Institute for Sustainable Futures

Beyond Extraction: Pathways for a 1.5°C-aligned Energy Transition with Less Minerals

prepared for Greenpeace International

By The University of Technology Sydney
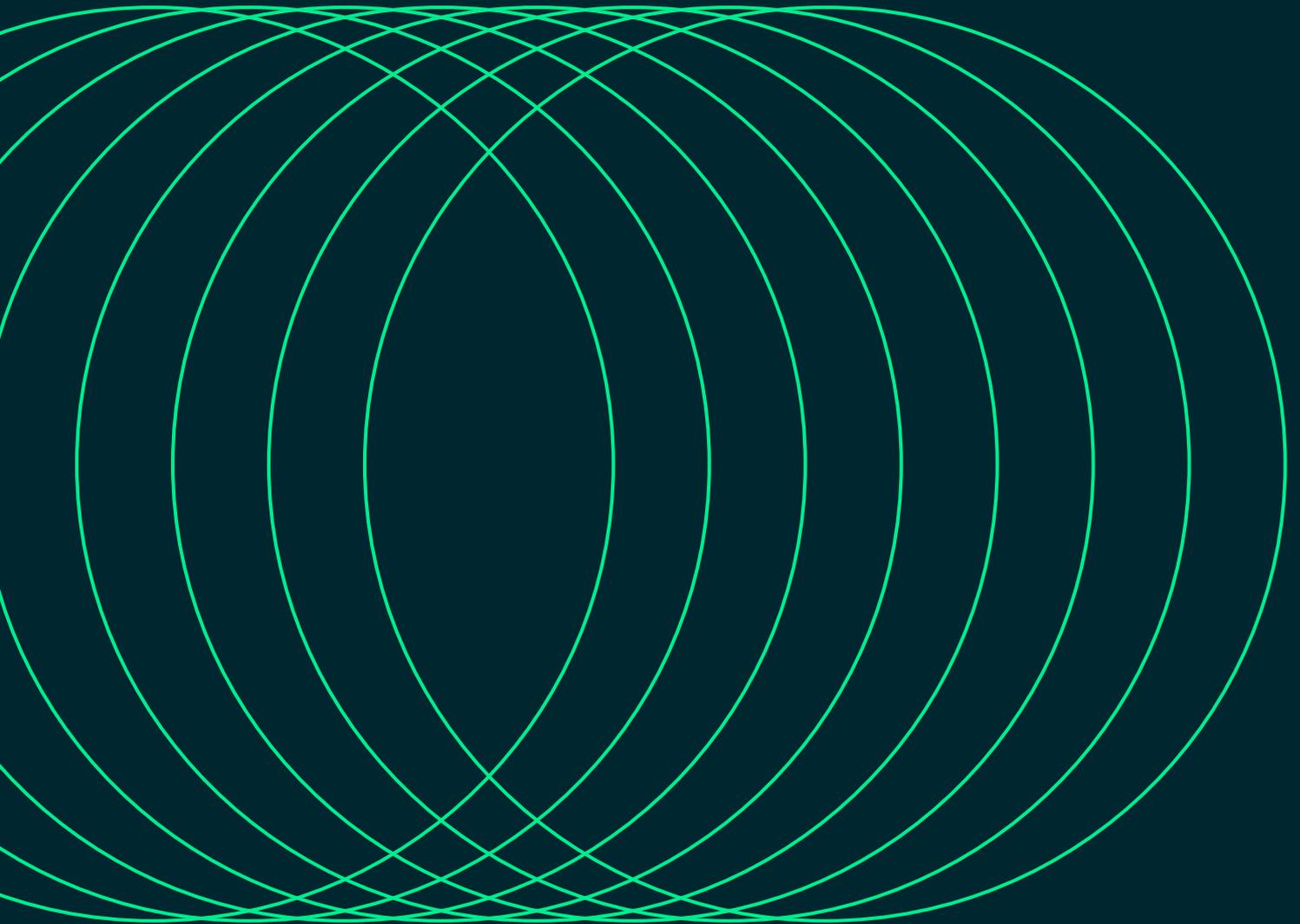Institute for Sustainable Futures

March 2026

About the authors

The Institute for Sustainable Futures (ISF) was established by the University of Technology Sydney in 1996 to work with industry, government and the community to develop sustainable futures through research and consultancy. Our mission is to create change toward sustainable futures that protect and enhance the environment, human wellbeing and social equity. We seek to adopt an inter-disciplinary approach to our work and engage our partner organisations in a collaborative process that emphasises strategic decision-making.

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www.isf.uts.edu.au

Cooperation Partner

This project has been conducted in cooperation with Greenpeace International, located in Amsterdam/ The Netherlands.

Citation

Acknowledgements

Disclaimer

Supplementary material

Background materials for the mapping process documented in chapters 6 and 8 are available at the Greenpeace International Global Restricted Areas map (https://maps.greenpeace.org/maps/gpint/restricted-areas/)

Result tables for the mineral resource calculation are available on the OECM web site (www.uts.edu.au/oecm)

Institute for Sustainable Futures

University of Technology Sydney

PO Box 123, Broadway NSW 2007
Australia

www.isf.edu.au

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Foreword from Greenpeace International

Minerals such as lithium, nickel, copper, and cobalt – often called 'transition minerals' or more broadly 'critical minerals' – are playing an increasingly pivotal role globally. The acquisition, processing, and supply chains of these minerals have increasingly become a dominant geopolitical focal point and source of tension. As new and existing energy technologies continue to develop and expand, the supply and demand for minerals – together with reckless proposals to source them – often grab headlines, whereas the environmental and social impacts of mining take a back seat. The suffering of Indigenous People and Local Communities (IP&LC) and the destruction of nature, both on land and in the deep sea, are often considered the necessary evil required for the energy transition.

Greenpeace believes that, with the right political choices, we can set aside critical ecosystems as off-limits to mining and protect the rights of IP&LC, while ensuring sufficient minerals to fuel an ambitious, Paris Agreement-aligned energy transition. As outlined in Greenpeace's Guiding Principles on Minerals for Energy Transition[1], by using a range of strategies and solutions, including prioritising minerals for transition use and redesigning our transport system with a focus on public and active mobility, the demand for minerals and therefore the need for new mining can be reduced, minimising its adverse impacts on people and nature.

Greenpeace International and the Institute for Sustainable Futures at the University of Technology Sydney have worked together to model the material demand of different 1.5°C-aligned energy transition scenarios. Together, we have visualised pathways for mineral sufficiency and efficiency, set strong recycling targets, and identified substitutes with less-transition-mineral-intensive technologies. These solutions – grounded in the Guiding Principles and aligned with a 1.5°C future – form the basis of the "Progressive Scenario (PRO)" presented in this report.

Greenpeace has also developed a Global Restricted Areas map,[2] which identifies areas in which extractive activities should be restricted because of their critical environmental, ecological, natural, and/or social significance. By comparing the Restricted Areas with the areas where transition mineral reserves are likely to occur, it becomes clear that the manufactured dilemma between destroying forests and the deep sea, as advocated by the mining lobby, is totally unjustified.

The findings in this report are encouraging. As outlined in the subsequent chapters, we can protect people and nature with less mining on land than is often projected, and without opening the ocean frontier to deep-sea mining – while transforming our energy and transport systems from fossil fuels to cheap, abundant, renewable energy powered by solar, wind, and smart energy solutions. This research supports the proposition that, with the right leadership, political choices, and policy incentives, we can harness existing and emerging technologies to minimise warming to no more than 1.5°C while protecting critical ecosystems, and with justice and equity embedded in all solutions related to the use and sourcing of transition minerals.

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1   Greenpeace International (2025). Minerals for Energy Transition: Greenpeace's Guiding Principles. Available at https://www.greenpeace.org/international/publication/75188/minerals-for-energy-transition-greenpeaces-guiding-principles/ (accessed 19 December 2025). All references to Greenpeace in this report refer to Greenpeace International unless otherwise indicated

2   Greenpeace International: Global Restricted Areas Map. https://maps.greenpeace.org/maps/gpint/restricted-areas/

Executive
Summary
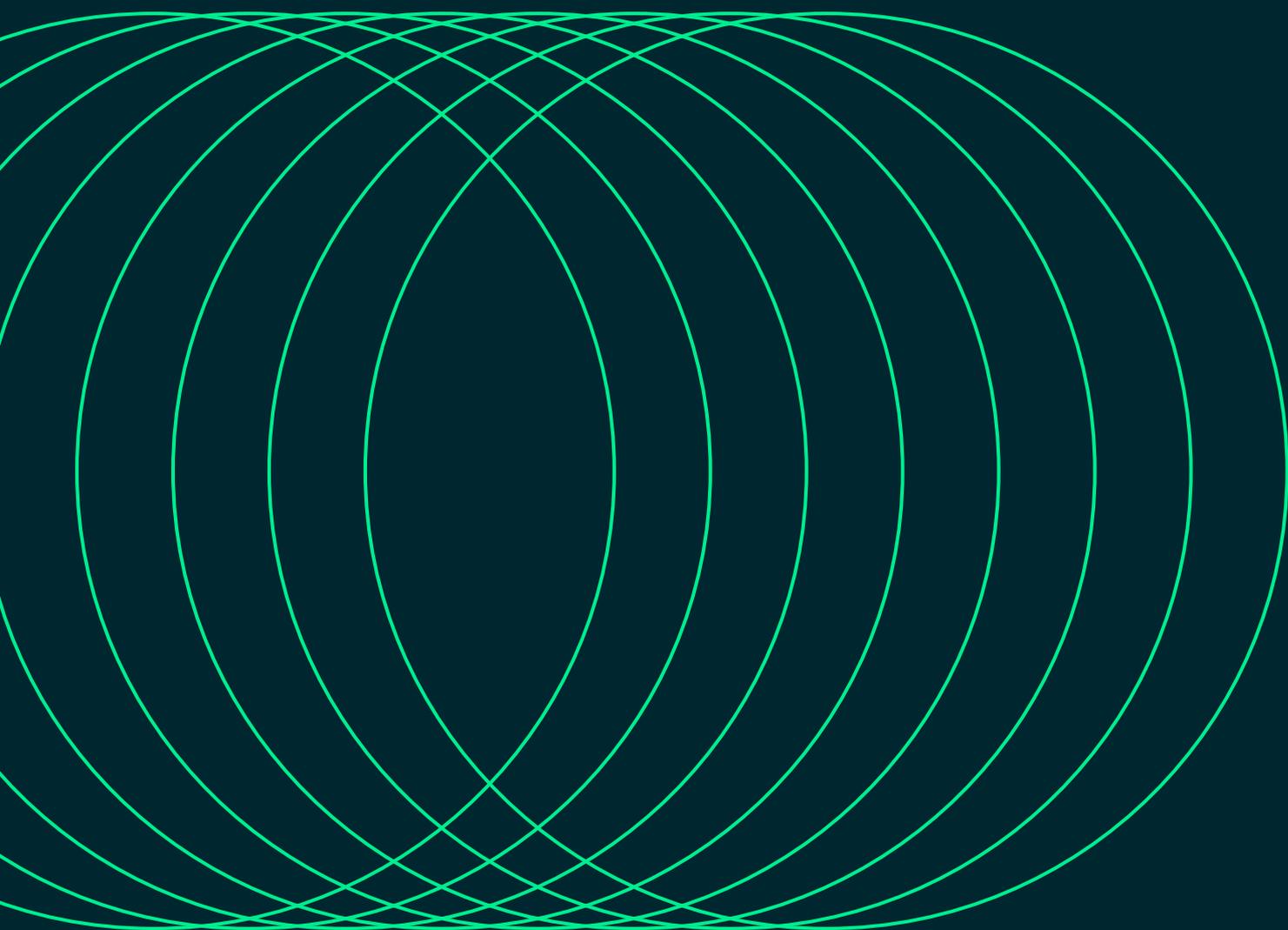
Introduction and approach

A rapid transition to 100% renewable energy and transport systems is needed to meet the goals of the Paris Climate Agreement and increase the chance of keeping global temperature rise below 1.5°C. With the expected growth of renewable energy generation and storage technologies, the resource requirement for such technologies requires careful considerations to minimise the negative environmental and social impacts of mineral mining.

Building on previous UTS-ISF research that explored the future demand for minerals requirements, responsible sourcing of minerals and the available supplies in the context of a renewable energy future[3 4], this study aims to update mineral demand prediction with latest technological advancement, particularly on battery chemistries, and examine strategies that can reduce overall demands like recycling and shift of transport model.

Three scenarios were developed, using the One Earth Climate Model (OECM) as the base energy assessment model, to examine the mineral resources requirements under different assumptions as detailed in Chapter 5:

i)   OECM Net Zero Scenario (OECM);

ii)   Progressive Scenario (PRO); and

iii) Progressive Accelerated Sodium-ion Battery Scenario (PRO-Na-ion).

Mapping Restricted Areas and Reserves Proxy Areas

To analyse the impact of future mining projects, Greenpeace has developed a Restricted Areas Map that identifies regions of critical ecological, natural, or social value. They simultaneously mapped Reserves Proxy Areas, or areas of potential mining activity, specifically for nickel, lithium, and cobalt. Understanding the spatial confluence of these two types of areas can inform future decisions on the exploration and exploitation of the mineral resources that underpin the energy transition.

Key Results

The resource requirements for nine minerals: copper, cobalt, graphite, dysprosium, lithium, manganese, neodymium, nickel, and vanadium were calculated.

