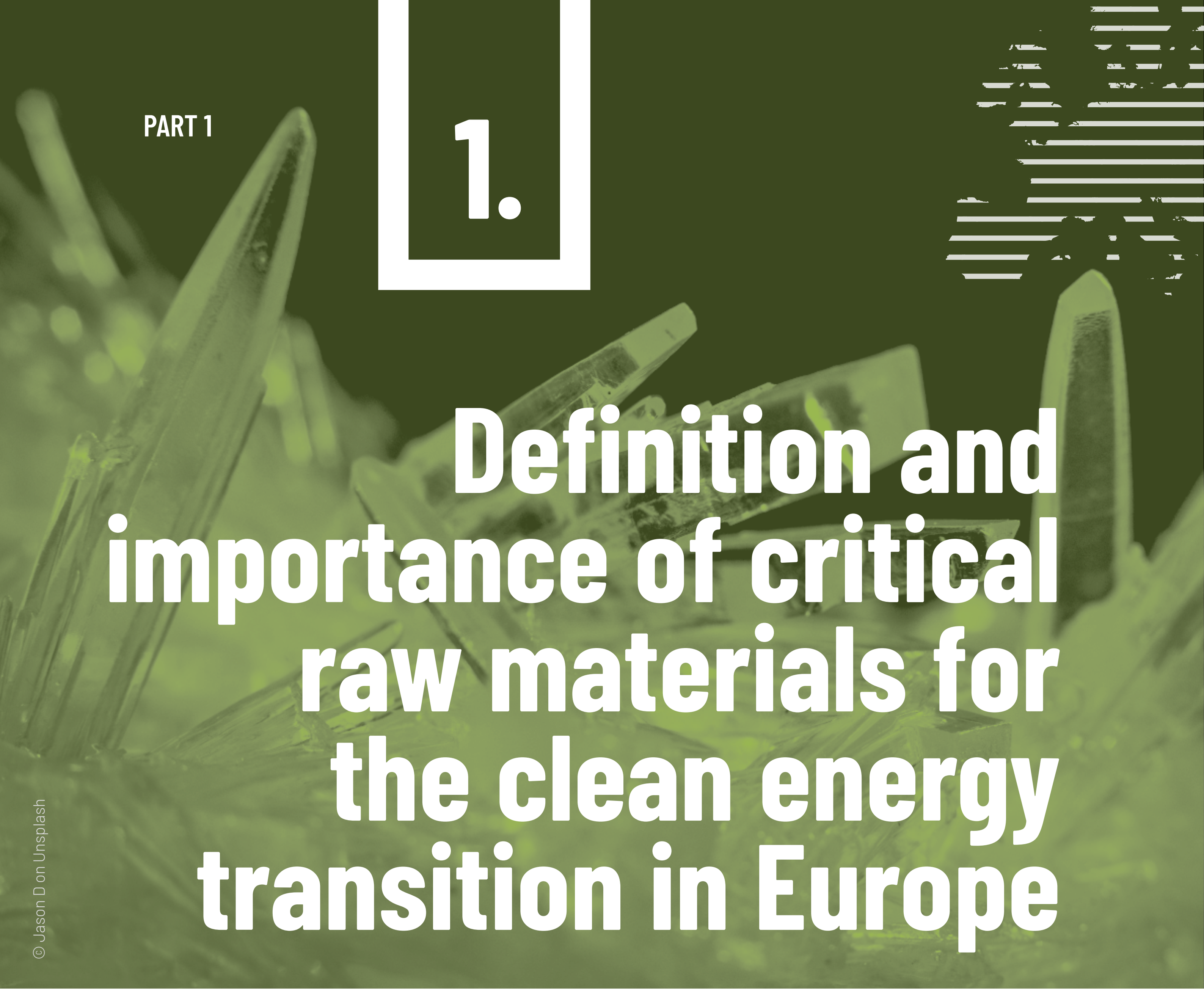
The analysis will initially explore the importance of CRMs for the clean energy transition (CET) in Europe. This will emphasise the broader geopolitical risks and supply chain dependencies specific to the region. General social, environmental, and ethical considerations linked to CRM sourcing and processing will then be identified. This will be followed by an overview of the latest EU policies, regulations, and initiatives related to CRMs, with a particular focus on the Critical Raw Materials Act (CRMA) proposed by the European Commission in March 2023, and its implications for the clean energy research sector. Given the global nature of CRM supply chains, international cooperation and trade will also be examined by analysing existing frameworks and initiatives that foster collaboration, address trade barriers, and enhance resource security.

The second part of the analysis will encompass a comprehensive exploration of pivotal facets related to the transition towards a cleaner and more sustainable future. The focus will be on the intricate interplay between the principles underpinning the circular economy, alternative materials, and substitution strategies, highlighting their profound implications for a carefully selected array of cutting-edge technologies. Before delving into the specifics of these technologies, section 7 will lay the groundwork by providing a precise definition of key concepts. Subsequently, sections 8 to 12 will examine five pivotal technologies: solar photovoltaic, wind, hydrogen, batteries, and power electronics. Within each of these technological domains, the focus will be on their general challenges, the scope of research and development (R&D) activities, and the far-reaching impacts these technologies have within the realms of clean energy and sustainability.

In conclusion, the policy analysis will consolidate the findings and insights presented throughout the document and propose a series of policy recommendations. These recommendations will be specifically designed to secure a sustainable and reliable supply of CRMs in the clean energy sector in Europe, aligning with the European Union's ambitious 2030 and 2050 neutrality objectives. In doing so, this report aims to actively contribute to the advancement of clean energy technologies while securing the accessibility of CRMs for a sustainable and low-carbon future.

PART 1

Importance, risks and policy context for CRMs in Europe’s energy transition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PART 1

1.

Definition and importance of critical raw materials for the clean energy transition in Europe

CRMs are those raw materials that are identified as economically and strategically important for the European economy, but at the same time have a high risk associated with their supply. These critical materials can be classified according to their chemical nature. All are minerals found in the Earth's crust as a result of inorganic processes. They can exist and be used in their elemental form or as chemical compounds. Most of today's critical materials are metals[1] and play a significant role in various strategic fields, including green technologies, digital industries, telecommunications, defence, aviation, microelectronics, medical equipment, and everyday devices such as smartphones.

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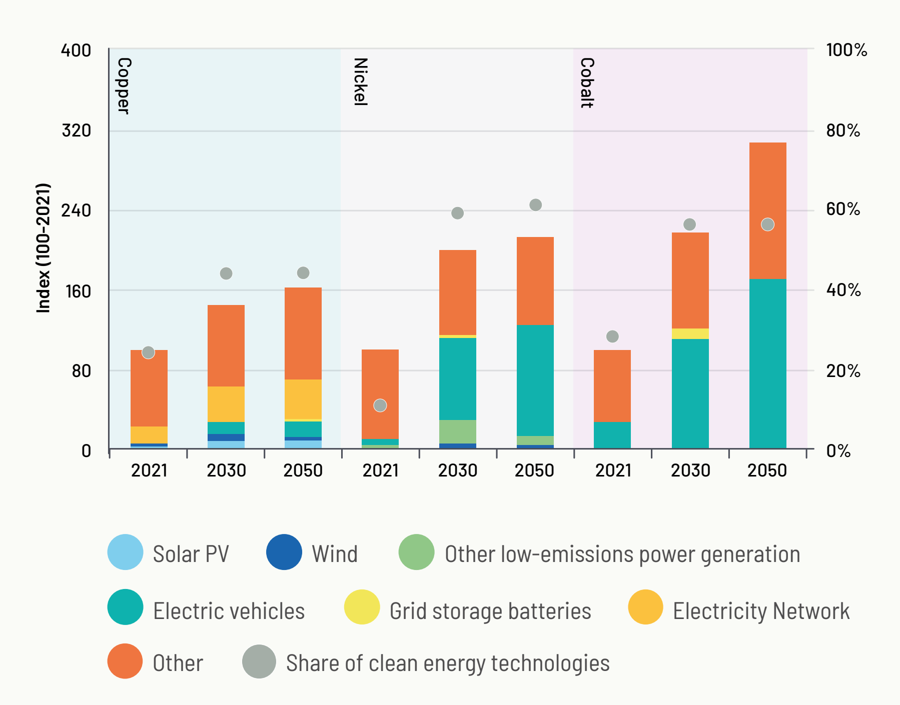
1. European Commission, 2020, Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability, available at: *https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0474&from=EN*

FIGURE 1:
Total demand for selected minerals by end use in the Net-Zero Scenario, 2021-2050 (source: IEA)



The transition to the "net-zero age", enabled by low-carbon technologies, is particularly materials-intensive. According to the International Energy Agency (IEA), achieving global net-zero emissions by 2050 would drive a remarkable surge in demand for critical materials. Short-term forecasts, up to 2030, point to an increase in CRM requirements of almost three and a half times current demand, surpassing 30 million tonnes. Even in a less ambitious scenario aligned with the Paris Agreement, significant growth in demand for specific CRMs is expected. Leading this demand surge are electric vehicles (EVs) and battery storage, low-emission power generation, and electricity networks. Regarding mineral demand for use in EVs and battery storage, the IEA forecasts a 30-fold increase by 2040. Among the minerals needed, lithium sees the fastest growth, with demand growing by over 40 times by 2040, followed by graphite, cobalt and nickel (around 20-25 times). On the other hand, electrolysers and fuel cell production will lead to an increase in nickel or platinum group metal requirements[2].

The European Commission echoes this trend, projecting substantial increases in CRMs to achieve the EU's 2050 climate neutrality goal[3], envisioning up to 60 times more lithium and 15 times more cobalt compared with current levels. For rare earth elements (REEs), essential in permanent magnets, a 10-fold increase in demand is forecast by 2050[4].

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2. IEA, 2021, The Role of Critical Minerals in Clean Energy Transitions, available at: *https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions*

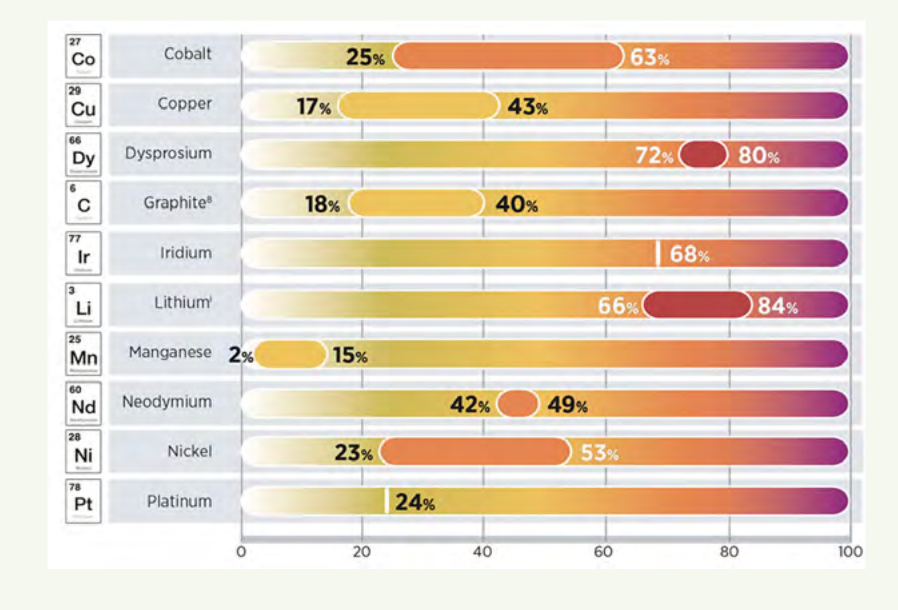
3. European Commission, 2020, Critical Raw Materials for Strategic Technologies and Sectors in the EU - A Foresight Study, available at: *https://rmis.jrc.ec.europa.eu/uploads/CRMs_for_Strategic_Technologies_and_Sectors_in_the_EU_2020.pdf*

4. European Parliament, 2023, Securing Europe's supply of critical raw materials: The material nature of the EU's strategic goals, available at: *https://www.europarl.europa.eu/RegData/etudes/BRIE/2023/739394/EPRS_BRI(2023)739394_EN.pdf*

For its part, the International Renewable Energy Agency (IRENA) introduces a "short-term scarcity ratio" comparing 2022 mining production with 2030 demand, notably highlighting significant growth in cobalt, lithium, and dysprosium demand in the years ahead (see Figure 2).

FIGURE 2:

Assessing disparity between current supply and expected demand in 2030 (source: IRENA)



While taking stock of these projections is essential, multiple uncertainties hinder a precise assessment of the need for specific raw materials. One such uncertainty is the unpredictable nature of disruptive innovation. Technological innovation affects demand for materials, with factors such as substitution, efficiency improvement, design optimisation, and the introduction of new materials, playing a significant role in shaping CRM demand trends. For instance, since 2015, shifts in EV battery chemistry, including a higher proportion of lithium ferrophosphate (LFP), have significantly reduced reliance on cobalt and nickel[5].

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5. IRENA, 2023, Geopolitics of the energy transition: Critical materials, available at: *https://mc-cd8320d4-36a1-40ac-83cc-3389-cdn-endpoint.azureedge.net/-/media/Files/IRENA/Agency/Publication/2023/Jul/IRENA_Geopolitics_energy_transition_critical_materials_2023.pdf?rev=f289d177cda14b9aaf2d1b4c074798b4*

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PART 1

Geopolitical risks and supply chain vulnerabilities

2.

The risk associated with the criticality of raw materials is often related to a concentrated supply, where a single event, such as a country's inability or unwillingness to export, can result in a severe scarcity of the material. The vulnerability arises from the impact of the absence of the resource on value generation, extending beyond the product's actual value and potentially leading to production stoppages across entire industries. Reliance on a limited number of countries for raw material sourcing makes other countries net importers, placing them in a highly dependent position. Since CRMs are essential inputs for energy transition components, equipment, and devices, potential supply disruption would not only affect the existing infrastructure but also have a significant impact on the pace and cost of decarbonisation[6].

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[6] IRENA, op. cit.

Taking a European perspective, many national and EU-funded mineral-related initiatives have highlighted the potential availability of specific CRMs, including those with a current 100% import dependency, such as antimony, bauxite, lithium, magnesium and REEs[7]. For instance, the Fennoscandian Shield, located between Sweden, Finland and North-western Russia, boasts a unique primary rock formation with rich ore deposits, potentially containing mineable areas. Nevertheless, figures available for the European Union show that it is between 75% and 100% reliant on imports of most materials[8]. Its import dependency on specific CRMs is exceptionally high, reaching 100% for borate, REEs and platinum group metals. Geographically, the EU is highly dependent on CRM imports from China (for several CRMs, including REEs), Russia, Turkey (borate) and the Democratic Republic of the Congo (cobalt). It currently imports all permanent magnets for wind turbines, primarily from China. As a point of reference, the average wind turbine in the EU requires 230 kg of permanent magnets per megawatt. The EU also has a strategic dependency on its supply of magnesium, an essential metal used in the mobility ecosystem to lower vehicle mass. Additionally, suppliers' diversity has decreased globally over the past few years.

FIGURE 3:

Biggest supplier countries of CRMs to the EU (source: European Commission report on the 2020 criticality assessment)

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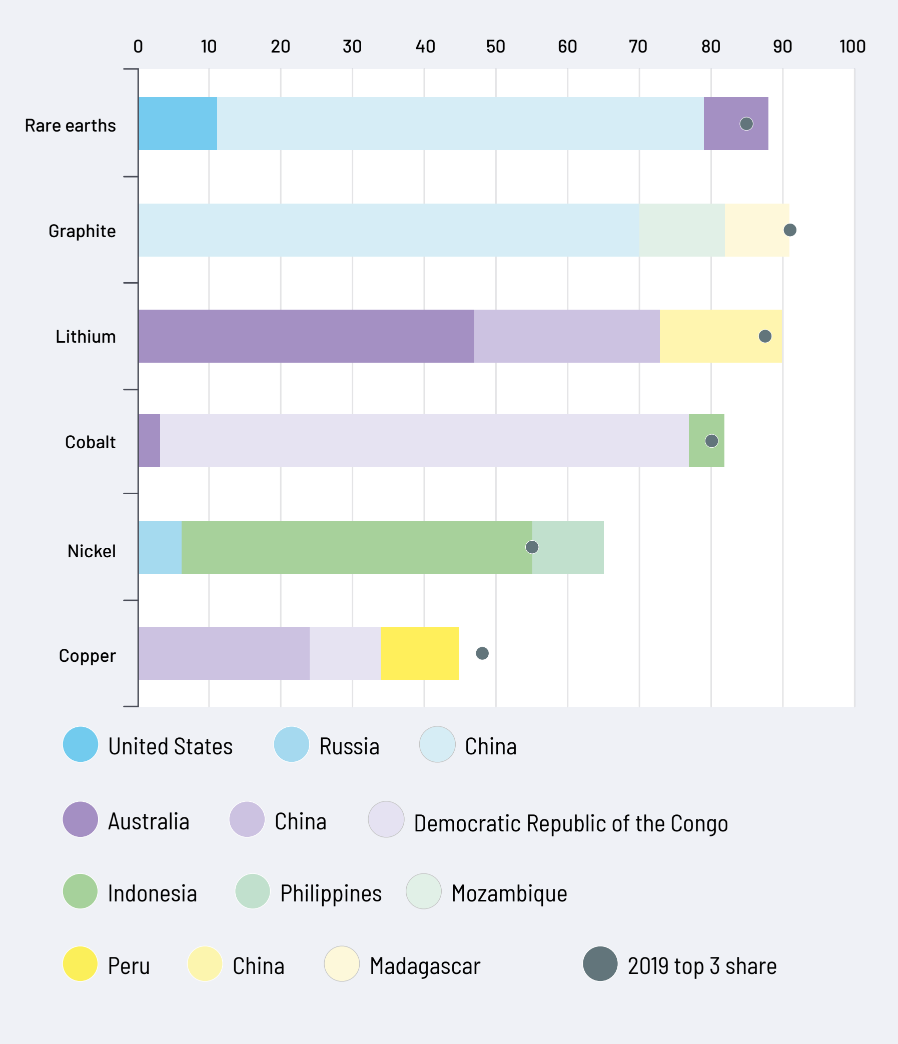
[7] MDPI, 2021, On the Possibilities of Critical Raw Materials Production from the EU's Primary Sources, available at: *https://www.mdpi.com/2079-9276/10/5/50*

[8] European Commission, 2020, Critical Raw Materials Resilience, op. cit.

In comparison with fossil fuels, the supply of CRMs tends to be more concentrated, posing a greater risk to market stability. Dependencies on CRM imports exist at different stages of the supply chain, with significant levels of concentration during extraction but much higher during processing. In fact, China is the sole country processing materials like graphite and dysprosium, and it accounts for 70% of cobalt and almost 60% of lithium and manganese processing[9].

FIGURE 4:
Share of top three producing countries in mining of selected minerals, 2022 (source: IEA)



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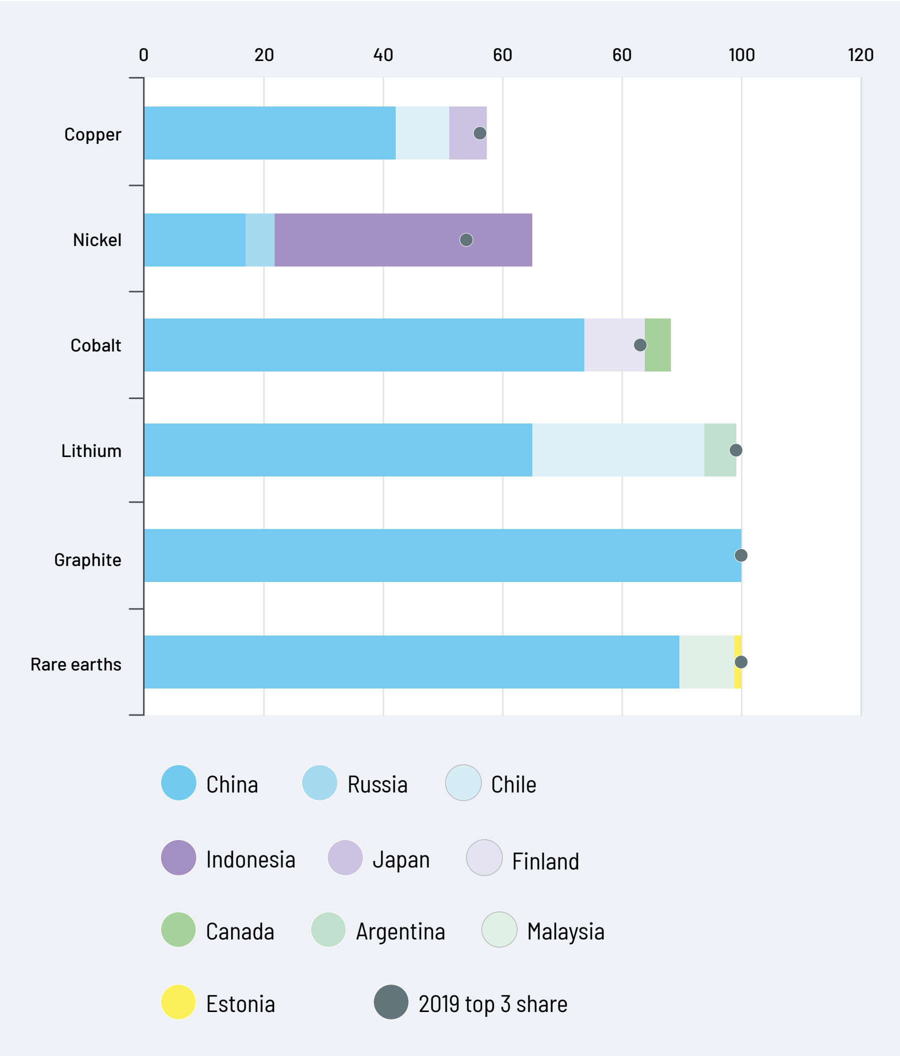
[9] IRENA, op. cit.