Comparison of Scenarios

The calculated mineral requirements for the OECM, the Progressive Scenario (PRO), and the Progressive Accelerated Na-ion Scenario (PRO-Na-ion) are compared with the results of the IEA report 'Global Critical Mineral Outlook 2025'. There are significant differences between the five scenarios that are compared in this section – not only regarding the assumed parameters for the mineral requirements, but also regarding the assumed energy demands and supply structures. The transport demand in both IEA scenarios is significantly higher than under the OECM and both Progressive scenarios. This leads to different battery market volumes. Furthermore, the material that is reused from the recycling collection is considered under the IEA scenarios, but not under the OECM/PRO scenarios. Therefore, there are significant uncertainties due to the methodological differences.

The IEA includes the copper demand for power generation and storage technologies and electric grids in their assessments, whereas the assessment of the OECM and PRO focuses on power generation and storage only. Therefore, the copper demand for power grids is deducted from the IEA results when comparing scenarios.

The results of the IEA scenarios 'Stated Policies Scenario' (STEPS) and 'Net-Zero Emissions by 2050' (NZE) are compared with the OECM and the PRO scenario.

3   Teske, S., Florin, N., Dominish, E., Giurco, D. (2016) Renewable Energy and Deep-Sea Mining: Supply, Demand and Scenarios. Report prepared by ISF for J.M. Kaplan Fund, Oceans 5 and Synchronicity Earth, July 2016, https://opus.lib.uts.edu.au/bitstream/10453/67336/1/DSM%20-%20 RE%20resource%20Report_9_FINAL%20DRAFT-NEWTITLE-ANDNAME.pdf (accessed 19 December 2025)

4   Dominish, E., Florin, N., Teske, S., 2019, Responsible Minerals Sourcing for Renewable Energy. Report prepared for Earthworks by the Institute for Sustainable Futures, University of Technology Sydney. Available at https://utsd8.prod.acquia-sites.com/sites/default/files/2019-04/ ISFEarthworks_Responsible%20minerals%20sourcing%20for%20renewable%20energy_Report.pdf (accessed 19 December 2025)

Figure: E1: Annual mineral demands, including recycling – comparison of IEA and OECM/PRO scenarios

Note: IEA recycling rates are lower than the ones used for OECM & PRO scenarios.
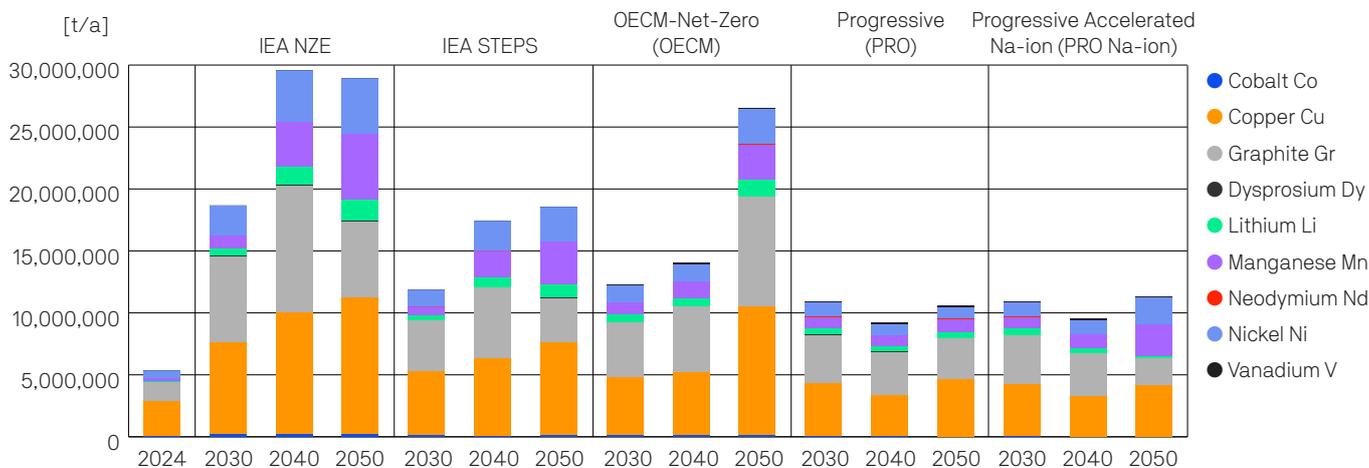
The demand for the analysed minerals in IEA Net-Zero is higher than under the OECM or PRO scenario. Besides the different recycling rates and methodologies applied, the difference is also attributable to the lower overall energy demand. The OECM and PRO scenarios are based on more-ambitious efficiency measures combined with an assumed lower annual production capacity for EVs and increased public transport services.

However, the trajectories in all scenarios shows the same trend. The PRO scenario has a lower resource demand than the IEA and OECM pathways due to the smaller market for EVs and the larger role for public transport (road and rail), amongst other factors.

Progressive Scenario – Mineral requirements with recycling

The Progressive Scenario (PRO) combines the ambitious energy efficiency measures of the OECM, with a shift towards high shares of public transport and other factors. The highest impact measure for mineral resource efficiency is a combination of lower demand and high recycling. The PRO Scenario has higher recycling quotes than the OECM, but the impact of reduced consumption is the key driver of the significantly lower mineral demand. The reduced resource requirement of the PRO is partly due to the assumed lower number of vehicles produced until 2050. The OECM leads to an accumulated global vehicle fleet of 2 billion passenger cars, about 800 million more than the estimated 1.2 billion cars[5] in 2022. The increase in vehicles in the PRO is 400 million, leading to 1.6 billion global passenger vehicles in 2050. Moreover, the different mix of battery technologies also contributes to a reduction in the mineral resources required.

High recycling rates reduce the pressure on resource requirements even further under the PRO. The highest annual mining extraction under the PRO (including recycling) is reduced for all minerals except vanadium to factors between 2 and 6 across all analysed minerals compared with the mineral demand for energy transition technologies in 2024. For vanadium, the annual demand is even slightly higher in 2040 and 2050 than that under the OECM due to the increased deployment of redox flow storage systems for power grid stabilisation and storage services.

5   Teske, S., Bratzel, S., Tellermann, R., Stephan, B., Vargas, M. (2022). Net Zero: The Remaining Global Market Volume for Internal Combustion Engines in Light-Duty Vehicles under a 1.5°C Carbon Budget Trajectory. Energies, 15(21), 8037. https://doi.org/10.3390/en15218037

Table: E1: Progressive Scenario (PRO) – Development of annual mineral demands, including recycling

Material Demand With Recycling		Material Demand for Energy Transition Technologies in 2024	Global Mining 2024	Share Energy Transition Materials	Annual Material Demand in 2030 Compared with 2024	Annual Material Demand in 2050 Compared with 2024	Annual Material Demand from Mining (Zero if material is sourced entirely from recycling)				
							2030	2035	2040	2045	2050
		[t/a]	[t/a]	[%]	[1]	[1]	[t/a]	[t/a]	[t/a]	[t/a]	[t/a]
Cobalt	Co	70,600	290,000	24%	1.8	0.0	124,000	173,000	98,400	0	394
Copper	Cu	2,808,000	23,000,000	12%	1.5	1.7	4,197,000	4,190,000	3,330,000	3,219,000	4,690,000
Graphite	Gr	1,505,000	1,600,000	94%	2.6	2.2	3,931,000	4,221,000	3,472,000	2,315,000	3,277,000
Dysprosium	Dy	1,530	1,800	85%	1.0	2.1	1,490	1,640	1,370	2,270	3,140
Lithium	Li	128,000	240,000	53%	4.3	3.6	545,000	514,000	421,000	329,000	465,000
Manganese	Mn	186,000	20,000,000	1%	4.9	6.0	914,000	939,000	894,000	836,000	1,107,000
Neodymium	Nd	14,600	16,000	91%	0.2	1.4	3,130	6,310	5,060	14,900	20,800
Nickel	Ni	562,000	3,700,000	15%	2.0	1.7	1,126,000	1,111,000	865,000	695,000	952,000
Vanadium	V	892	100,000	1%	60.4	102.4	53,900	112,000	104,000	93,600	91,300

Table E2 shows the overall mineral resources required compared with the known mineral reserves and resources under the PRO. The assumptions under PRO have highest impact in lowering the utilisation rate for lithium (-25%), cobalt (-22%), graphite (-19%) and nickel (-11%) when compared to the OECM material demand versus reserves. Compared with the resources, all the analysed minerals have a material demand for energy transition technologies of less than 12%.

Table E2: Progressive Scenario (PRO): Development of annual mineral demands, including recycling

Material Demand with Recycling.		Current Global Reserves (USGS Statistic 2024)	Current Global Resources (USGS Statistic 2024)	Total 2024–2050	Total Material Demand in comparison with global reserves & resources	
					Cumulative Material Demand (Scenario) in [tonnes] 2024–2050 versus Reserves	Cumulative Material Demand (Scenario) in [tonnes] 2024–2050 versus Resources
		[t]	[t]	[t]	[%]	[%]
Cobalt	Co	11,000,000	25,000,000	2,617,000	24%	10%
Copper	Cu	980,000,000	3,500,000,000	102,437,000	10%	3%
Graphite	Gr	290,000,000	800,000,000	90,464,000	31%	11%
Dysprosium	Dy	1,100,000	1,980,000	56,000	5%	3%
Lithium	Li	30,000,000	115,000,000	12,317,000	41%	11%
Manganese	Mn	1,700,000,000	UNKNOWN	24,809,000	1%	UNKNOWN
Neodymium	Nd	12,800,000	23,040,000	281,000	2%	1%
Nickel	Ni	130,000,000	350,000,000	26,697,000	21%	8%
Vanadium	V	18,000,000	63,000,000	1,929,000	11%	3%

Progressive Scenario with Accelerated Na-ion – Mineral requirements with recycling

The Progressive with Accelerated Na-Ion Scenario (PRO-Na-ion) aims to reduce the global lithium demand further by assuming a different battery mix. A direct comparison of both Progressive scenarios shows that the demand for graphite and vanadium also decreases. This scenario is achievable if the Na-ion battery technology dominates the market from around 2040 onwards.

Table E3: Annual mineral demand increase in 2050 compared to 2024 demand under the PRO and PRO Accelerated Na-Ion scenarios, including recycling.

	2024 -2050	
	PRO	PRO-Na-ion
Cobalt	0.0	0.3
Copper	1.7	1.5
Graphite	2.2	1.4
Dysprosium	2.1	2.1
Lithium	3.6	1.2
Manganese	6.0	13.7
Neodymium	1.4	1.4
Nickel	1.7	3.9
Vanadium	102.4	47.2

Table E4 shows that the utilisation rate for all minerals compared with the known resources is less than or equal to 10%, whereas compared with currently known reserves, all of the analysed minerals have an utilisation rate of less than or equal to 35%.

Table E4: Progressive Scenario Accelerated Na-ion (PRO-Na-ion) – Development of annual mineral demands, including recycling

Material Demand With Recycling.		Total Material Demand Relative to Global Reserves & Resources				
		Current Global Reserves (Statistic 2024)	Current Global Resources (Statistic 2024)	Total 2024–2050	Cumulative Material Demand (Scenario) in [tonnes] 2024–2050 versus Reserves	Cumulative Material Demand (Scenario) in [tonnes] 2024–2050 versus Resources
		[t]	[t]	[t]	[%]	[%]
Cobalt	Co	11,000,000	25,000,000	1,907,000	17%	8%
Copper	Cu	980,000,000	3,500,000,000	99,144,000	10%	3%
Graphite	Gr	290,000,000	800,000,000	81,894,000	28%	10%
Dysprosium	Dy	1,100,000	1,980,000	57,000	5%	3%
Lithium	Li	30,000,000	115,000,000	10,462,000	35%	9%
Manganese	Mn	1,700,000,000	UNKNOWN	33,402,000	2%	UNKNOWN
Neodymium	Nd	12,800,000	23,040,000	283,000	2%	1%
Nickel	Ni	130,000,000	350,000,000	33,631,000	26%	10%
Vanadium	V	18,000,000	63,000,000	1,695,000	9%	3%

Comparison of OECM and PRO

Finally, the annual mineral demands under the OECM and PRO pathways are compared for the years 2030–2050 in five-year intervals. The successful implementation of the PRO assumptions in the transport sector will lead to significant resource savings and will reduce the volume of total mineral extraction required between 2024 and 2050 by one third compared to the OECM. An accelerated Na-ion battery pathway would have a significant impact on reducing the global lithium demand.

Figure E2: Annual mineral demands, including recycling – comparison of scenarios
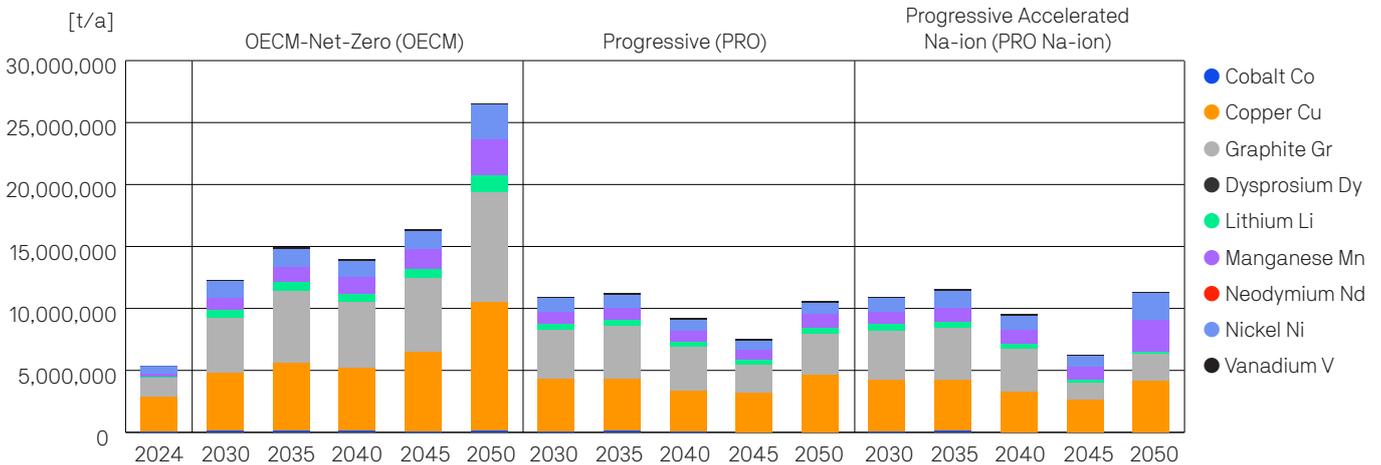
The significant material demand reduction between the OECM and the Progressive Accelerated Na-ion Scenario (PRO-Na-ion) – both with recycling – (see Figure E2 and Figure E3) shows that material reduction does not end with recycling. A progressive transport policy that prioritises public transport and reduces individual transport leads to less vehicles and therefore less material demand for EVs. Both Progressive scenarios successfully reduce the peak mineral demand from around 27 million tonnes under the OECM to just over 10 million tonnes.