FIGURE 5:
Share of top three producing countries in processing of selected minerals, 2022 (source: IEA)



Over the past few decades, as China's domestic demand for CRMs has increased and the country has stepped up its efforts to manage complete CRM value chains, its strategically defined long-term industrial policies have significantly contributed to this objective. Specifically, China holds a dominant market position throughout the entire supply chain of REEs. Whenever there is a shortage in domestic supply, China has also been investing in mining projects for CRMs abroad, including cobalt in the Democratic Republic of the Congo (DRC), Papua New Guinea, and Zambia[10].

CRM supply chains are extensive and intricate, rendering them susceptible to various disruptions, including natural disasters, logistical challenges, unfair trading practices (e.g. export restrictions and dumping), low environmental or health and safety standards, geopolitical tensions, and armed conflicts. The unique characteristics of CRM markets, often smaller in scale compared with bulk commodities like steel, contribute to a high risk of price shocks. Furthermore, these markets experience inelastic supply due to the capital-intensive and lengthy lead times required for investment in increased production capacity. The oligopolistic nature of the mining

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[10] IRENA, op. cit

industry, dominated by a few major companies, further exacerbates this situation. For instance, the top five mining companies control 61% of lithium output, and 56% of cobalt output[11].

Another supply-side risk in CRM production is "co-production dependency". Some CRMs are obtained as by-products of one or more primary metals extracted from geological ores. For instance, almost all indium production, necessary for manufacturing solar panels, energy storage systems, LED lighting, and thin-film electronics, occurs as a by-product of zinc. Consequently, the production of CRMs depends on the dynamics of larger commodity markets, in this case, zinc. This dependency introduces inelasticity and a lack of transparency to CRM markets, which are characterised by a limited number of participants, asymmetric information between market participants and observers, and incomplete data on production, prices, trade flows, and inventories.

Moreover, knowledge gaps persist concerning vulnerabilities within CRM supply chains. In particular, at EU level, coordination to date has been insufficient to effectively monitor, manage the risks of and proactively address potential disruptions in CRM supply.

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[11] IRENA, op. cit.

PART 1

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3.

General social, environmental and ethical considerations linked to CRM sourcing and processing

Supply-side risks associated with CRM production encompass negative environmental, health, ethical and social impacts in various countries, potentially impeding production-scaling efforts and exposing CRM users to reputational risks. To begin with, mining and processing operations entail significant water consumption and various contamination risks, including the discharge of wastewater. Furthermore, hazardous waste is generated, as exemplified by REE mining, which involves the separation and removal of radioactive elements such as uranium and thorium. In fact, for every ton of REEs produced, the mining process generates 13 kg of dust, 9,600 to 12,000 cubic metres of waste gas, 75 cubic metres of wastewater, and one ton of radioactive residue[12].

Environmental events such as floods, droughts and other natural disasters also pose direct risks to CRM production, exacerbated by climate change.

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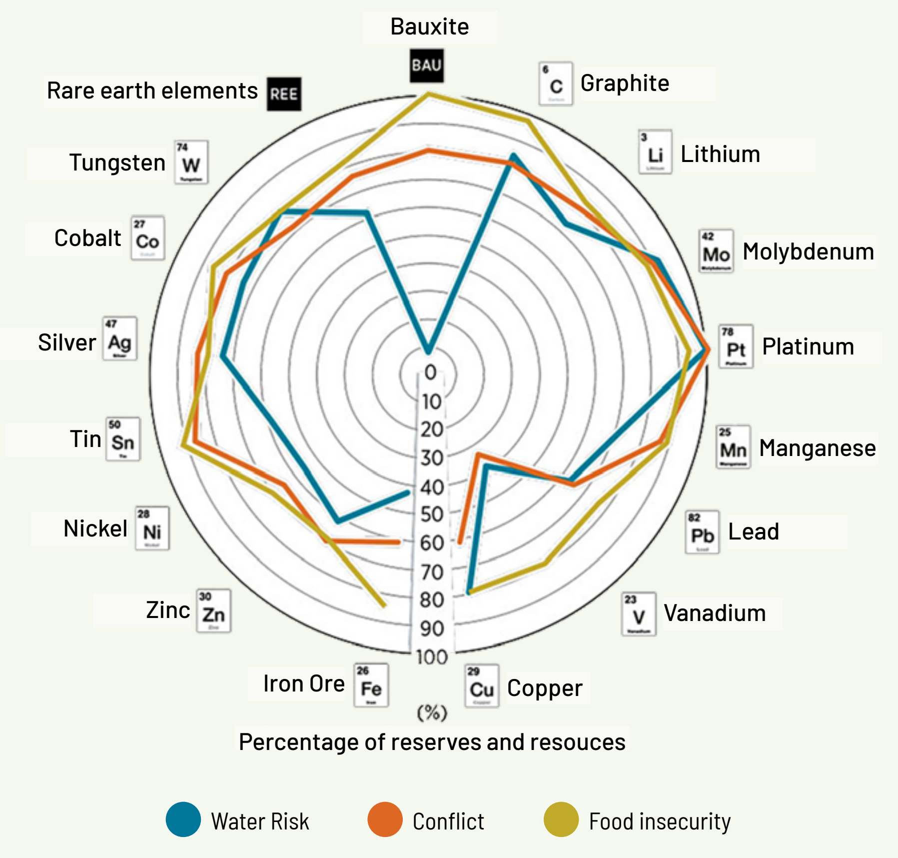
[12] Nayar, J., 2021, Not So "Green" Technology: The Complicated Legacy of Rare Earth Mining. *Harvard International Review*, available at: *https://hir.harvard.edu/not-so-green-technology-the-complicated-legacy-of-rare-earth-mining/*

In particular, water scarcity can hinder copper and lithium production, both highly water-dependent, with over 50% of current production occurring in areas facing high water stress levels[13]. Sourcing and processing of CRMs are also commonly associated with poor working conditions, workplace hazards, and human rights issues. Artisanal cobalt mines in the DRC serve as a stark illustration of these challenges. These sites often lack adequate supervision, leading to hazardous conditions and unsafe mines. This situation has severe consequences for workers' health, including exposure to radon, a radioactive gas that produces harmful particles when it decays. Furthermore, human rights are compromised, with child labour being highly prevalent in these mines: children work in approximately 30% of cobalt small-scale mine sites in the DRC[14]. Additionally, the complex issue of corruption arising from these operations further aggravates human rights concerns[15]. Finally, risks are heightened when mines are located close to indigenous or farming land, which is the case for nearly a third of mining projects relevant to the energy transition. These sites are particularly sensitive to water and food insecurity or the potential for sparking conflicts[16].

FIGURE 6:

Co-occurrence of water risk, conflict and food insecurity for critical mineral mining projects located on or near indigenous or rural land (source: Owen et al., 2022)



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[13] IRENA, op. cit.

[14] European Parliament, op.cit.

[15] Noirfalisse, Q. & Zajtman, A., 2022, Cobalt, l'envers du rêve électrique | ARTE [Video], available at: *https://www.arte.tv/fr/videos/093032-000-A/cobalt-l-envers-du-reve-electrique/*

[16] IRENA, op. cit.

In the context of Europe, the predominantly unfavourable view of mining poses an additional obstacle to the initiation of projects intended to boost the EU's domestic supply of critical raw materials. While the importance of specific raw materials for various industries and technological progress is acknowledged, anxieties regarding environmental impacts and the welfare of local communities have had a significant impact on public opinion. Recent mining projects, such as lithium exploration in Portugal, have, for example, raised concerns about potential adverse effects at the local level, including habitat destruction, water pollution, and contributions to climate change[17]. Moreover, communities often voice apprehension about the lasting impacts on health, livelihoods, the environment, landscapes and cultural heritage.

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[17] European Parliament, op. cit.

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PART 1

EU legislative and policy background

4.

In 2008, the European Commission launched the Raw Materials Initiative[18], recognising the importance of raw materials for the EU's competitiveness and the need for a more resource-efficient and sustainable approach. The initiative introduced 10 actions, including establishing a list of critical raw materials at EU level, which was first published in 2011. To foster innovation and address challenges related to CRMs and non-energy raw materials, the European Innovation Partnership on Raw Materials was formed in 2012[19], serving as a platform for collaboration among stakeholders.

In 2015, EIT RawMaterials[20] was created as an innovation community within the European Institute of Innovation and Technology (EIT) with the objective of driving innovation along the raw materials value chain and securing the supply of CRMs to European industries. Additionally, the Raw Materials Supply Group, an expert panel comprising national authorities

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[18] European Commission, 2008, The raw materials initiative: meeting our critical needs for growth and jobs in Europe, available at: *https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52008DC0699*

[19] European Commission, 2012, Innovation Partnerships: new proposals on raw materials, agriculture and healthy ageing to boost European competitiveness, available at: *https://ec.europa.eu/commission/presscorner/detail/en/IP_12_196*

[20] EIT, Developing raw materials into a major strength for Europe, available at: *https://eitrawmaterials.eu/*

and stakeholders established back in the 1970s, has played a pivotal role in supporting the Commission in legislative proposals, policy initiatives and the implementation of existing EU programmes and policies.

In March 2020, the EU introduced a new industrial strategy[21] to reinforce its industrial and strategic autonomy, focusing on global competitiveness, climate neutrality and digitalisation. As part of this strategy, an action plan on CRMs was released in September 2020, outlining measures to enhance resilience, reduce dependency, promote sustainable sourcing and diversify supply. The plan also led to the establishment of the European Raw Materials Alliance (ERMA)[22] in September 2020, with the aim of facilitating investments in the raw materials value chain, and with a focus on areas such as REE magnets and motors, and materials for energy storage and conversion. ERMA has identified investment projects across Europe, potentially meeting 20% of Europe's rare-earth magnet needs from domestic sources by 2030.