In comparison with the PRO scenario, the Progressive Accelerated (PRO-Na-ion) case reduced the demand for lithium even further by shifting battery technologies towards sodium ion (Na-ion) batteries.

Reducing minerals for the required energy transition to decarbonise the global economy must follow a three-step approach:

1. Maximise recycling of materials (circular economy)
2. Reduce the production volume of electric vehicles by implementing public transport and shared vehicles
3. Prioritise battery technologies with high material efficiencies and abundant minerals to reduce mining of rare or difficult-to-obtain materials.

Figure E3: Comparison of lithium demand under five different scenarios including recycling
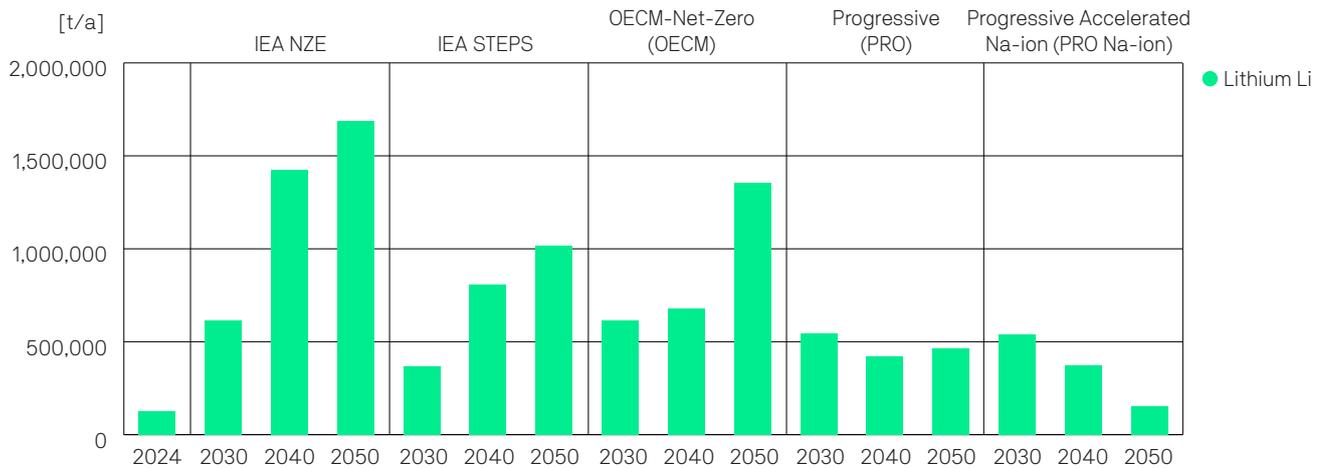
Comparison of projected mineral demands of cobalt, lithium and nickel with estimated reserves outside Restricted Areas

When Reserves Proxy Areas are superimposed on the Restricted Areas Map, the analysis suggests approximately 45% of global nickel reserves, 57% of lithium reserves, and 27% of cobalt reserves as reported by USGS (2025) may lie within Restricted Areas that should be off-limits to mining. Comparing just the estimated reserves (by area) located outside key Restricted Areas together with the PRO-Na-ion Scenario demand estimate, transition demand represents the equivalent of 47% of nickel reserves, 81% of lithium reserves, and 24% of cobalt reserves located outside these areas, suggesting that there are enough reserves outside key Restricted Areas to satisfy the demand in this scenario.

Although individual reserve boundaries cannot be precisely defined at the global scale, this approach provides a scalable framework for identifying the development pressures that may emerge globally in Restricted Areas. This analysis highlights the need to accelerate solutions that reduce our dependence on newly mined minerals to reduce potential development pressures.

Recommendations

The renewable energy transition is an opportunity to promote the stewardship of both primary sources and technologies at end-of-life. As renewable energy technologies become the major driver of demand for the key metals examined in this report, there is potential to improve the sustainability of the supply chain for these metals more broadly.

Five key interventions are required for a green and just energy transition with less minerals:

1. Reduce mineral demand through investment and delivery of shared mobility systems like improved public transport and smaller, more efficient cars

2. Incentivise battery technology substitution towards alternatives requiring less lithium, cobalt, or nickel

3. Design for circularity and scale up recycling

4. Prioritise mineral use for essential energy transition needs

5. Protect 'Key Restricted Areas' from mining development.

1 Introduction
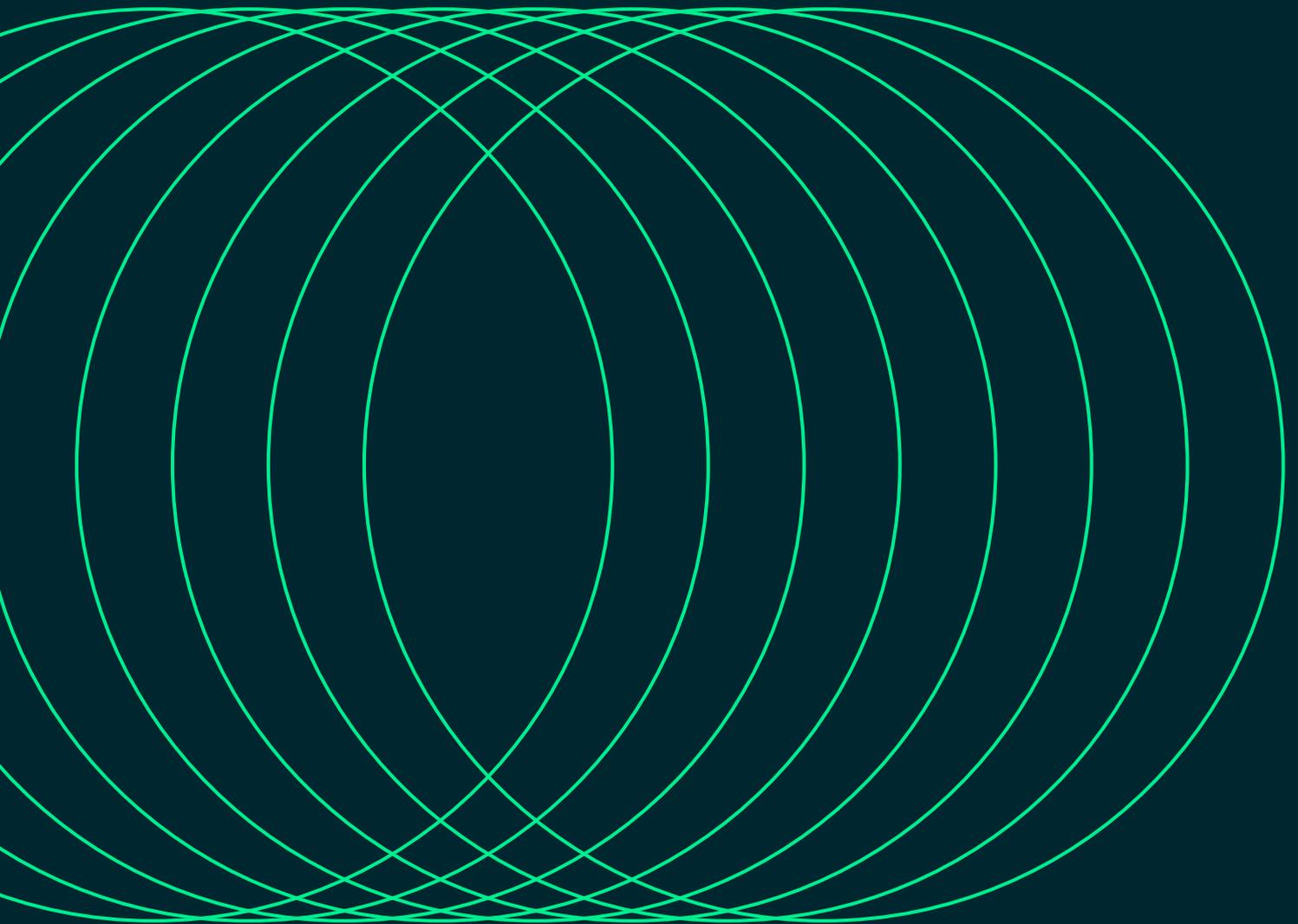
The Paris Climate Agreement aims to hold global warming to well below 2 degrees Celsius (°C) and to "pursue efforts" to limit it to 1.5°C. To accomplish this, countries have submitted Intended Nationally Determined Contributions (NDCs) outlining their post-2020 climate actions. In 2017, the Institute for Sustainable Futures (ISF) at the University of Technology Sydney (UTS) started an interdisciplinary research project[6] to develop practical pathways to achieve the Paris climate goals based on a detailed bottom-up examination of the potential of the energy sector, to avoid reliance on net negative emissions later.

The research has been published with Springer Nature in two 500-page open access books 'Achieving the Paris Climate Agreement Goals' in February 2019 (Part 1) and August 2022 (Part 2), which together were downloaded over 450,000 times by mid-2023.

The study focuses on the ways in which humans produce energy, because energy-related carbon dioxide (CO_2) emissions are the main driver of climate change. The analysis also considers the development pathways for non-energy-related emissions and mitigation measures for them, because it is essential to address their contributions if we are to achieve the Paris climate change targets. In this context, ISF has developed 100% renewable energy scenarios for over 50 countries.

As well as country-specific 100% renewable energy scenarios, ISF has expanded the methodology and is now able to develop energy pathways consistent with the 1.5°C Paris Climate Agreement requirement for specific industry sectors, such as the steel, aluminium, and chemical industries, as well as detailed mobility and transport scenarios.

Interdisciplinary Research: Responsible Resources, Circular Economy, and 1.5°C Paris-aligned Pathways

The One Earth Climate Model (OECM) not only focuses on energy and emissions pathways but provides a holistic approach that also considers resource requirements. In 2016, UTS-ISF published the first research to investigate the metal resource requirements for a global 100% renewable energy-based pathway[7]. A second analysis, published in 2019[8], investigated the responsible sourcing of minerals and examined the intersection of the future demand for metals and their available supply in the context of a renewable energy future. New technologies for the decarbonisation of the energy system globally will shift the requirements of global mineral mining.

Metals in increasing demand that might be subject to future mining operations are considered in this analysis, to understand the likely increases in their demand and the possible implications for mining. These insights can also inform consideration of the ways to reduce demand for these minerals by increasing the intensity of use, for example by shifting from private vehicles to shared vehicles and transport, and by recycling minerals at the end of their technical lifetimes.

The different metals considered are:

1. Copper
2. Cobalt
3. Graphite
4. Dysprosium
5. Lithium
6. Manganese
7. Neodymium
8. Nickel
9. Vanadium

In this report, we focus on the listed minerals because they are all required in the key energy transition technologies and could potentially be sourced in sensitive areas rich in biodiversity.

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6   In co-operation with the German Aero Space Center (DLR) and the University of Melbourne. The One Earth Climate Model methodology is based on the Greenpeace International Energy [R]evolution scenario series (2004 – 2015).

7   Teske, S., Florin, N., Dominish, E., Giurco, D. (2016). Renewable Energy and Deep-Sea Mining: Supply, Demand, and Scenarios. Report prepared by ISF for J.M.Kaplan Fund, Oceans 5 and Synchronicity Earth, July 2016, https://opus.lib.uts.edu.au/bitstream/10453/67336/1/DSM%20-%20RE%20resource%20Report_9_FINAL%20DRAFT-NEWTITLE-ANDNAME.pdf (accessed 19 December 2025)

8   Dominish, E., Florin, N., Teske, S. (2019), 'Responsible Minerals Sourcing for Renewable Energy', Report prepared for Earthworks by the Institute for Sustainable Futures, University of Technology Sydney. https://earthworks.org/wp-content/uploads/2019/04/Responsible-minerals-sourcing-for-renewable-energy-MCEC_UTS_Earthworks-Report.pdf (accessed 19 December 2025)

2 The Carbon Budget and 1.5°C Global Temperature Increase

According to the United Nations Framework Convention on Climate Change (UNFCCC), to limit global warming to 1.5°C, greenhouse gas (GHG) emissions must peak before 2025 at the latest and decline to 43% by 2030. At the time of writing – November 2025 – global emissions are still increasing but are expected to plateau within the next few years.

The latest available scientific information is contained in the Intergovernmental Panel on Climate Change (IPCC)'s Sixth Assessment Report *Climate Change 2021: The Physical Science Basis*[9]. According to the IPCC definition, 67% likelihood is 'good', whereas 50% likelihood is 'fair' (Table 1). The OECM aims to limit the global mean temperature rise to 1.5°C with 'good' likelihood. Therefore, the 'science-based target' for the OECM 1.5°C pathway, in terms of the global carbon budget between 2020 and 2050, is set between 400 Gt CO_2 (67% likelihood) and 425 Gt CO_2 (60% likelihood).