To promote sustainable sourcing and increase awareness and trust, the European Commission published a set of voluntary EU principles for sustainable raw materials in September 2021. These principles aim to align Member States' understanding of sustainable extraction and processing. Additionally, the Commission announced the establishment of a roundtable on environmentally and socially sustainable raw materials mining, bringing together public authorities, industry, NGOs and social partners to foster dialogue on CRM sourcing issues in the EU[23].

Regarding research and innovation (R&I), the European Commission allocated €500 million between 2014 and 2020 to CRM research projects. Additionally, €260 million was committed for the 2021-2022 period under Horizon Europe. The 2023-2024 work programme for Cluster 4 sets out a range of funding opportunities for projects specifically focusing on resilient value chains. Furthermore, important projects of common European interest (IPCEIs)[24] (IPCEIs), such as those in the battery value chain, aim to support strategic initiatives in the development of CRM-related projects.

The European Union's policy and legislation concerning critical raw materials have recently significantly evolved in response to the United States' Inflation Reduction Act (IRA). This 2022 legislative package combines large-scale green subsidies with healthcare savings and new revenue measures, aiming to combat inflation while promoting US clean energy production. The IRA's economic impact on the EU, in terms of competitiveness and innovation, is substantial in the CRM sector. In particular, IRA subsidies are partially linked to the origin of CRMs used in clean technology, potentially leading to trade imbalances.

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[21] European Commission, 2020, A new industrial strategy for Europe, available at: *https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0102*

[22] ERMA, available at: *https://erma.eu/*

[23] European Parliament, op. cit.

[24] TThink Tank European Parliament, 2022, Important projects of common European interest: State of play, available at: *https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2022)729402*

In response to the IRA, in February 2023, the European Commission unveiled a Green Deal Industrial Plan for the Net-Zero Age[25], with a focus on boosting the EU's net-zero industry. The Critical Raw Materials Act (CRMA)[26] was launched on 16 March 2023 as part of this plan. This document introduces the concept of strategic raw materials (SRMs), a subset of CRMs and used in strategic sectors such as renewable energy, digital technology, space and defence. These materials are projected to experience increased demand compared with current supply levels, and scaling up production presents challenges likely to create supply risks in the near future. Based on this assessment, a list of strategic raw materials[27] has been drawn up by the European Commission, which will be reviewed at least every four years[28]. The proposed regulation on CRMs (CRMA) aims to enhance the functioning of the single market by establishing a framework to ensure the EU's access to a secure and sustainable supply of CRMs. The regulation has four specific objectives: strengthening the entire SRM value chain, diversifying the EU's SRM imports, enhancing the EU's capacity to monitor and mitigate CRM supply risks and ensuring the unhindered movement of CRMs and CRM-containing products in the EU market while promoting high levels of environmental protection, circularity and sustainability. The proposal is currently with the European co-legislators and is expected to be finalised by the end of 2023 or the beginning of 2024.

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[25] European Commission, 2023, A Green Deal Industrial Plan for the Net-Zero Age, available at: *https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52023DC0062*

[26] European Commission, 2023, Proposal for a Critical Raw Materials Act, available at: *https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023PC0160*

[27] Annex I to the Proposal for a Regulation of the European Parliament and of the Council establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) 168/2013, (EU) 2018/858, 2018/1724 and (EU) 2019/1020: *resource.html (europa.eu)*

[28] European Commission, 2023, Critical Raw Materials: ensuring secure and sustainable supply chains for EU's green and digital future, available at: *https://ec.europa.eu/commission/presscorner/detail/en/ip_23_1661*

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PART 1

5.

International policies, cooperation and trade

Enhancing domestic production, processing and recycling alone will not be sufficient to meet the entire demand for CRMs in the EU, as outlined in the European Commission's Communication *"A secure and sustainable supply of critical raw materials in support of the twin transition"*[29] accompanying the Critical Raw Materials Act. Consequently, the EU will remain reliant on imports of such raw materials for the majority of its consumption. The purpose of the Communication is to outline the EU's strategy for international engagement concerning CRMs. With no established international cooperation framework, the EU primarily depends on international trade.

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[29] European Commission, 2023, A secure and sustainable supply of critical raw materials in support of the twin transitions, available at: *https://circabc.europa.eu/rest/download/7ce37e41-1d9a-4f96-a24b-4f89207700bf*

Here, the key tool for the EU to shape international trade patterns is the signing of free trade agreements (FTAs) containing CRM sections, as recently achieved with Chile and Australia. FTAs are viewed as a means to enhance stability between partners by establishing a predictable commercial environment and preventing export restrictions on CRMs. This favourable environment can, in particular, incentivise European companies to invest in third countries and facilitate the exchange of CRMs. However, the EU has already reduced its tariffs on CRM purchases to a minimum, meaning that trade barriers associated with the import of these products are already very low. Consequently, the potential benefits of FTAs in stimulating investment in CRMs may be more limited than expected[30].

In this context, the EU and the USA are currently in bilateral negotiations for a critical raw materials agreement, aiming to grant the US and EU FTA partner status. However, this agreement means that the EU would be faced with the risk of joining a discriminatory institutional arrangement, potentially violating Article XXIV of the General Agreement on Tariffs and Trade (GATT)[31] concerning regional trade agreements. Unlike FTAs with economies less influential than the USA, e.g. Australia or Chile, negotiating with the United States carries the risk of establishing an exclusive trade agreement between two major economies. Consequently, this poses challenges to the EU's efforts to maintain a non-discriminatory trade environment while pursuing access to CRMs through bilateral agreements.

In addition to the aforementioned partnerships with Australia and Chile, the EU has recently established Strategic Partnerships with Canada, Ukraine, Kazakhstan and Namibia to address these circumstances. The aim is to streamline raw material value chains, enhance collaboration and promote sustainability and governance standards. The aforementioned European Commission Communication[32] underscores the pivotal role of these tools in strengthening EU cooperation with third countries. This will be achieved by encouraging sustainable investments across CRM value chains with the goal of translating economic opportunities into mutually beneficial outcomes.

Additionally, the European Commission has announced its intention to establish a Critical Raw Materials Club with reliable partners that are keen to develop their own CRM industries[33]. This alliance will focus on strengthening global supply chains, reinforcing the World Trade Organization (WTO), expanding its network of sustainable investment facilitation agreements and free trade agreements and intensifying enforcement to counteract unfair trade practices.

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30. Bruegel, 2023, Why Europe's critical raw strategy has to be international, available at: *https://www.bruegel.org/analysis/why-europes-critical-raw-materials-strategy-has-be-international*

31. World Trade Organization, The General Agreement on Tariffs and Trade (GATT 1947), Article XVIII – XXXVIII, available at: *https://www.wto.org/english/docs_e/legal_e/gatt47_02_e.htm*

32. European Commission, 2023, A secure and sustainable supply of critical raw materials in support of the twin transitions, op. cit.

33. Ibid.

Lastly, forging new partnerships with emerging markets and developing economies can be facilitated through the EU's primary foreign investment policy, the Global Gateway strategy. Launched by the EU in 2021, this strategy is a financial tool designed to tackle global challenges, ranging from fighting climate change to improving health systems, and boosting the competitiveness and security of global supply chains[34]. Leveraging this approach to finance infrastructure, mining and processing of CRM-related projects beyond the EU is expected to yield a substantial influx of investment.

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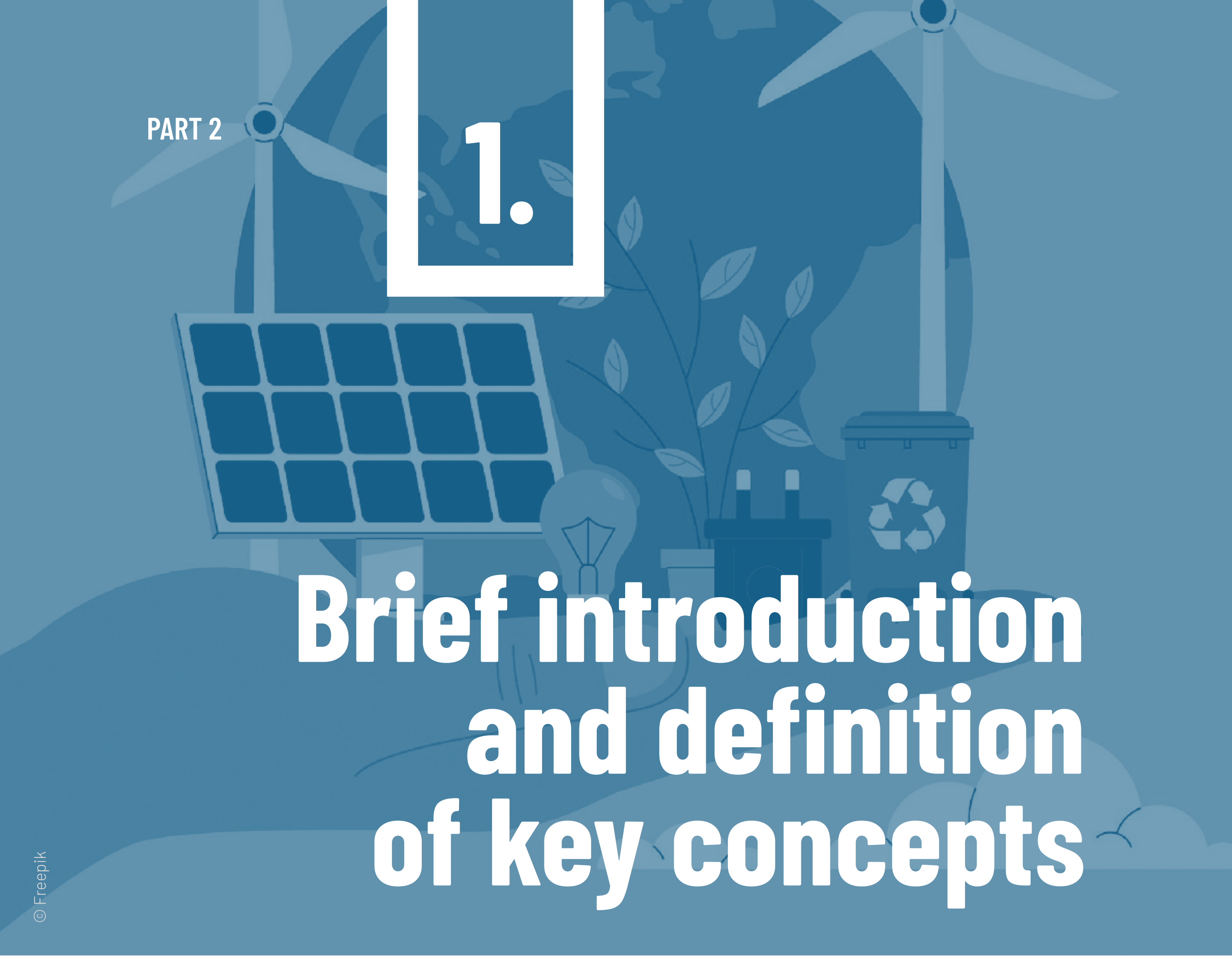
[34] European Commission, Global Gateway, available at: *https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/stronger-europe-world/global-gateway_en*

PART 2

Circular economy, substitution and alternative materials: focus on the relevance of CRMs for selected technologies



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PART 2

1.