Table 1: Carbon budget and likelihood of limiting global warming to temperature targets – IPCC AR6, 2021

Global Warming between 1850-1900 and 2010-2019°C		Historical cumulative CO_2 emissions from 1850 to 1900 [$GtCO_2$]					
1.07 (0.8-1.3; likely range)		2390 (+/- 240; likely range)					
Approximate global warming relative to 1850-1900 until temperature limit [°C]	Approximate global warming relative to 2010-2019 until temperature limit [°C]	Estimatedx remaining carbon budgets from the beginning of 2020 [$GtCO_2$]					Variations in reductions in non-CO_2 emissions
		Likelihood of limiting global warming to temperature limit					
		17%	33%	50%	67%	83%	Higher or lower in accompanying non-CO_2 emissions can increase or decrease the values on the left by 220 $GtCO_2$ or more
1.5	0.43	900	650	500	400	300	
1.7	0.63	1,450	1,050	850	700	550	
2.0	0.93	2,300	1,700	1,350	1,150	900	

What is the international process regarding carbon budgets?

Achieving the goal of the 2015 Paris Climate Agreement will require the total decarbonisation of the global energy system by 2050, with an emissions peak between 2020 and 2025[10] and a drastic reduction in non-energy-related GHGs, including land-use-related emissions[11]. Based on the Agreement, countries have agreed to regularly report their GHG emissions and submit their NDCs, describing their planned measures to reduce their GHG emissions. In 2021, the 'Global Stocktake' process began to collect the latest data on emissions and to assess future developments based on the NDCs already commenced. According to the UNFCCC, the Global Stocktake '*enables countries and other stakeholders to see where they're collectively making progress toward meeting the goals of the Paris Agreement – and where they're not. It's like taking inventory*'[12].

What happens if 1.5°C pathways implementation is delayed?

The total remaining global carbon budget required to limit the temperature increase to 1.5°C (with 67% likelihood) is 400 $GtCO_2$. According to the IPCC, an increased carbon budget of 500 $GtCO_2$ will reduce the likelihood to 50%, and a carbon budget of 650 $GtCO_2$ will reduce it to only 33%. A delay of 5 years – across all sectors and countries – will increase the global carbon emissions from 426 $GtCO_2$ under the 1.5°C OECM scenario to 585 $GtCO_2$, and the likelihood of meeting the + 1.5°C target will decrease to <50%. A delay of 7 years will increase the total emissions to 649 $GtCO_2$ in 2020 – 2050, reducing the likelihood of achieving the target to 33%. A closer look at the development of sector-specific emissions and the increase in emissions if implementation is delayed shows that those of the *Transport* sector and *Building* sector will be significant. A 7-year delay in the *Road Transport* sector alone will increase emissions in 2020 – 2050 by 39 $GtCO_2$.

9   IPCC (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Edited by S.L. Masson-Delmotte, V. P. Zhai, A. Pirani, J.B.R. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, B.Z. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu. Cambridge University Press. Available at: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report.pdf

10   *Ibid* – see above.

11   Rogelj, J. et al. Paris Agreement climate proposals need a boost to keep warming well below 2 °C. Nature 2016;534(7609):631 – 639. Available at: https://doi.org/10.1038/nature18307

12   UNFCCC (2023a) Global Stocktake, United Nations Climate Change. Available at: https://unfccc.int/topics/global-stocktake (accessed: March 2024).

3 The One Earth Climate Model: Background & Methodology

The OECM is an integrated energy assessment model that was originally developed in an interdisciplinary research project between the University of Technology Sydney, the German Aerospace Centre (DLR), and the University of Melbourne between 2017 and 2019. The task was to develop a detailed 1.5°C pathway targeting the energy-related GHG emissions trajectory for 10 world regions. OECM 1.0 was developed based on established DLR and UTS energy models, and consisted of three independent modules:

1. Energy system model (EM): a mathematical accounting system for the energy sector (Simon et al., 2018)[13].
2. Transport scenario model (Transport Energy Model, TRAEM), with high technical resolution (Pagenkopf et al., 2019)[14].
3. Power system analysis model [R]E 24/7, which simulates an electricity system on an hourly basis and at geographic resolution to assess the requirements for infrastructure, such as grid connections between different regions and electricity storage types, depending on the demand profiles and power-generation characteristics of the system (Teske et al., 2015) [15].

Based on the OECM (Teske et al., 2019)[16], UTS-ISF, in close co-operation with the UN-convened Net Zero Asset Owners Alliance, updated the OECM 1.0 model. The Accelerated OECM 2.0 merges the energy system model (EM), the transport model (TRAEM), and the power system model ([R]E 24/7) into one MATLAB-based energy system module. OECM 2.0 has now been applied to 19 countries and the EU27 region, which formed the G20 in 2023, to produce energy scenarios and fair carbon budgets for each country, as well as detailed carbon budgets for key industries in each country.

The Global Industry Classification Standard (GICS) was used in OECM 2.0 to allow the design of energy and emissions pathways for clearly defined industry sectors (sectoral pathways). Finding pathways to reduce emissions for industry sectors requires very high technical resolution for the calculation and projection of future energy demands for supplies of electricity, (process) heat and fuels, which are necessary for, as an example, the steel and chemical industries. An energy model with high technical resolution must be able to calculate the energy demand based on either sector-specific GDP projections or market forecasts of material flows, such as the demand for steel, aluminium, or cement in tonnes per year.

The methodology chapter outlines five fundamental elements of the modelling process (described below):

i)   Databases and model calibration;
ii) Sector and sub-sector definitions;
iii) Cost calculations;
iv) A demand module; and
v)   A supply module.

The following sections provide a detailed overview of the methodology of the different OECM components.

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13   Simon, S., Naegler, T., Gils, H.C. (2018) Transformation towards a renewable energy system in Brazil and Mexico – technological and structural options for Latin America. Energies 2018:11;907.

14   Pagenkopf, J., van den Adel, B., Deniz, Ö., Schmid, S. (2019) Transport transition concepts. In: Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-Energy GHG Pathways for +15 °C and +2 °C. 2019:131 – 59.

15   Teske, S. (2015) Bridging the Gap between Energy and Grid Models, Developing an integrated infrastructural planning model for 100% renewable energy systems in order to optimise the interaction of flexible power generation, smart grids and storage technologies. Chapter 2, 2015.

16   Teske, S., Pregger, T., Naegler, T., Simon, S., Pagenkopf, J., van den Adel, B., et al. (2019) Energy scenario results. In: Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-Energy GHG Pathways for + 1.5°C and +2 °C. 2019:175 – 401.

3.1 Databases and Model Calibration

The OECM uses several databases for energy statistics, energy intensities, technology market shares, and other market or socio-economic parameters. The calculation of the energy balance for the base year is based on the International Energy Agency (IEA)'s Accelerated World Energy Balances (IEA, 2021)[17] and additional sector- and nation-specific databases. The energy statistics for a calculated country and/or region are uploaded via an interface module. The data for each year from 2005 onwards until the last year for which data are available are used to calibrate the model. This process is based on the Energy System Model (EM), which was developed by the German Aerospace Centre (DLR). The market shares are calculated based on the IEA statistics and a technical database for energy intensities for various appliances and applications across all sectors. These data are inputs, and the calibration process is performed with a standardised Excel tool. The calibration method is briefly outlined below, using the Transport sector as an example. To calibrate the model, the transport demand of the past decade is recalculated based on the available energy statistics. The IEA's Accelerated World Energy Balances provides the total final energy demand by transport mode – aviation, shipping, rail, or road – by country, region or globally. However, it provides no further specification of the energy use within each of the transport modes. Therefore, a further division into passenger and freight transport is made, and energy use is calculated using percentage shares (Table 2). These proportions are determined with literature research, together with the average energy intensity for each of the transport modes for passenger and freight vehicles.

Table 2: Calibration for calculating the transport demand

Calculation Concept	Process	Until 2019	Unit	Comment
Transport Demand				
Aviation, Shipping, Rail, and Road – Past to Present				
Annual Demand	Data	Database	[PJ/yr]	Data: IEA Accelerated World Energy Balances
Passenger Share	Input	Literature	[%]	Shares of total energy demand from the literature
Freight Share	Input	Literature	[%]	Shares of total energy demand from the literature
Average Energy Intensity – passenger transport	Data	Literature	[MJ/pkm]	Literature review – based on current supply mix
Average Energy Intensity – freight transport	Data	Literature	[MJ/tkm]	Literature review – based on current supply mix
Passenger-kilometres	Calculation	= Annual Demand/ Energy Intensity	[pkm]	Checked against OECD statistics
Tonne kilometres	Calculation		[tkm]	Checked against OECD statistics
Annual Growth/Decline – passenger-kilometres	Calculation	= Annual Demand previous year/Annual Demand calculated year	[%/yr]	Calculated to understand the trend between 2005 and 2020
Annual Growth/Decline – tonne-kilometres	Calculation		[%/yr]	
Population – indicator of passenger transport development	Data	Database	[million]	Data: UN
GDP per capita indicator of passenger & freight transport development	Data	Database	[$GDP/ capita]	Data: World Bank
GDP – indicator of freight transport development	Data	Database	[$GDP]	Data: World Bank

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17   IEA (2021) IEA World Energy Statistics and Balances. https://doi.org/https://doi.org/10.1787/enestats-data-en

The annual transport demand in passenger-kilometres per year [pkm/yr] and tonne-kilometres per year [tkm/yr] is calculated as the annual energy demand divided by the average energy intensity by mode (Table 3). In this work for Australia, these results were compared with statistics from the Bureau of Infrastructure and Transport Research Economic (BITRE)[18], which provide both parameters, pkm/yr and tkm/yr. Calibrating the model based on historical data ensures that the basis of the scenario projections for the coming years and decades is correctly mapped and that the changes are calculated most realistically.

For the forward projection of the transport demand, the calculation method is reversed: the demand for each transport mode is calculated based on the annual change, as a percentage. The calculated total annual passenger-kilometres and tonne-kilometres are the inputs for the energy demand calculation.

Table 3: Methodology of OECM 2.0 – Projection of transport demand based on the changing demand in kilometres.

Process	2020–2050	Unit	Comment
Aviation, Navigation, Rail, Road – Projection			
Calculation	= (passenger km previous year) × (increase/decrease in %/yr)	[pkm]	Starting point: base year 2019
Calculation	= (tonne km previous year) × (increase/decrease in %/yr)	[tkm]	Starting point: base year 2019
Input	INPUT in %/yr	[%/yr]	Assumption
Input	INPUT in %/yr	[%/yr]	Assumption
Calculation	INPUT in %/yr	[million]	Assumption based on UN projection
Calculation	= $GDP/population	[$GDP/capita]	
Calculation	INPUT in %/yr	[$GDP]	Assumption based on World Bank projection
Result	Time series 2020–2050: Passenger-km per year & region	[pkm/yr]	Input for energy demand calculation
Result	Time series 2020–2050: Freight-km per year & region	[tkm/yr]	Input for energy demand calculation

This methodology for calibration and projection is used across all sectors.

3.2 Sector Boundaries: Sectors and Sub-sectors

The OECM was developed to calculate energy pathways for geographic regions, as documented by Teske et al. (2019)[19]. It was further developed to meet the requirements of the financial industry and to design energy and emissions pathways for clearly defined industry sectors (sectoral pathways). The finance industry uses different classification systems to describe sub-areas of certain branches of industry. Those scenario sector boundaries are based on the GICS classification. The GICS is an important economic classification system[20], but the GICS sub-industries do not match the IEA statistical breakdown of the energy demands of certain industries. Although the OECM allows all the GICS-coded sub-industries to be calculated, the availability of statistics limits the resolution of the sectoral pathways. For example, the statistical data for the textile and leather industry are stored in the IEA database, but the database does not separate the two industries further (see also Teske et al 2022[21]).

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18 The Bureau of Infrastructure and Transport Research Economics (BITRE) provides economic analysis, research, and statistics on infrastructure and transport issues to inform Australian Government policy development and wider community understanding. BITRE is part of the Data, Analytics and Policy Division of the Department of Infrastructure, Transport, Regional Development, Communications and the Arts. (https://www.bitre.gov.au/)

19 Teske, S., Pregger, T., Naegler, T., Simon, S., Pagenkopf, J., van den Adel, B., et al. Energy scenario results. In: Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-Energy GHG Pathways for + 1.5°C and +2 °C. 2019;175 – 401.

20 MSCI website, which provides an overview of the Global Industry Classification Standard (GICS). (2021). https://www.msci.com/our-solutions/indexes/gics.

21 Teske, S., Niklas, S., Talwar, S., et al. 1.5°C pathways for the Global Industry Classification Standard (GICS) sectors chemicals, aluminium, and steel. SN Applied Sciences 2022;4:125. https://doi.org/10.1007/s42452-022-05004-0

3.3 Demand module

The demand module uses a bottom-up approach to calculate the energy demand for a process (e.g., steel production) or a consumer (e.g., a household) in a region (e.g., a city or country) or for transport services over a period. One of the most important elements of this approach is the strict separation of the original need (e.g., to get from home to work), how this need can be satisfied (e.g., with a tram), and the kind of energy required to provide this service (in this case, electricity). This basic logic is the foundation for the energy demand calculation across all sectors: buildings, transport, services, and industry. Furthermore, the energy services required are defined: electricity, heat (broken down into four heat levels: < 100°C, 100–500 °C, 500–1000 °C, > 1000 °C), and fuels for processes that cannot (yet) be electrified. Synthetic fuels, such as hydrogen, are part of both the demand module, because electricity is required to produce it, and the supply module, because it is an energy source for other processes, such as manufacturing.

3.3.1 Input parameters

As in basic energy models, the main drivers of the energy demand are the development of the population, and economic activity, measured in GDP. Figure 1 shows the basic methodology of the OECM demand module. The tier 1 inputs are population and GDP by region and sector. Whereas 'population' defines the number of individual energy services, which determines the energy required per capita, the economic activity (in GDP) defines the number of services and/or products manufactured and sold. The tier 1 demand parameters are determined by the effect that a specific service requires. The demand parameters for population are defined by the need for food, shelter (buildings), and mobility, and – depending on the economic situation and/or lifestyle of the population – the demand for goods and services.

Figure 1: Tier 1 and tier 2 input parameters for the assessment of energy demand
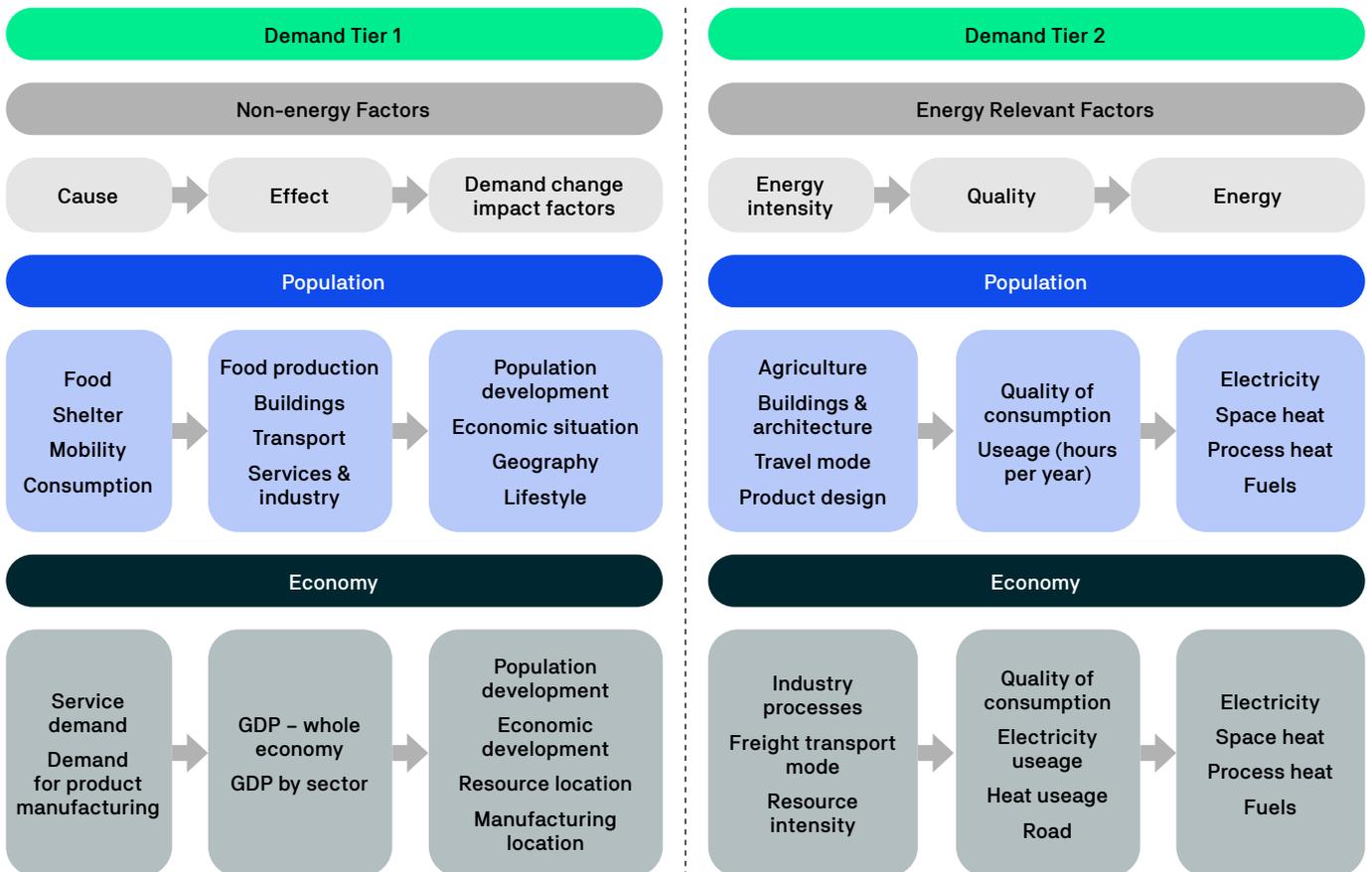
Economic activity (measured in GDP) is a secondary input and is directly and indirectly dependent upon the size of the population. However, a large population does not automatically lead to high economic activity. Both population and projected GDP are inputs from external sources, such as the United Nations or the World Bank. The tier 1 input parameters themselves are strictly non-technical. For instance, the need to produce food can be satisfied without electricity or (fossil) fuels. Food production is a service, which can be provided by the human workforce. The tier 2 demand parameters are energy-relevant factors, and describe technical applications, their energy intensities, and the extent to which an application is used. For example, if passenger road transport is required, the technical application 'LDV' can be chosen to satisfy the demand. In this example, the energy intensity for an LDV with an internal combustion engine (ICE) is, for example, 1.5 MJ/km.

The energy intensity multiplied by the application (vehicle) defines the total energy demand (e.g., if the use is 15,000 km per year, the total energy demand will be 1.5 MJ/km × 15,000 km/yr = 22,500 MJ/yr). The application – in this example, an LDV with ICE – can be replaced with another application, such as an EV with a reduced energy intensity of 0.5 MJ/km. The transport energy demand decreases, whereas the transport service (15,000 km) remains stable. In a second step, the actual transport service can be reduced or increased or shifted to another transport mode altogether (such as light rail) by the modeller. This very basic and simple principle is used for every application in each of the main sectors: *Buildings* (*Residential + Commercial*), *Industry*, and *Transport*. Those sectors are broken down into multiple sub-sectors, such as aviation, shipping, rail, and road for *Transport*, and further into applications, such as vehicle types. The modular programming allows the addition of as many sub-sectors and applications as required.

3.4 Supply Module

After the demand has been calculated, the supply of electricity, heat, and fuels is calculated. The supply does not differentiate between the demand sectors. Therefore, the electricity demand for all sectors – *Residential*, *Industry*, and *Transport* – is aggregated and is provided as a total value. Consequently, no specific electric generation mix for the *Transport* sector, for example, is considered.

Table 4: Examples of generation and storage technologies – highlighted technologies incl. in resource assessment

Electricity generation			Electricity storage		
Power plants	Combined heat and power plants	Heating plants	Electrical	Thermal	Hydrogen
Hard coal	Hard coal	Coal	**Lithium battery**	Water tank	Tank
Lignite	Lignite	Lignite	Pumped hydro	Molten salt	Pipeline
Gas	Gas	Gas			
Oil	Oil	Oil			
Diesel	Biomass	Biomass			
Biomass	Geothermal	Solar collectors			
Hydro	Hydrogen	Geothermal			
Wind		Hydrogen			
PV					
Concentrated Solar Power					
Geothermal					
Solar thermal					
Ocean energy					
Hydrogen					

The supply module consists of three main elements:

i)   Supply technology;

ii) Storage technology; and

iii) The infrastructure for the power supply (the capacities of power lines).

For the generation of electricity and heat, the model considers all the technologies in the energy market, from both renewable and non-renewable sources. In addition to the generation of pure electricity and heat, the entire range of combined heat and power systems is covered.

Storage technologies include batteries and the use of hydrogen from electrolysers. The calculation of heat storage is possible, but has not yet been used in the OECM scenarios because heat demand profiles with hourly resolution for whole countries are not available from open-source databases. Dispatch strategies that reflect market and policy factors are defined for electricity and heat generation. Whether electricity from solar photovoltaic (PV) or onshore and offshore wind turbines has priority dispatch ahead of fossil-fuel power plants and how storage systems are used can be determined. Each technology has a specific conversion efficiency. Heat generation technologies are also defined by the temperature levels they can provide. For example, residential solar collectors can only supply low-temperature heat and will therefore not be considered for high-temperature process heat. A power sector analysis with hourly resolution to analyse the storage demand was beyond the scope of this research.

The technologies shown in Table 4 are considered in the power system analysis to estimate GHG emissions from the power sector.

However, the assessment of the mineral demand is only conducted for wind, solar PV, concentrated solar thermal, hydrogen, and power system storage batteries.

3.5 OECM Output and Areas of Use

Commodities and/or GDP are the main drivers of the energy demand for industries. The projection of, for example, the global steel demand in tonnes per year over the next few decades is discussed with the industry and/or client. OECM 2.0 can calculate either a single specific sector, or a whole set of sectors.

In this research, various industry projections are combined to estimate both the total energy supply required and the potential energy-related emissions. Thus, the emissions involved in achieving a specific target or budget can be broken down by specific industries. Table 5 provides an overview of the main parameters that can be used to set specific targets for industries.

Table 5: Examples of energy-related key performance indicators (KPIs) for setting net zero targets, calculated with OECM

Sector	Parameter	Units	Base year 2019	Projection 2025, 2030, 2035, 2040, 2045, 2050
Commodities				
Water Utilities	Water withdrawal	[billion m³/yr]	Input	Calculated projection with annual growth rates discussed with client
Chemical Industry	Economic development	[$GDP/yr]	Input	
Steel Industry	Product-based market projection	[tonnes steel/yr]	Input	
Aviation	Passenger-kilometres	[million passenger-km/yr]	Input	
Energy Intensities				
Water Utilities	Waste-water treatment	[kWh/m³]	Input	Technical target (KPI) Calculated with annual progress ratio based on technical assessment
Chemical Industry	Industry-specific energy intensity	[MJ/$GDP]	Input	
Steel Industry	Energy intensity	[MJ/tonne steel]	Input	
Aviation	Energy intensity per transport service	[MJ/passenger-km]	Input	
Energy Demand				
Water Utilities	Final energy demand	[PJ/yr]	Input	Output – industry-specific scenario(s)
Chemical Industry	Electricity demand	[TWh/yr]	Input	
Steel Industry	Process heat demand by temperature level	[PJ/yr]	Input	
Aviation	Final energy demand	[PJ/yr]	Input	
	Total final energy demand	[PJ/yr]	Input	
Energy Supply				
Water Utilities	Electricity generation by technology	[TWh/yr]	Input	Output – based on developed scenario Supply for all (sub-)sectors.
Chemical Industry	(Process) heat by technology	[PJ/yr]	Input	
Steel Industry	Fuel supply by fuel type	[PJ/yr]	Input	
Aviation	Fuel supply by fuel type	[PJ/yr]		
	Total final energy supply by fuel type	[PJ/yr]	Input	
Energy-related Emissions				
	Electricity – specific CO_2 emissions	[gCO₂/kWh]	Calculated	Output – KPI for utilities
	Electricity – total CO_2 emissions	[t CO₂/yr]	Calculated	Output – KPI for utilities
	(Process) heat – specific CO_2 emissions	[gCO₂/kWh]	Calculated	Output – KPI for industry
	Transport service energy	[g CO₂/kilometre]	Calculated	Output – KPI for industry
	(Process) heat – total CO_2 emissions	[tCO₂/yr]	Calculated	Output – KPI for industry
Product–specific Emission				
Water Utilities	Emissions intensity	[kgCO₂/m³]	Calculated	KPI – water utilities
	Total energy-related CO_2 emissions	[tCO₂]	Calculated	KPI – water utilities
Chemical Industry	Emissions intensity	[kgCO₂/$GDP]	Calculated	KPI – chemical industry
	Total energy-related CO_2 emissions	[tCO₂]	Calculated	KPI – chemical industry
Steel Industry	Emissions intensity	[kgCO₂/t steel]	Calculated	KPI – steel industry
	Total energy-related CO_2 emissions	[tCO₂]	Calculated	KPI – steel industry
Aviation	Emission intensity	[kgCO₂/passenger km]	Calculated	KPI – aviation industry
	Total energy-related CO_2 emissions	[tCO₂]	Calculated	KPI – aviation industry

Energy intensities are both input data for the base year and key performance indicators (KPI)s for future projections. The effect of a targeted reduction in the energy intensity each year and the resulting energy demand and carbon emissions can be calculated, e.g., for the *Transport* service industry.

All sector demands are supplied by the same energy supply structure in terms of electricity, process heat (for each temperature level), and total final energy. Finally, specific carbon intensities, such as CO_2 per tonne-kilometre or, CO_2 per tonne of steel or per cubic metre of wastewater treatment, are calculated (and can be used to set industry targets).

All input and output OECM data are available as MATLAB-based tables or graphs, or as standard Excel-based reports.