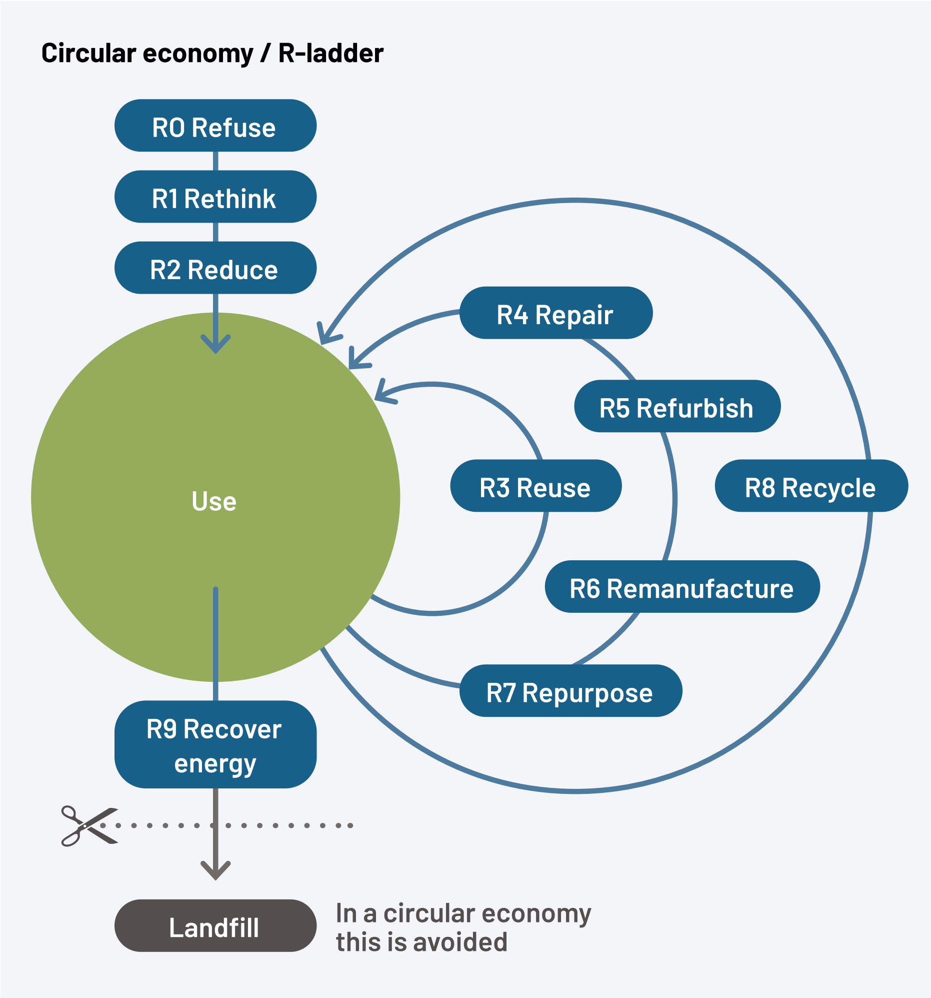
Brief introduction and definition of key concepts

Numerous technologies relying on CRM input have the potential to advance the clean energy transition. In this section, the focus will be particularly on exploring the relevance of CRMs for selected technologies, namely solar photovoltaic (PV), wind, hydrogen, batteries and power electronics. The goal is to pinpoint research priorities, tackle challenges and assess prospective impacts, considering relevant socio-economic factors. Before delving into the details of each, an overview of the key concepts used throughout the analysis is provided.

A. CIRCULAR ECONOMY:

The circular economy concept originated as a response to the linear "take-make-use-dispose" model, aiming to transition towards a regenerative growth model that operates within planetary resource boundaries. In a circular economy, the focus is on preserving the value of products, materials and resources within the economy for as long as possible, thereby minimising waste generation.

FIGURE 7: R-ladder of circularity strategies (source: The Netherlands Environmental Assessment Agency)



This evolving concept has recently seen the emergence of an innovative approach that is gaining prominence: the R-ladder. This hierarchical framework provides guidance for managing products throughout their entire life cycle, encompassing stages such as R0: Refuse, R1: Rethink, R2: Reduce, R3: Reuse, R4: Repair, R5: Refurbish, R6: Remanufacture, R7: Repurpose, R8: Recycle and R9: Recover energy[35].

While this approach should ideally inform policymaking in the relevant areas, the present analysis specifically focuses on the R-ladder within the selected technologies that offer more immediate practicality, with a particular emphasis on recycling.

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[35] Netherlands Environmental Assessment Agency, 2017, Circular economy: Measuring innovation in the product chain, available at: *https://www.pbl.nl/sites/default/files/downloads/pbl-2016-circular-economy-measuring-innovation-in-product-chains-2544.pdf*

B. SUBSTITUTION AND ALTERNATIVE MATERIALS

In the context of this analysis, substitution is regarded as a tool for replacing critical raw materials with more abundant and environmentally sustainable alternatives. It is worth noting that substitution can extend beyond material replacement, offering opportunities to re-evaluate entire product systems, leading to enhanced sustainability.

The European Union recognises the significance of substitution in securing raw material supplies, as evidenced by its strategies and recent legislation, including the Critical Raw Materials Act. Substitution presents a strategic approach to reduce the EU's dependence on raw material imports, complementing efforts to strengthen domestic supply chains, diversify sourcing and enhance resource efficiency[36]. This strategic approach involves the use of alternative substances capable of replacing resource-critical, toxic or underperforming materials. It is particularly valuable in mitigating potential bottlenecks in CRM supplies, especially in sectors such as alternative vehicles, energy, machinery and information technology.

In the upcoming sections, substitution is presented as part of the solution when it comes to addressing the demand for critical raw materials in technological manufacturing. Within this framework, alternative materials are also examined to ensure the continuous advancement of a given technology. The inclusion of substitution and the adoption of these alternatives are interconnected with the goal of enhancing efficiency and performance.

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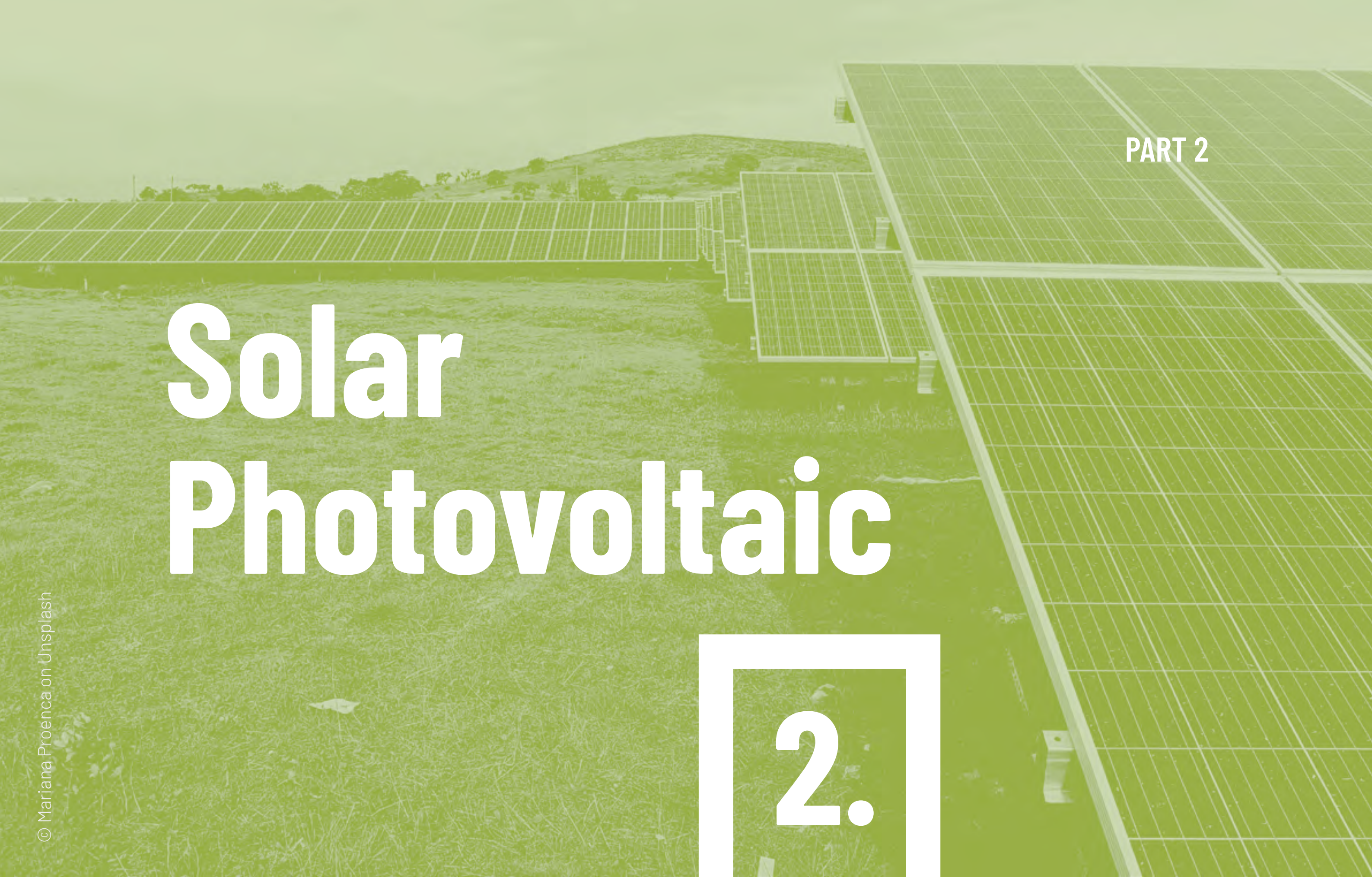
[36] European Commission, 2016, Substitution of critical raw materials in low carbon technologies: lighting, wind turbines and electric vehicles, available at: *https://publications.jrc.ec.europa.eu/repository/handle/JRC103284*



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PART 2

Solar Photovoltaic

2.