4 Methodology – Mineral Resource Calculation Module
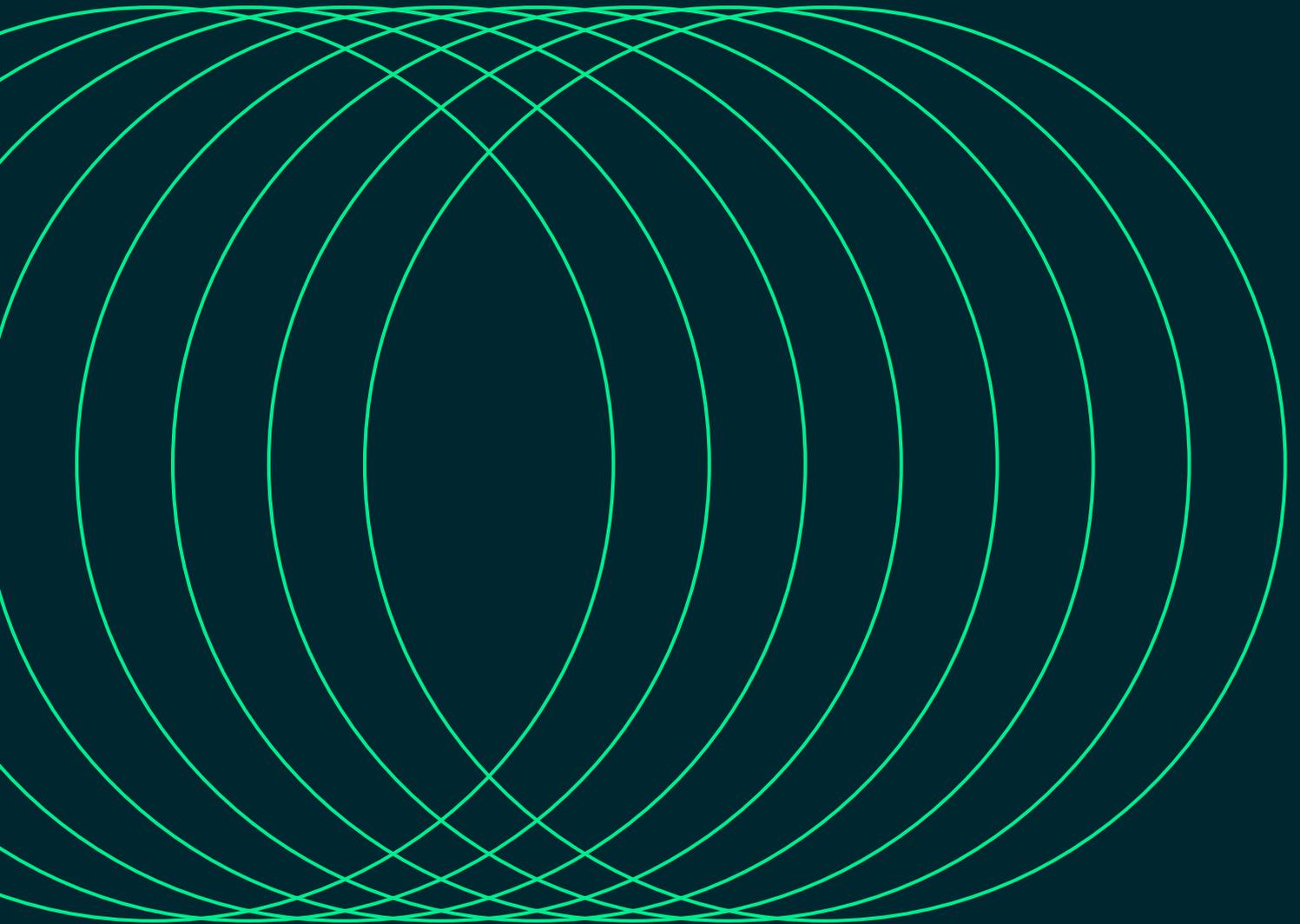
In this section, we describe the development of the methodology of the OECM resource module from the selection of the minerals analysed to the calculation of the quantities required under different scenario and time series.

4.1 Methodology: Calculation of Mineral Resource Requirement

The mineral resource requirements for the energy pathways, developed under the Paris Agreement to limit global warming to 1.5°C, include the 'OECM Net-Zero (OECM)', the 'Progressive (PRO), and the 'Progressive Accelerated Na-ion Scenario (PRO-Na-ion)'. The pathways are calculated based on the following main parameters:

1. Technology sector: generation, storage, application

2. Technology group: generation technologies, storage technologies, electric mobility (application)

3. Technology type: refers to specific technologies within a technology group, e.g., Lithium-ion battery

4. Quantity of technology: refers to the number of EV's, installed capacity in GW or storage capacity in GWh

5. Mineral intensity per unit of quantity

Table 6 shows the calculation matrix for the assessment of mineral resource requirements for energy scenarios. Although not all technology groups are listed, the table shows all parameters.

Table 6: Calculation matrix for the assessment of mineral resource requirements for energy scenarios (example)

	Technology			Market share of technology variation		Quantity of technology			Resource Intensity – Base year			Projected future Resource Intensity			Total required material under calculated scenario		
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
Sector	Technology Group	Technology Type	Technology Type variation and/or component	Status Quo [%]	Estimation development until 2030/2050 [%]	by quantity [1]	by capacity [GW]	by energy unit [GWh/a]	by quantity [t/unit]	by capacity [t/GW]	by energy unit [t/GWh]	by quantity [t/unit]	by capacity [t/GW]	by energy unit [t/GWh]	Base year [t/year]	2050 [t/year]	Development [%/a]
Generation	Solar PV	c-Si		X%	X% +/- Y%		●			●		+/- X%	+/- X%	+/- X%	●	●	+/- X%
		CIGS		X%	X% +/- Y%		●			●		+/- X%	+/- X%	+/- X%	●	●	+/- X%
		CdTe		X%	X% +/- Y%		●			●		+/- X%	+/- X%	+/- X%	●	●	+/- X%
	Concentr. Solar	Parabolic trough		X%	X% +/- Y%		●			●		+/- X%	+/- X%	+/- X%	●	●	+/- X%
		Central tower		X%	X% +/- Y%		●			●		+/- X%	+/- X%	+/- X%	●	●	+/- X%
	Onshore Wind	Direct-drive excited synchronous generator		X%	X% +/- Y%		●			●		+/- X%	+/- X%	+/- X%	●	●	+/- X%
		Doubly fed induction generator		X%	X% +/- Y%		●			●		+/- X%	+/- X%	+/- X%	●	●	+/- X%
	Offshore Wind	Direct-driven permanent synchronous generator		X%	X% +/- Y%		●			●		+/- X%	+/- X%	+/- X%	●	●	+/- X%
		Permanent magnet synchronous generator		X%	X% +/- Y%		●			●		+/- X%	+/- X%	+/- X%	●	●	+/- X%
Storage	Batteries	Lithium-ion	Mobile storage applications	X%	X% +/- Y%			●		●	●	+/- X%	+/- X%	+/- X%		●	+/- X%
		Lithium-ion phosphate	Mobile storage applications	X%	X% +/- Y%			●		●	●	+/- X%	+/- X%	+/- X%		●	+/- X%
		Lithium Nickel-Cobalt-Aluminium-Oxide	Mobile storage applications	X%	X% +/- Y%			●		●	●	+/- X%	+/- X%	+/- X%		●	+/- X%
		Vanadium redox flow	Stationary storage	X%	X% +/- Y%			●		●	●	+/- X%	+/- X%	+/- X%		●	+/- X%
		Lithium sulphur	Stationary storage	X%	X% +/- Y%			●		●	●	+/- X%	+/- X%	+/- X%		●	+/- X%

4.2 Selection process of minerals for this assessment

To understand the minerals that are critical for the energy transition and where their requirements are highest for renewable energy and storage technologies, we undertook a literature review of publications that analyse the requirement of minerals for the energy transition by international organisations such as the IEA, the European Commission, agencies of the USA, the World Bank, and the World Economic Forum. These identified 12 minerals of high importance (bold), nine of which were analysed in depth in this report because of their strong relevance for the OECM climate-mitigation pathways. This review shows how priorities for minerals differ among geographic jurisdictions and global organisations. It has also helped the OECM researchers to narrow down a previous extended list of minerals. Table 7 shows the mineral strategies from different geographic regions including the EU and USA, in addition to global databases from the IEA, World Bank and World Economic Forum. Priorities and definitions on what minerals are considered 'critical' vary geographically based on the region's own resources, abundances, and potential supply chain risks. This list aims to generate a shared understanding of the key minerals for the energy transition and will guide our selection of critical minerals.

Table 7: Review of minerals for the renewable energy transition and RE technologies

All Critical Minerals (CM)	Key application(s)	HIGH CM needs reported for technologies (IEA, 2021)[22]	Global CM's Outlook (IEA, 2024)[23]	Critical Raw Material 5th List (EU, 2023)[24]	U.S. CM for Energy (DOE, 2023)[25]	U.S. CM (DOE, 2023)	World Bank (2024)[26]	World Economic Forum (2023)[27]
Aluminium	Energy grid, wind, PV, batteries	PV, CSP, Electricity Network, EV, Battery Storage	✪	✪	✗	✗	✗	✪
Arsenic		✪	✪	✗	✪	✗	✪	✪
Antimony		✪	✪	✗	✪	✗	✪	✪
Bauxite		✪	✪	✗	✪	✪	✪	✪
Baryte/Barite		✪	✪	✗	✪	✗	✪	✪
Beryllium		✪	✪	✗	✪	✗	✪	✪
Bismuth		✪	✪	✗	✪	✗	✪	✪
Boron		✪	✪	✪	✪	✪	✪	✪
Cadmium	Solar PV Cells (CdTe cells only)	✪	✪	✪	✪	✪	✪	✪
Cerium		✪	✪	✪	✪	✗	✪	✪
Caesium		✪	✪	✪	✪	✗	✪	✪
Chromium	Wind, CSP, Hydrogen	Wind, Geothermal	✪	✪	✪	✗	✗	✪
Cobalt	**EVs and Storage**	**EVs and Storage**	✗	✗	✗	✗	✗	✗
Coking coal		✪	✪	✗	✪	✪	✪	✪
Copper	**Wiring, Energy infrastructure, Batteries**	**PV, Wind, Grid, Bioenergy, EVs and Storage**	✗	✗	✗	✗	✗	✗

22 IEA (2021), The Role of Critical Minerals in Clean Energy Transitions, IEA, Paris. **https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions**, p. 45

23 IEA (2024), Global Critical Minerals Outlook 2024, IEA, Paris **https://www.iea.org/reports/global-critical-minerals-outlook-2024**

24 EU (2023) Critical raw materials. **https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en**

25 DOE (2023) U.S. Energy Department (2023) Notice of Final Determination on 2023 DOE Critical Materials List. **https://www.govinfo.gov/content/pkg/FR-2023-08-04/pdf/2023-16611.pdf**

26 World Bank (2024) Minerals for Climate Action. **https://documents.worldbank.org/en/publication/documents-reports/documentdetail/099052423172525564**, p. 20: Table 1.2

27 World Economic Forum (2024) Energy Transition and Geopolitics: Are Critical Minerals the New Oil? White Paper, CM list from Energy Transition Commission (2023) **https://www.energy-transitions.org/publications/material-and-resource-energy-transition/**

All Critical Minerals (CM)	Key application(s)	HIGH CM needs reported for technologies (IEA, 2021)[22]	Global CM's Outlook (IEA, 2024)[23]	Critical Raw Material 5th List (EU, 2023)[24]	U.S. CM for Energy (DOE, 2023)[25]	U.S. CM (DOE, 2023)	World Bank (2024)[26]	World Economic Forum (2023)[27]
Erbium		✪	✪	✪	✪	✗	✪	✪
Europium		✪	✪	✪	✪	✗	✪	✪
Feldspar		✪	✪	✗	✪	✪	✪	✪
Fluorine		✪	✪	✪	✗	✪	✪	✪
Fluorspar		✪	✪	✗	✪	✗	✪	✪
Gadolinium		✪	✪	✪	✪	✗	✪	✪
Gallium	Solar PV	✪	✪	✗	✗	✗	✪	✪
Germanium		✪	✪	✗	✪	✗	✪	✪
Graphite	EVs and Storage	✪	✗	✗	✗	✗	✗	✗
Hafnium		✪	✪	✗	✪	✗	✪	✪
Helium		✪	✪	✗	✪	✪	✪	✪
Holmium		✪	✪	✪	✪	✗	✪	✪
Indium	Perovskite and CIGS Solar Cells	Hydrogen	✪	✪	✪	✗	✗	✪
Iridium		✪	✪	✪	✪	✗	✪	✪
Iron		✪	✪	✪	✪	✪	✗	✪
Dysprosium	Wind, EVs and Storage, Solid state batteries	Wind, Battery storage EV	✗	✗	✗	✗	✗	✗
Lanthanum		✪	✪	✪	✪	I	✪	✪
Lithium	EVs and Storage	EVs and Storage	✗	✗	✗	✗	✗	✗
Lead		✪	✪	✪	✪	✪	I	✪
Lutetium		✪	✪	✪	✪	✗	✪	✪
Magnesium		✪	✪	✗	✗	✗	✪	✪
Manganese	Li-iron Batteries	✪	✪	✗	✪	✗	✗	✪
Molybdenum		✪	✪	✪	✪	✪	I	✪
Neodymium	Wind, EVs and Storage, Solid state Batteries	EVs and Storage, Wind	✗	✗	✗	✗	✗	✗
Nickel	Wind, CSP, Battery Storage, Hydrogen	Geothermal, EVs and Storage, Hydrogen	✗	✗	✗	✗	✗	✗
Niobium		✪	✪	✗	✪	✗	✪	✪
Platinum (PGM)	Hydrogen	Hydrogen	✪	✗	✗	✗	✪	✪
Phosphate Rock		✪	✪	✗	✪	✪	✪	✪
Phosphorous		✪	✪	✗	✪	✪	✪	✪
Praseodymium		✪	✪	✪	✗	✗	✪	✪
Samarium		✪	✪	✪	✪	✗	✪	✪
Scandium		✪	✪	✪	✪	✗	✪	✪
Silicon	Solar PV, batteries	✪	✪	✗	✗	✪	✪	✪
Silicon carbide		✪	✪	✪	✗	✪	✪	✪
Silver	Solar PV	✪	✪	✪	✪	✪	✗	✪
Selenium		✪	✪	✪	✪	✪	✪	✪
Electrical Steel		✪	✪	✪	✗	✪	✪	✪