A. GENERAL CHALLENGES

Currently, approximately 95% of the photovoltaic (PV) module market is based on the use of crystalline-silicon wafers as the active semiconductor material for light absorption and conversion. The remaining 5% of the market relies on the use of thin-film semiconductors such as cadmium telluride (CdTe) and Copper Indium Gallium Selenide (CIGS) as active materials.

To further enhance the energy conversion efficiency of PV panels, tandem technology is being developed. In this approach, two solar cells are stacked on top of each other, working together to convert sunlight into electricity more efficiently than a single solar cell. The most prevalent tandem configuration to date features a perovskite-based top cell and a silicon-based (or CdTe- or CIGS-based) bottom cell.

In order to achieve climate neutrality by 2050, the current annual global PV module production of approximately 300 GW will need to be increased by a factor of 5-10 over the next decade. This heightened demand will place significant strain on the use of critical raw materials such as silver, indium, bismuth and tellurium, all of which are essential for PV module manufacturing.

In crystalline-silicon PV technology, the key CRMs currently used are silver, bismuth and potentially silicon. Silver serves as a metal contact for the silicon solar cells, and although only a small amount of silver is used per

PV module, it is estimated that in 2023, the total silver consumption for global PV module production will represent approximately 12% of annual worldwide silver production.

Bismuth, on the other hand, is employed for the interconnection of silicon solar cells. Silicon itself serves as the main active absorber material. Although silicon is the second most abundant material in the Earth's crust, nearly all crystalline-silicon PV wafers are currently manufactured in Asia, particularly in China. For CdTe-based PV modules, tellurium emerges as the primary limiting CRM. Lastly, in perovskite-based and tandem modules, the indium used in transparent conductive oxides (TCOs) presents challenges due to its scarcity and needs to be significantly reduced.

B. SCOPE OF R&D ACTIVITIES AND IMPACTS

In order to accommodate an annual PV module production volume of 3 TW (terawatts) over the coming decades, consumption limits have been established for silver, bismuth and indium[37]. These limits are based on the practical assumption that PV production should not exceed 20% of the world's annual production volume for a specific material. They serve as benchmarks for PV R&D, aimed at reducing the usage of silver, bismuth and indium per gigawatt (GW) of silicon PV module production.

Beyond the reduction of material quantities per PV module, PV R&D also concentrates on the complete or partial substitution of these materials with less critical alternatives (e.g. replacing silver contacts with copper ones). Additionally, the focus is on achieving full and easy recyclability of PV modules, enabling the reuse of CRMs from old modules in the production of new PV modules.

In the case of CdTe modules, tellurium is a vital component of the active semiconductor material, forming the core of the PV device. Consequently, the potential for reducing tellurium usage is relatively limited in this context. This limitation significantly restricts the potential for scaling up CdTe PV module production volumes

In addition to technological research, Europe is working towards re-shoring the entire PV production value chain, which is of paramount importance from both a security of supply perspective and a socio-economic standpoint. In particular, re-establishing sufficiently large silicon wafer production in Europe will be crucial in terms of security of supply. However, Europe must take a cautious approach, investing only in those PV technologies that perform best in terms of low CRM usage.

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37. *Journal of Energy & Environmental Science*, 2021, Y. Zhang et al., Design considerations for multi-terawatt scale manufacturing of existing and future photovoltaic technologies: challenges and opportunities related to silver, indium and bismuth consumption, available at: *https://pubs.rsc.org/en/content/articlelanding/2021/ee/d1ee01814k*

PART 2


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3. Wind

A. GENERAL CHALLENGES

Wind energy is set to become Europe's primary source of electricity, potentially supplying up to 50% of all power consumed in the EU by 2050. Steel, iron and cement together account for 90% of the total mass of modern wind turbines. However, regarding critical raw materials, it is crucial for the European sector to ensure access to all CRMs used in wind turbines. This encompasses not only rare earths, nickel, manganese, copper and aluminium but also secondary materials such as ferrous scrap, glass fibre and carbon fibre.

Given the technology trends in wind power, turbines are rapidly increasing in size and moving further offshore. With the global offshore wind industry still in an early growth stage, European companies that acquire expertise in offshore wind supply chains can leverage their knowledge and experience to expand into international markets where offshore wind development is emerging.

Offshore turbine deployment favours the use of permanent magnet (PM) direct-drive (DD) generators, which currently account for a 60% share of the offshore market. The IEA predicts that this will increase to 95% by 2040[38]. Although PMDDs offer higher turbine efficiency and reliability compared with the gearbox option, their use will amplify dependence on CRMs such as copper and REEs, which are essential components of permanent magnets. Economic and geopolitical considerations pose challenges in the use of these materials due to supply chain risks.

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[38] IEA, 2021, op.cit.

B. SCOPE OF R&D ACTIVITIES AND IMPACTS:

The wind energy sector faces several challenges related to critical raw materials, necessitating focused R&D efforts to ensure its long-term sustainability. One key challenge is to reduce reliance on REEs in generator technologies, with particular emphasis on developing alternative PMDD generators or optimising existing ones to minimise REE usage. Additionally, comprehending and addressing air gap behaviour in wind turbines, especially in floating platforms, is crucial due to larger generators requiring more magnet materials as a result of increased air gaps.

R&D activities should encompass predictive modelling and optimisation techniques to efficiently manage air gap dimensions. Advancing alternative generator technologies, such as polyphase transverse flux (PTF)[39], is another priority, with the goal of raising their technology readiness level (TRL) to provide more sustainable and efficient options. Optimising existing generator technologies through innovative cooling methods and materials has the potential to increase power output and energy yield, while also addressing CRM scarcity issues. Lastly, the wind energy sector must develop efficient recycling methods for CRMs, in particular REEs, used in turbine components to reduce environmental impact and reliance on primary resource extraction.

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[39] Polyphase transverse and/or commutated flux systems: *https://patents.google.com/patent/US20110062723*

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PART 2

Hydrogen

4.

A. GENERAL CHALLENGES

Polymer electrolyte water electrolysers (PEWEs) are used to produce hydrogen by electrochemical splitting of water. This process is based on the electrolysis of water, producing hydrogen and oxygen from water using electrical activation. Electrolysers consist of an anode and a cathode, separated by an electrolyte (a conductive substance due to the presence of mobile ions[40]). There are different types of water electrolysis cells, depending on the electrolyte used (e.g. alkaline cell, proton exchange membrane, solid electrolyte cell)[41]).In many instances, PEWEs using proton exchange membrane electrolyser (PEMEL) technology emerge as the most promising option. This is mostly due to their compact design, low footprint, simplicity, versatile operational range, rapid response, safety features, high hydrogen purity and potential to achieve high differential pressures.

The hydrogen and oxygen produced can be used either to regenerate electricity, or as clean transportation fuel. Polymer electrolyte fuel cells (PEFCs) are often chosen for this purpose. The polymer electrolyte allows

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[40] Office of Energy Efficiency & Renewable Energy, Hydrogen Production: Electrolysis, available at: *https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis*

[41] *Journal of The Electrochemical Society*, 2017, Identifying Critical Gaps for Polymer Electrolyte Water Electrolysis Development, available at: *https://iopscience.iop.org/article/10.1149/2.1441704jes/meta*

hydronium ions to pass from the anode, where the hydrogen is oxidised, to the cathode, while the passage of electrons enables the generation of an electric current[42]. Additionally, alkaline exchange water electrolysis (AEWE) and alkaline exchange fuel cells (AEFCs) are gaining prominence. Here, polymer membranes are also employed, but they facilitate the movement of anions (exchanged for hydroxide ions) rather than protons.

Ongoing efforts in the development of all these polymer-based cells are centred on reducing or eliminating the use of CRMs such as platinum- (Pt, used in the cathode) and iridium- (Ir, used in the anode) based electrocatalysts. Furthermore, there is a drive to replace fluorine-containing polymers in electrolytes or diffusion media with alternatives that are less environmentally harmful while delivering comparable performance and durability. The successful integration of non-fluorinated ionic polymer materials into fuel cells and water electrolysers is pivotal to achieving the sustainability and circularity objectives outlined by the EU in its new Circular Economy Action Plan[43] for a hydrogen-based economy. However, devices constructed using these novel materials must surpass their counterparts, which rely on perfluorosulfonic acid (PFSA) ionomers, in terms of performance, durability, longevity and economic feasibility.

B. SCOPE OF R&D ACTIVITIES AND IMPACTS:

In the most highly regarded PEFCs and PEWEs, complete elimination of platinum group metal (PGM) catalysts is an unrealistic goal (at least for applications with high power density requirements). However, with advances in catalyst layer design and engineering optimisation, drastic advances in the mass activity of PGM-type electrocatalysts can be achieved, enabling corresponding reductions in their loadings.

This has already been demonstrated for fuel cells (PEFCs), operating with platinum, the activity of which has increased 1000-fold since the 1960s. The situation is less advanced in the case of PEWEs, where intensive and accelerated R&D efforts must focus on increasing the mass activity of iridium by at least a factor of 40 in the next 5-10 years.

Specifically, for PEMELs, one potential anode catalyst is bimetallic iridium oxide with optimised composition, geometries and structures to enhance iridium's specific activity. Alternatively, nanostructured non-PGM anodes or mixed oxides based on catalytic formulations substituting iridium could also be explored. Nevertheless, the heavy reliance on iridium at the anode still poses a significant bottleneck for large-scale PEMEL adoption. For cathode catalysts, possible routes involve Pt-free catalysts based on transition metal phosphides of controlled size and stoichiometry.

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[42] Larisa Karpenko-Jereb, Takuto Araki, 2018, Fuel Cells and Hydrogen, Chapter 3 - Modeling of Polymer Electrolyte Fuel Cells (pages 41-62), ISBN 9780128114599, available at: *https://www.sciencedirect.com/topics/chemical-engineering/polymer-electrolyte-fuel-cell*

[43] The EU Circular Economy Action Plan: *https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en*

Additionally, a breakthrough in the development of fluorine-free anion exchange (polymer) membranes (AEMs) for AEWE and AEFCs would be transformative for the field of sustainable hydrogen technology. The shift to alkaline operating conditions would open the door for a wide selection of Pt-group metal-free catalysts, such as the very promising class of layered double hydroxide catalysts (e.g. nickel-based). Once anionic polymers with sufficient stability and performance have been synthesised, it will be crucial to achieve their rapid integration into the catalyst layers and optimise the design, fabrication and operation of these layers.

PART 2

Batteries

5.

A. GENERAL CHALLENGES:

Batteries constitute a pivotal component within the future global energy framework. In the Net-Zero Scenario, the projected trajectory entails an impressive 35-fold expansion in installed grid-scale battery storage capacity between 2022 and 2030, forecast to reach 970 GW. In particular, around 170 GW of capacity is set to be installed in 2030 alone, marking a significant escalation from a mere 11 GW in 2022[44]. Simultaneously, the share of EVs in total sales needs to reach around 60% by 2030. Projections envisage a considerable increase in the global electric car fleet, reaching almost 350 million vehicles by 2030, a substantial surge from the 16.5 million EVs on the road at the end of 2021[45].

The market for lithium-ion batteries, the currently dominant technology for EVs and short-term (up to a few hours) energy storage applications, continues to grow at a stunning pace. This growth raises concerns about the corresponding demand for raw materials and the associated environmental and societal impacts, which are becoming increasingly prominent. Several materials used in lithium-ion batteries, such as lithium, nickel, cobalt, graphite and vanadium, fall into the category of critical raw materials. These materials are further affected by geopolitical issues, such as cobalt extraction conditions in the DRC. Concerns are also strongly linked to China's current dominance, with over 90% control of the production of anode and cathode materials, as well as the supply of materials for their

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[44] IEA, Grid-scale Storage, available at: *https://www.iea.org/energy-system/electricity/grid-scale-storage#programmes*

[45] IEA, 2022, *By 2030 EVs represent more than 60% of vehicles sold globally, and require an adequate surge in chargers installed in buildings*, IEA, Paris *https://www.iea.org/reports/by-2030-evs-represent-more-than-60-of-vehicles-sold-globally-and-require-an-adequate-surge-in-chargers-installed-in-buildings*, Licence: CC BY 4.0

manufacture. For these reasons, and to reduce dependence on China, Europe is exploring the possibility of relocating the battery value chain within its own borders and to various like-minded countries externally, with the aim of enhancing supply chain resilience and stabilising manufacturing.

B. SCOPE OF R&D ACTIVITIES AND IMPACTS:

To secure the production of batteries for EVs and short-term (several minutes to a few hours) energy storage applications, reductions in critical raw materials such as nickel, cobalt, graphite and lithium in lithium-ion batteries, or vanadium in redox-flow batteries, are essential. Simultaneously, there is a need to explore new battery chemistries, such as sodium-ion batteries, as well as other chemistries based on metal anodes, including lithium, sodium, magnesium, zinc and aluminium.

R&D activities focused on direct recycling of electrode materials, rather than extraction of metals from spent batteries, are crucial from a circularity and sustainability standpoint. Organic electrode materials show promise in terms of sustainability, but their relatively low energy performance and high self-discharge must be addressed.

For medium-term (days, up to one month) to long-term (months to seasons) storage, new open battery system concepts have been introduced. Here, energy storage is decoupled from the cell volume by using external electrode material storage. Recent pioneering research has been conducted on technologies such as sodium/seawater and aluminium/air batteries. These technologies exploit either sodium metal extracted from seawater or aluminium produced from alumina (Al2O3) as reactive species to store renewable electricity, which can be oxidised to regenerate electricity on demand. These reactive metals have significantly higher volumetric energy densities than hydrogen[46], up to about 10 times that of liquefied hydrogen.

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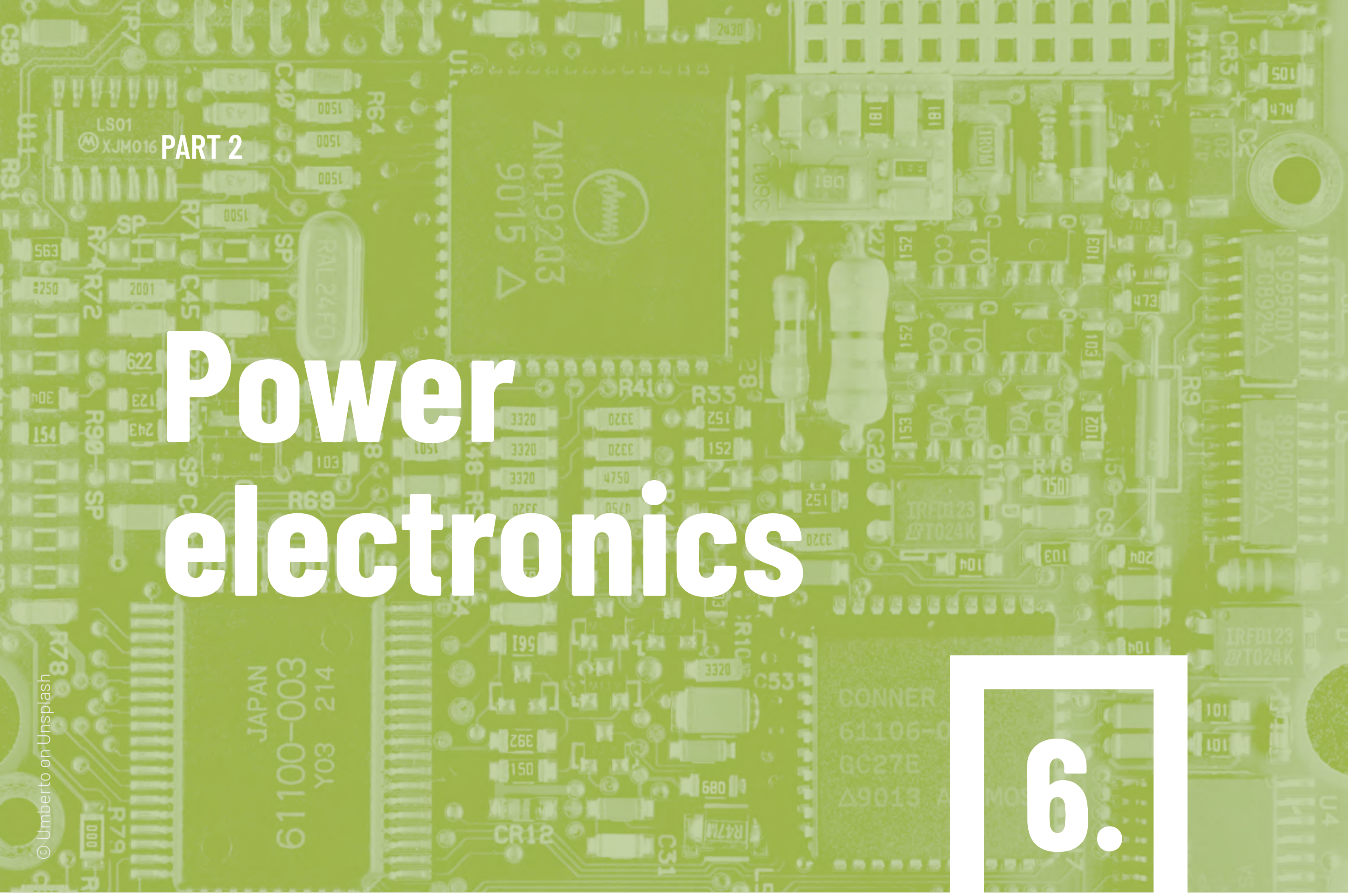
46. L. Barelli et al., 2020, Reactive Metals as Energy Storage and Carrier Media: Use of Aluminum for Power Generation in Fuel Cell-Based Power Plants, *Energy Technology*, vol. 8, no. 9, p. 2000233, doi: 10.1002/ENTE.202000233

PART 2

Power electronics

6.



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A. GENERAL CHALLENGES

In the coming decades, the market for power electronic systems will become aligned with the significant expansion of renewable energy generation, electric mobility, the production of green hydrogen, the intermediate storage of electrical energy using electrochemical means and the corresponding expansion of electrical transmission and distribution networks across all voltage levels. Additionally, power electronics will play a crucial role in various areas, including industry, agriculture and residential, tertiary and data centres, supporting digitalisation and artificial intelligence (AI). Specifically, power electronics will pervade the future energy landscape, encompassing energy storage and management through smart grids. This will involve the use of renewable energies, low-loss power transmission (e.g. with high-voltage direct current (HVDC) lines, also incorporating superconducting power cables or components), efficient power distribution (local grids with bidirectional power flow), as well as the integration of energy storage systems into the grid.

Critical raw materials are essential for constructing power electronic systems and are primarily concentrated in power semiconductors, in the components required to cool these semiconductors and in passive components for filtering currents and voltages. Regarding power semiconductors, wide-bandgap (WBG) materials such as silicon carbide (SiC) and gallium nitride (GaN) are increasingly used in addition to standard silicon (Si) devices. The use of these materials involves relatively small quantities. In contrast, passive components within power electronic systems and the expansion of power grids require significant quantities of copper and aluminium for power lines, as well as iron and steel for electromagnetic components.

Technological advances in power electronics, from the component level to the system level, will be necessary to facilitate the emergence of new technological trends. Furthermore, efforts are needed to incorporate these various objectives into a circular economy framework and, consequently, reduce demand for CRMs.

B. SCOPE OF R&D ACTIVITIES AND IMPACTS

Regarding power electronic systems themselves, the use of WBG power semiconductors plays a pivotal role. While these materials are finding their way into switching power supplies and increasingly into the field of electromobility, their advantages could also be harnessed in energy applications in the future. Despite the critical nature of WBG semiconductors, they are required in very small quantities and can significantly enhance overall efficiency. In fact, losses in power electronic systems could be reduced by approximately half, resulting in not only increased efficiency but also a direct increase in power density. This, in turn, would lead to a significant reduction in the quantities of materials required, including a reduction in the use of other CRMs. Moreover, the use of these high-voltage WBG semiconductors enables device miniaturisation.

The expansion of DC (direct current) grids at ever-higher voltages for power transmission and distribution, or at much higher current by exploiting the benefits of superconductors, also holds the promise of reducing the materials required for grid expansion. This is because DC lines are much more efficient than AC (alternating current) transmission lines for the same material expenditure. Future research will therefore focus on the development of the converter, protection and insulation technologies needed to achieve this objective.

Furthermore, new technologies for medium-frequency galvanic isolation of network sections will gain importance, as they can achieve material savings of more than 90% compared with transformers operating at the prevailing 50/60Hz frequencies. Additionally, an increase in energy efficiency can be attained through the use of superconducting power cables and components, further reducing the usage of CRMs such as copper and aluminium in transmission systems, rare earth material in high-power wind power plants, and plastic and paper as insulating materials due to lower voltage requirements.