All Critical Minerals (CM)	Key application(s)	HIGH CM needs reported for technologies (IEA, 2021)[22]	Global CM's Outlook (IEA, 2024)[23]	Critical Raw Material 5th List (EU, 2023)[24]	U.S. CM for Energy (DOE, 2023)[25]	U.S. CM (DOE, 2023)	World Bank (2024)[26]	World Economic Forum (2023)[27]
Strontium		✿	✿	✗	✿	✿	✿	✿
Tantalum		✿	✿	✗	✿	✗	✿	✿
Tellurium		✿	✿	✿	✿	✗	✿	✿
Terbium		✿	✿	✿	✗	✗	✿	✿
Tin		✿	✿	✿	✿	✗	✿	✿
Titanium		✿	✿	✗	✿	✗	✗	✿
Tungsten		✿	✿	✗	✿	✗	✿	✿
Zinc	Wind	✿	✿	✿	✿	✗	✗	✿
Vanadium	Long duration Battery Storage (utility scale)	✿	✿	✗	✿	✗	✗	✿
Ytterbium		✿	✿	✿	✿	✗	✿	✿
Yttrium		✿	✿	✿	✿	✗	✿	✿
Zirconium		✿	✿	✿	✿	✗	✿	✿

Legend:	
✗	included in reference
✿	not included reference
Final List	Highlighted minerals are selected minerals assessed in this report
Previously included	Minerals highlighted bold were initially included as renewable energy relevant minerals
Full list of reviewed CMs	The table reviewed all minerals listed in by the reviewed references

4.3 Selected Minerals and Potential Recycling Rates

The demand for critical minerals is expected to increase as the transition to renewable energy technologies progresses and the electrification of mobility, mainly driven by EV batteries, accelerates. Table 8 shows the current (2024) and future demands (until 2040) for cobalt, copper, graphite, rare earth minerals (dysprosium, neodymium), lithium, manganese, nickel, and vanadium, as well as the secondary supplies and re-use rates of these minerals. Shares of the demand for renewable energy technology are largely driven by technological choices. For example, the share of cobalt demand in renewable energy is expected to grow at a minimum rate until 2040, or to return to its current 2024 rate given the projected trend towards cobalt-free batteries.

At the same time, lithium demand in renewable technology is increasing. Another relevant aspect in the supply and demand value chains is mining locations. Table 8 shows that the top mining countries, based on USGS 2023 data, are in the Global South. For example, manganese mining is concentrated in South Africa and Gabon, highlighting the potential geopolitical uncertainties that can pose supply risks and shortages. These will place greater pressure on Western mining locations, such as Australia (Sokolova et al., 2025).

In cases where critical minerals can be substituted – for example, the shift from lithium-ion to sodium-ion batteries, or the shift from permanent-magnet motors to non-permanent-magnet motors for wind turbines – the pressures on future demand and mining locations can be reduced.

Table 8: Nine selected minerals: market trends, potential recycling rates, material substitutes and mining locations

| | Key applications, | Projected trend/ Peak demand | Share of clean energy technologies in total critical mineral demand (IEA 2025[28]) | | Secondary supply and re-use rates | Secondary supply and re-use rates | Substitutes (IEA, 2021[29], p. 44; IEA 2024[30]; Calvo & Valero, 2022)[31] | Top mining countries (USGS, 2023) |
			In 2024	Projected for 2040 (IEA STEPS)	in 2024 data (IEA STEPS)	2040 (IEA STEPS)		
Cobalt	Superalloys, catalysts, and batteries (IEA, 2024[32]; UNEP, 2011)	Battery applications accounted for 73% of the cobalt demand in 2023. EVs made up 96% of the demand growth in 2023 (Cobalt Institute, 2024). Projections for the future cobalt demand could be 6–30 times higher than that in 2021 (IEA, 2021), depending upon battery chemistry choices, e.g., lower if there is a shift towards high nickel because nickel is expected to increase until 2040	32% (IEA, 2025[33])	41% (IEA, 2025)	13% (IEA, 2025)	33% (IEA, 2025)	Cobalt demand for lithium-ion batteries is expected to decrease or remain at current levels, given the trend towards cobalt-free EV batteries (IEA (2025, Maisel et al 2023)[34].	DR Congo, Indonesia, Russia (Cobalt Institute, 2024; USGS, 2023)[35]
Copper	Wiring, energy infrastructure, batteries (IEA, 2024[36], 2025; UNEP, 2011)[37]	Increasing demand (IEA, 2025)	29% (IEA ,2025)	36% (IEA, 2025)	20% (IEA, 2025)	34% (IEA, 2025)	Replacement of Cu plumbing with plastic polyethylene (PEX) or high-density polyethylene (HDPE), replacement of overhead copper distribution and underground cables with aluminium.	Chile, Peru, DR Congo
Graphite	Battery storage (IEA, 2024)	Increasing, partly driven by EV uptake (IEA, 2025)[38]	32% (IEA, 2025)	52% (IEA, 2025)	3% (IEA, 2025)	2% (IEA, 2025)	Replacement of natural graphite with synthetic graphite, linked to higher emissions, but reduced impurities enhance battery performance.	China, Mozambique, Brazil
Dysprosium	Permanent magnets used in motors (wind, EVs) (IEA, 2024)	Increasing demand (until 2050) (IEA, 2025)	21% (rare earth elements [REE] combined)	31%	42%	40%	Replacement of permanent-magnet motors in EVs with non- permanent-magnet materials. But will increase car weight, reduce efficiency.	China, Australia, Myanmar

28 IEA (2025), Rare earth elements, IEA, Paris https://www.iea.org/reports/rare-earth-elements-2 (accessed 21 November 2025)

29 IEA (2021), The Role of Critical Minerals in Clean Energy Transitions, IEA, Paris https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

30 IEA (2024), Recycling of Critical Minerals, IEA, Paris https://www.iea.org/reports/recycling-of-critical-minerals (accessed 21 November 2025)

31 UNEP (2011). Recycling Rates of Metals – A Status Report. A Report of the Working Group on Global Metal Flows to the International

32 IEA (2025), Cobalt, IEA, Paris https://www.iea.org/reports/cobalt-2 (accessed 21 November 2025)

33 IEA (2025), Cobalt, IEA, Paris https://www.iea.org/reports/cobalt-2 (accessed 21 November 2025)

34 Maisel, F., Neef, C., Marscheider-Weidemann, F., & Nissen, N. F. (2023). A forecast on future raw material demand and recycling potential of lithium-ion batteries in electric vehicles. Resources, Conservation and Recycling, 192, Article 106920. https://doi.org/10.1016/j.resconrec.2023.106920

35 Cobalt Institute (2024) Cobalt Market Report 2023, Available at https://www.cobaltinstitute.org/wp-content/uploads/2025/02/Cobalt-Market-Report-2023.pdf (21 November 2025)

36 IEA (2025), Copper, IEA, Paris https://www.iea.org/reports/copper-2 (accessed 21 November 2025)

37 UNEP (2011). Recycling Rates of Metals – A Status Report. A Report of the Working Group on Global Metal Flows to the International

38 IEA (2025), Graphite, IEA, Paris https://www.iea.org/reports/graphite-2 (accessed 21 November 2025)

	Key applications,	Projected trend/ Peak demand	Share of clean energy technologies in total critical mineral demand (IEA 2025[28])		Secondary supply and re-use rates	Secondary supply and re-use rates	Substitutes (IEA, 2021[29], p. 44; IEA 2024[30]; Calvo & Valero, 2022)[31]	Top mining countries (USGS, 2023)
			In 2024	Projected for 2040 (IEA STEPS)	in 2024 data (IEA STEPS)	2040 (IEA STEPS)		
Lithium	Battery storage incl. EVs (IEA, 2024)	Increasing until 2050 (IEA, 2025)[39]	62% (IEA, 2025)	87% (IEA, 2025)	4% (IEA, 2025)	10% (IEA, 2025)	Shift to sodium-ion batteries. Uptake of vanadium flow technologies in storage.	Australia, China, Chile
Manganese	Li-ion Batteries (IEA, 2024)	Manganese demand will increase (IEA 2021) but supply is subject to shortages and geopolitics (Sokolova et al., 2025)	n/a	n/a	Recycling mainly from scrap steel	n/a	Manganese is irreplaceable in all modern applications (Sokolova et al. 2025)[40].	South Africa, Gabon, Australia
Neodymium (REE combined)	Permanent magnets used in motors (wind, EVs) (IEA, 2024), solid-state batteries	Increasing demand (until 2050) (IEA, 2025)	see dysprosium (combined REE)	see dysprosium (combined REE)	see dysprosium (combined REE)	see dysprosium (combined REE)	Replacement of permanent-magnet motos in EVs with non-permanent-magnet motors. But will increase car weight, reduce efficiency	China, Australia, Myanmar
Nickel	Permanent magnets used in motors (wind, EVs) (IEA, 2024), CSP, battery storage, H_2 (electrolysers) (Bruce et al., 2025)[41]	Increasing demand until 2040 (IEA, 2025)	17% (IEA, 2025)	42% (IEA ,2025)	2% (IEA, 2025)	5% (IEA 2025)		Indonesia, New Caledonia, Philippines
Vanadium	Redox batteries, solid-state batteries (Leba Akman et al., 2025[42])	Demand increase depending on cathode chemistry, market uptake, and rate of (early) commercialisation of VFBs	n/a	n/a	n/a	n/a	Other battery chemistries	China, Russia, South Africa

39 IEA (2025), Lithium, IEA, Paris https://www.iea.org/reports/lithium-2 (accessed 21 November 2025)

40 Sokolova, I., Nwaila, G. T., Ntunka, M. G., Klochkov, S., Michaux, S., Moscardini, E., Toro, L., & Ghorbani, Y. (2025). From abundant resource to critical commodity: Forecasting manganese supply and assessing its sustainability. Sustainable Materials and Technologies, 44, Article e01349. https://doi.org/10.1016/j.susmat.2025.e01349

41 Bruce S, Delaval B, Moisi A, Ford J, West J, Loh J, Hayward J (2021) Critical Energy Minerals Roadmap. CSIRO, Australia. https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/csiro-futures/mineral-resources/critical-energy-minerals-roadmap

42 Leba Akman, A., Arslan, M. Z., & Farsak, M. (2025). The rise of vanadium redox flow batteries: A game-changer in energy storage. Journal of Alloys and Compounds, 1038, Article 182869. https://doi.org/10.1016/j.jallcom.2025.182869

The development of future recycling rates for energy transition technology solutions (batteries, EVs, solar, wind) and mineral building blocks (cobalt, copper, lithium, nickel, and other minerals; see Table 8 for uses and key applications), as outlined in the subsequent section, has been guided by regional directives, including the 2023 Battery Regulation (EU) 2023/1542 and the 2021 EEB report(EEB, 2021)[43], which was jointly developed by NGOs, and proposes more ambitious future recycling rates, reaching beyond the EU directive (Table 9). Both the 2023 EU Regulation and the EEB report highlight the need to scale up recycling rates for copper, cobalt, nickel and lithium from 2025 onwards. Table 9 shows the recommended recycling rates for cobalt, copper, lithium and nickel for 2025 and 2030 for the European Union, which have been considered for the recycling assumptions in this research project.

Table 9: Recycling rates recommended by EU regulation and EEB, listed from most to least-ambitious targets

Source	item	Mineral	unit	2025	2030
2021 EEB report (joined NGO report)	Recycling rate	Cobalt	[%]	90%	
2021 EEB report (joined NGO report)	Recycling rate	Copper	[%]	95%	98%
2021 EEB report (joined NGO report)	Recycling rate	Lithium	[%]	95%	98%
2021 EEB report (joined NGO report)	Recycling rate	Nickel	[%]	70%	
2023 Battery Regulation (EU) 2023/1542[44]	Material recovery rate	Cobalt	[%]	90%	95%
2023 Battery Regulation (EU) 2023/1542	Material recovery rate	Copper	[%]	90%	95%
2023 Battery Regulation (EU) 2023/1542	Material recovery rate	Lithium		50%	80%
2023 Battery Regulation (EU) 2023/1542	Material recovery rate	Nickel	[%]	90%	95%
2023 Battery Regulation (EU) 2023/1542	Material recovery rate	Lead	[%]	90%	95%
2006 Battery Directive 2006/66/EC[45]	Battery recycling efficiency	Cobalt	[%]	75%	
2006 Battery Directive 2006/66/EC	Battery recycling efficiency	Copper	[%]		
2006 Battery Directive 2006/66/EC	Battery recycling efficiency	Lead	[%]	65%	
2006 Battery Directive 2006/66/EC	Battery recycling efficiency	Lithium	[%]		
2006 Battery Directive 2006/66/EC	Battery recycling efficiency	Other Waste Batteries	[%]	50%	

43 EEB (2021) Enhancing-the-sustainability-of-batteries: A joint NGO position paper on the EU Battery Regulation Proposal. European Environmental Bureau. https://eeb.org/wp-content/uploads/2021/03/Enhancing-the-sustainability-of-batteries_5.5.2021.pdf

44 EU (2023) Battery Regulation (EU) 2023/1542, ANNEX XII. https://eur-lex.europa.eu/eli/reg/2023/1542/oj/eng

45 EU (2006) Battery Directive 2006/66/EC, ANNEX III. https://eur-lex.europa.eu/eli/dir/2006/66/oj/eng

4.3.1 Assumed recycling rates

To reduce mineral extraction (mining) for minerals, the recycling of minerals from products that have reached the end of their lives is essential. In this study, we examine not only the potential demands for the minerals analysed and the associated impact on their extraction, but also the role of ambitious recycling strategies. Therefore, higher recycling rates were assumed for the initial years – 2025 to 2030 – to determine their effects on mineral demands. The recycling rates presented here are intended to be technical and ecological benchmarks, not predictions. In this context, it is important to note that the reuse of existing applications ('second life') is explicitly excluded.