PART 3

Policy Recommendations for achieving a sustainable and secure supply of CRMs in the European clean energy sector

Based on the preceding policy analysis, the clean energy community within EERA has developed a set of policy recommendations. These underscore the crucial role of clean energy research in reducing dependence on limited CRM sources, while securing a reliable supply for the clean energy sector and aligning with the European Union's ambitious 2030 and 2050 neutrality goals.

PART 3

General recommendations

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1. PROMOTE A CIRCULAR ECONOMY APPROACH TO CRITICAL RAW MATERIALS

a. Promote a circular economy approach for sustainable CRM use and device longevity.

Enhance material efficiency by prioritising resource efficiency, as well as durability and robustness to increase device longevity. Adopt a comprehensive approach, considering the 9R-ladder (Refuse, Rethink, Reduce, Reuse, Repurpose, Remanufacture, Refurbish, Repair, Recycle, Recover energy) within a circular framework, with the focus on the initial stages. Establish a preferential framework for repurposed devices, prioritising alternatives over recycling.

b. Encourage the substitution of CRMs with alternatives where feasible.

Prioritise the development and implementation of performance-maintaining substitution technologies. Facilitate the substitution of CRMs with renewable, non-critical alternatives, or materials locally available within Europe.

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c. Strengthen the role of R&I in circularity.

R&I will play a pivotal role in reducing reliance on primary CRM sources by adopting a 9R-ladder circular economy perspective and identifying non-critical raw materials as substitutes when feasible.

d. Develop recycling knowledge, infrastructure, technologies and processes.

- Invest in the development of robust recycling infrastructure specifically tailored to efficiently recover critical raw materials from end-of-life electronic and other technological products.
- Promote the advancement of recycling technologies designed for critical raw materials. Invest in R&D to enhance the technological maturity of recycling processes, thereby increasing the percentage of materials that can be recycled.
- Invest in R&D to expand knowledge regarding the recycling of critical raw materials found in electronic and other technological components.
- Invest in new-generation laboratories such as self-driving labs (SDLs) or materials acceleration platforms (MAPs) that combine automation and AI.
- Establish an open database on best practices in recycling and achievable material qualities. Collecting systematic data and extracting metadata is critical for establishing automated software for synthesis based on machine learning, characterisation and post-analysis. Additionally, ensure that the FAIR principles (findable, accessible, interoperable and reusable) are integrated into the processes.

2. SCALE UP INVESTMENT IN RESEARCH, INNOVATION AND TECHNOLOGY DEPLOYMENT ACROSS ALL TRLS

a. Immediately boost R&I investment.

Increased and easier-to-access public and private funding is necessary to accelerate the identification and conception of new technologies that can reduce the usage of critical raw materials and/or improve recovery rates in recycling processes.

b. Establish a coordinated EU CRM supply chain monitoring body.

Create a dedicated EU authority responsible for actively monitoring, assessing and managing vulnerabilities within CRM supply chains. This body should ensure effective coordination between EU Member States, industries and research institutions to proactively address potential CRM supply disruptions.

c. Introduce societal readiness early in the innovation process.

To prevent R&D projects with higher TRLs from failing at later stages for non-technology-related reasons, introducing societal readiness early in the innovation process can help identify optimal pathways and mitigate resistance to necessary transitions in later stages. This includes incorporating stakeholder foresight and considering citizens' perspectives early in the technology development process, before scaling up production capacity.

3. ENSURE A FAIR SUPPLY CHAIN AT GLOBAL, NATIONAL, REGIONAL AND LOCAL LEVELS

a. Promote diversification of CRM supply.

Increase the number of CRM sources to reduce reliance on a single country or a limited number of countries, thereby preventing market monopolies. Prioritise collaboration with like-minded nations that share EU values in this endeavour.

b. Work towards establishing ethical supply chains.

Make sure CRM supply chains take into due consideration social, environmental and humanitarian concerns by aligning primary sourcing strategies with the United Nations Sustainable Development Goals (SDGs).

c. Foster workforce skill development.

Ensure the availability of the required workforce, equipped with essential skills to actively contribute to the CRM sector. Establish appropriate training, reskilling and upskilling schemes to dynamically align the workforce with evolving industry demands.

d. Upscale domestic mining in alignment with the objectives outlined in the EU Critical Raw Materials Act.

Promote responsible and sustainable domestic mining, guided by research insights and in accordance with the CRMA's goal of meeting 10% of domestic demand from domestic mining. Ensure transparent, inclusive decision-making processes to garner social acceptance for European mining projects, while focusing on reducing permitting and other administrative lead times whenever possible. Effective stakeholder engagement, comprehensive environmental impact assessments and robust mitigation measures are essential components of these processes.

4. ESTABLISH EFFECTIVE ECONOMIC MECHANISMS TO ENSURE EUROPE'S COMPETITIVENESS

a. Establish compensation mechanisms for CRM trade.

Develop an appropriate adjustment mechanism to promote mining and technology development in Europe, drawing inspiration from tools like the Carbon Border Adjustment Mechanism (CBAM). This aims to establish the level playing field needed to maintain competitiveness while upholding and promoting ethical CRM value chains.

b. Secure equitable treatment for European CRM value chains globally.

Recognise and guarantee equitable treatment for European mining and processing industries to address distortions in the global level playing field and enhance European competitiveness in the global market.

5. STRATEGICALLY INCREASE INTERNATIONAL COLLABORATION

a. Strengthen global partnerships for CRM supply resilience

Given that the EU may never achieve complete self-sufficiency in CRM supply, Europe should enhance global engagement with ESG-compliant partners. Expanding trade networks will decrease dependence on less reliable regions, enhance supply chain resilience and promote investment predictability and trade stability. This can be achieved by leveraging existing partnerships, including bilateral agreements and the Global Gateway strategy.

b. Implement an international database on CRMs.

Enhance collaboration with like-minded countries to clarify CRM requirements and locations. Draw inspiration from ventures such as the Critical Minerals Mapping Initiative (CMMI)[47], which unites geological organisations from Canada, Australia and the USA to pool expertise and establish a global database for critical mineral geochemistry, including the development of mineral deposit classification schemes.

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[47] United States Geological Survey by Geology, Geophysics, and Geochemistry Science Center, 2023, Critical Minerals Mapping Initiative, available at: *https://www.usgs.gov/centers/gggsc/science/critical-minerals-mapping-initiative-cmmi*

PART 3

Specific recommendations for the selected technologies

1. SOLAR PV

a. In Europe, invest exclusively in solar PV production technologies aligned with the 2050 climate neutrality objectives.

The solar PV industry has established maximum CRM usage values permissible per GW of PV production to ensure compatibility with the upscaling needed to achieve climate neutrality by 2050. Funding should be directed towards the expansion of PV technologies that can operate within these established limits. CRM considerations should be elevated to a central criterion in determining which PV technologies warrant upscaling. Furthermore, allocating additional research funding to accelerate CRM reduction initiatives within PV technology will be essential.

b. Prioritise R&D for full PV module recyclability.

Prioritise R&D activities that focus on achieving full and easy recyclability of PV modules, enabling the reuse of CRMs from old modules in the production of new PV modules.

2. WIND

a. Ensure comprehensive access to CRMs for the European wind industry.

It is crucial that the European wind industry has access to all critical materials used in wind turbines, including not only raw materials such as rare earths, nickel, manganese, copper and aluminium but also secondary materials such as ferrous scrap, glass fibre and carbon fibre.

b. Invest in recycling of permanent magnets.

Given that permanent magnet (PM) direct-drive (DD) generators already account for a 60% share of the offshore market, which the IEA predicts will increase to 95% by 2040, the availability of CRMs such as copper and REEs must be ensured. Dependence on these CRMs can be reduced by investing in research to recycle PMDDs.

3. HYDROGEN

a. Reduce dependence on platinum group metals (PGMs).

Foster research initiatives aimed at decreasing reliance on PGMs, particularly platinum and iridium, within hydrogen-related technologies. Prioritise efforts to enhance the mass activity of platinum and iridium to reduce their usage in technologies such as PEMEL.

b. Encourage research into the development and implementation of alkaline cells.

Promoting a shift towards alkaline exchange water electrolysis (AEWE) and alkaline exchange fuel cells (AEFCs) would lessen reliance on PGMs and enable the EU to explore promising technologies, such as layered double hydroxide catalysts (e.g. nickel-based). Additionally, encourage research into the production of suitably stable anionic polymers, followed by their implementation and optimisation.

4. BATTERIES

a. Promote circular energy storage.

Encourage the development and implementation of innovative circular energy storage systems that facilitate the recycling of active materials during the charging processes powered by renewable sources. This approach will reduce the socio-economic and environmental impacts associated with recycling methods used after a product's end of life.

b. Prioritise silicon-rich anodes in EV batteries.

Promote R&D efforts to expedite the adoption of silicon-rich anodes over nickel-rich cathodes in lithium-ion batteries used in EVs. This transition will enhance battery performance and reduce reliance on critical raw materials.

c. Accelerate adoption of lithium metal all-solid-state batteries.

Advocate the rapid introduction of lithium metal anode all-solid-state batteries into the market. These advanced battery technologies offer improved safety, energy density and sustainability, contributing to the transition to cleaner energy solutions.

d. Promote repurposing over recycling.

Whenever appropriate, promote repurposing of degraded performance devices or components into less critical applications. For instance, repurposing of ageing EV batteries that are losing capacity into stationary domestic batteries where lower energy density does not jeopardise functionality.

e. Enhance European battery production sustainability.

Foster European battery production within a sustainable framework that reduces reliance on critical raw materials. Emphasise the increased utilisation of alternative materials and ensure manufacturing practices prioritise environmental protection and worker well-being.

5. POWER ELECTRONICS

a. Promote wide-bandgap semiconductor integration.

Encourage and invest in the development and implementation of wide-bandgap semiconductors, including materials such as gallium and silicon, in power electronic systems. This integration aims to halve losses in power electronic systems, resulting in not only increased efficiency but also a direct increase in power density and a significant reduction in the quantities of materials required.

b. Embrace direct current (DC) transmission.

Promote the use of DC transmission over alternating current (AC) for power transmission and distribution networks. Prioritise DC-based transmission technologies to improve energy efficiency and reduce the materials required for grid expansion.

c. Develop and integrate superconducting components into systems.

The use of superconducting materials increases energy efficiency and reduces dependence on critical raw materials (e.g. copper, aluminium and rare earths) in power electronics systems.

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