Table 10: Assumed recycling rates

Recycling rates at end-of-life for renewable energy technologies		Recycling for Technology		
Technology		OECM	PRO	PRO-Na-ion
Batteries	Current to 2029	70%		
	2030–2040	70%	85%	85%
	2041–2050	90%	95%	95%
	Potential	95%		
Electric vehicles	Current to 2029	70%		
	2030–2040	70%	85%	85%
	2041–2050	90%	95%	95%
	Potential	95%		
Solar PV	Current to 2029	70%		
	2030–2040	70%	70%	70%
	2041–2050	81%	81%	81%
	Potential	81%		
Wind	Current to 2029	90%		
	2030–2040	90%	90%	90%
	2041–2050	95%	95%	95%
	Potential	95%		

Table 10 shows the assumed recycling rates for the analysed technologies until 2029, between 2030 and 2040 and for the last decade of this analysis to 2050. The recycling rates are assumed for all minerals included in the technology. It is assumed that, on average globally, 70% of all EV and BESS batteries will be recycled, and that all minerals will be recovered at the same percentage. This is a simplification, because not all minerals are always returned to the recycling loop ('yield rates') in equal proportions. The 'yield rates' of minerals are, in practice, not 100%.

It is important to highlight, that the IEA takes yield rates – the material that is technically recovered from the recycling methods – into account, while this research does not include it. Furthermore, there is some methodological ambiguity to what extent IEA projections consider secondary supply (recycling) and or secondary use (secondary life). Therefore, the calculated mineral demand documented from the IEA publication and the results of this analysis are only indicative.

For documentation purposes, we include the original paragraph from the 'IEA Critical Minerals Outlook 2025'[46]:

'Primary supply requirements have been assessed by deducing projected secondary supply from projected total demand. Secondary production is estimated with two parameters: the average recycling rate and the lifetime of each end-use sector. The recycling rate is the combination of the end-of-life collection rate (the amount of a certain product being collected for recycling) and the yield rate (the amount of material a recycling process can actually recover). For emerging technologies such as lithium-ion batteries, we assume collection rates increase at a faster pace. For batteries, the collection rates gradually increase from around 45% in the early 2020s to 80% by 2040 in the NZE Scenario. The yield rate is assumed to vary according to the technical limitations for the extraction of each mineral using the currently available recycling methods. The reuse rates are much lower than the collection rate for recycling as the use of second-life batteries (in grid applications) faces many technical and regulatory obstacles. Losses from manufacturing processes are also taken into account. For primary supply requirements for mined materials, a certain level of loss ratio during refining processes is assumed.'

4.3.2 Assumed technical lifetime for the analysed applications

The technical lifetime assumed for the calculation of mineral resource requirements for the key energy transition technologies has a significant impact on the results. For the material demand, it is essential to know how many applications are manufactured. After the end of the assumed technical lifetime, the products will be replaced, and their replacement has two main effects on the material calculation:

1. Whether the material can be recycled.
2. The increase in the overall product quantity required to implement the energy transition scenario.

Example: The OECM scenario requires wind turbines with a total installed capacity of around 2,000 GW in 2030 which must double to approximately 4,000 GW in 2035, an increase of 2000 GW in 5 years. This requires an increase of the annual manufacturing capacity from 117 GW in 2024 to 400 GW/a by 2030. With an assumed lifetime of 20 years for each wind turbine, all wind turbines installed in 2010 must be replaced in 2030 and the capacity installed in 2011 must be replaced in 2031 to further increase the overall installed capacity. The global wind market in 2010 was 36 GW and in 2011 was 41 GW. Therefore, the required new capacity – which will require the resources for wind turbines – would be 436 GW in 2030 and 441GW in 2031.

Although, the experience of the past indicates that the technical lifetimes of wind turbines, solar PV generators, concentrated solar power plants and EV are higher than the assumed lifetimes (see Table 11), we have chosen industry standards as a precautionary principle to avoid the underestimation of mineral resources.

Table 11: Assumed technical lifetimes of the technologies analysed

Technology	Assumed average technical lifetime
Solar Photovoltaics	20 years
Concentrated Solar Power (CSP) Plants	20 years
Wind (Onshore & Offshore)	20 years
EV (including batteries)	12 years
Battery Electric Storage Systems (BESS)	12 years

46 IEA (2025), Global Critical Minerals Outlook 2025, IEA, Paris. Available at https://www.iea.org/reports/global-critical-minerals-outlook-2025

4.4 Battery Chemistries and Properties

The electrification of mobility and energy storage is driven by the commercialisation, mass-manufacture, and increasing uptake of battery types. In this research, we consider different battery chemistries and their characteristics that are relevant for the electrification of the energy sector. These include the currently available and applied battery types, and the battery types projected to increase their market share and commercial applications until 2050, while others are phased out.

Our research differentiates between two battery applications: batteries used for mobility and those used for energy storage. Electric mobility includes passenger and commercial EVs and the electrification of two- and three-wheeler vehicles. The batteries used for energy storage systems include front-of-the-meter systems, i.e., utility-scale battery storage systems with capacities of several megawatt (MW) and durations of megawatt hours (MWh); and behind-the-meter applications, such as home battery systems, which range in units of kilowatts (kW), with shorter durations, measured in kilowatt hours (kWh).

In 2020, lithium battery types dominated the mobility and energy storage sectors. Traditionally, high-nickel-based lithium-ion batteries (e.g., NMC, NCA) had the largest market share in both sectors. However, the global market share of other battery types such as Lithium-Iron Phosphate batteries (LFP), predominantly manufactured in China, has been increasing, from 7% in 2018 to 27% in 2022 (IEA, 2023, GPI 2025)[47,48]. For EV applications, LFP reached a global market share of 48% in 2024 (Moeller et al., 2024; IEA, 2025)[49,50]. We assess the currently used battery chemistries, trends, costs, and demands to understand what the global battery chemistry mix could look like in the future.

4.4.1 NMC and NCA batteries

High-nickel-based lithium-ion batteries, including NMC and NCA chemistries, have played a central role in the electrification of the energy sector (IEA, 2023)[47] because their energy density is high and they are suitable for both EVs and stationary storage. NMC batteries have various ratios, such as NMC 111, which uses equal parts nickel, manganese, and cobalt. Others, such as 622 and 811, have an increased nickel content to boost their energy density.

4.4.2 LFP batteries

LFP batteries have rapidly gained prominence as a cost-effective and durable lithium-ion chemistry, particularly suited for EVs and stationary storage (IEA, 2023).[47] They have benefited from the broader 'battery domino effect', in which falling costs and increasing energy densities across battery technologies have accelerated their adoption across sectors (Rocky Mountain Institute, 2023).[51] LFP cells typically offer lower energy densities than nickel-based chemistries, but (IEA. 2023)[47] highlights the potential for improved energy density based on changes in battery chemistries. However, LFP batteries excel in thermal stability, safety, and longevity, making them ideal for applications in which volume is less constrained. The analysis of the Rocky Mountain Institute (2023)[51] indicated that the affordability and long-life cycle of LFP batteries are key to their growing role in displacing fossil fuels, especially for grid storage and entry-level EVs, and continued innovation is expected to further improve their performance and expand their market share. China has led the global LFP market, leveraging its dominance in battery manufacturing to scale production (70% of all batteries are produced in China; IEA 2025)[50] and deployment and to reduce costs (LFP batteries are 30% cheaper than NMCs; IEA, 2025)[50], with Europe and the USA scaling up investments. Future projections indicate that nickel-based chemistries will be increasingly replaced by LFP batteries, which are more affordable, safer, and have longer life cycles (Moeller et al., 2024)[49]. The 2024 Battery Mineral Loop report by Rocky Mountain Institute[51] states that shifts in the chemistry mix, together with improvements in recycling and efficiency, are expected to drive peak demand for nickel and cobalt by the mid-2030s, with LFP and other alternatives playing a growing role in reducing our reliance on mined minerals.

47 IEA (2023). Global EV Outlook 2023. IEA, Paris **https://www.iea.org/reports/global-ev-outlook-2023** (accessed: 10 November 2025)

48 GPI (2025). Batteries in Transition – Innovation, Uncertainty and the Minerals Behind Them. 11 November, 2025 **https://www.greenpeace.org/international/batteries-in-transition-report/**

49 Moeller, T., Cepnik, C., Azevedo, M., Campagnol, N., Kinzel, Y., 2024. The battery chemistries powering the future of electric vehicles. McKinsey & Company. Available at: **https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/the-battery-chemistries-powering-the-future-of-electric-vehicles** (accessed: 10 November 2025)

50 IEA (2025). The battery industry has entered a new phase. IEA, Paris **https://www.iea.org/commentaries/the-battery-industry-has-entered-a-new-phase** (accessed: 10 November 2025)

51 Rocky Mountain Institute (2023). X-Change: Batteries. The Battery Domino Effect, December 2023, available at: **https://rmi.org/wp-content/uploads/dlm_uploads/2023/12/xchange_batteries_the_battery_domino_effect.pdf**

4.4.3 Sodium-ion (Na-ion) batteries

Sodium-ion batteries use sodium as the main carrier for charging. They are similar to lithium-ion batteries, and can include minerals such as copper, nickel and manganese (Wathoni et al., 2025; Yao et al., 2025).[52,53] Sodium-ion batteries also have a wider temperature range of operation, improved safety, and potential cost advantages relative to Li-ion batteries after scaling, and the materials required are more geographically dispersed than lithium. As sodium-ion batteries are coming closer to the energy density of LFP batteries they are expected to start gaining greater market shares. Their application to two- and three-wheeler vehicles (micromobility), passenger EVs and BESS (GPI, 2025; IEA, 2025; Passerini et al., 2024)[48,50,54] is expected to grow. The increased use of Na-ion batteries in passenger EVs may further reduce the cost of EVs and will increase the uptake of EVs. Considering the recent developments in improving the energy density of Na-ion batteries (GPI, 2025)[55], in this report, we develop a scenario that assumes an increased uptake of Na-ion batteries for all vehicle types from 2030, including commercial EVs such as heavy duty EVs (this is beyond the projections in GPI, 2025[60].

The specific mineral requirements of Na-ion batteries and their increased technical performances lead to the development of the Accelerated Na-ion scenario.

4.4.4 Lithium sulphur batteries

Lithium sulphur (Li-S) battery technologies use sulphur as the negative battery electrode and lithium as the positive electrode. They are rechargeable, light, have a high energy density and a lower reliance on transition minerals (IEA, 2025)[56]. IEA's Global EV Outlook (2025, p. 153)[56] projects that Li-S batteries will be commercialised by 2030 and could find applications in commercial road transport (long-distance trucks), shipping (short-distance boats), and the aviation sector. Xu et al. (2020)[57] developed a scenario (based on the IEA Sustainable Development scenario) in which Li-S increases from 3% in 2030 to 30% by 2050. Other future applications may include large-scale grid energy storage solutions with breakthroughs and improvements in the ability of Li-S batteries to charge and discharge rapidly, whereas the current state-of-the-art Li-S batteries show slow charge – discharge rates (Li et al., 2024, Savage, 2024).[58,59] IEA (2025)[56] has reported that Li-S batteries currently face several challenges, including "improving volumetric energy density (Wh/L), enhancing durability and addressing safety concerns related to the use of lithium metal anodes" (p. 143f).

52 Wathoni, A.Z., Madurani, K.A., Lai, C.W., Kurniawan, F. Comprehensive review of sodium-ion battery materials: Advances and performance challenges. ChemPhysMater 2025;4(4):344 – 359. https://doi.org/10.1016/j.chphma.2025.06.003

53 Yao et al. Critically assessing sodium-ion technology roadmaps and scenarios for techno-economic competitiveness against lithium-ion batteries. Nature Energy 2025;10:404 – 416 https://doi.org/10.1038/s41560-024-01701-9)

54 Passerini, S., Barelli, Linda., Baumann, Manuel., Peters, Jens., & Weil, Marcel. (Eds.). (2024, p. 92). Emerging Battery Technologies to Boost the Clean Energy Transition : Cost, Sustainability, and Performance Analysis (1st ed. 2024.). Springer International Publishing. https://doi.org/10.1007/978-3-031-48359-2

55 GPI (2025). Batteries in Transition – Innovation, Uncertainty, and the Minerals Behind Them. 11 November 2025. https://www.greenpeace.org/international/batteries-in-transition-report/

56 IEA (2025). Global EV Outlook 2025. IEA, Paris https://www.iea.org/reports/global-ev-outlook-2025

57 Xu, C., Dai, Q., Gaines, L. et al. Future material demand for automotive lithium-based batteries. Communications Materials 2020;1:99. https://doi.org/10.1038/s43246-020-00095-x

58 Li, H., Meng, R., Ye, C. et al. Developing high-power Li||S batteries via transition metal/carbon nanocomposite electrocatalyst engineering. Nature Nanotechnology 2024;19:792 – 799. https://doi.org/10.1038/s41565-024-01614-4

59 Savage, C. (2024). Fast-charging lithium – sulphur batteries on the horizon. University of Adelaide Newsroom, March 2024, available at https://www.adelaide.edu.au/newsroom/news/list/2024/03/14/fast-charging-lithium-sulphur-batteries-on-the-horizon

Table 12: Battery chemistries for EV and BESS in 2020 and 2025

		Mobility						Battery storage systems	
		All passenger EVs		Commercial EVs		2-and 3-wheelers			
	Unit	2020	2025	2020	2025	2020	2025	2020	2025
LFP	[%}	17%	54%	54%	89%	20%	34%	30%	91%
LMFP	[%}	0%	1%	0%	1%		3%		
LMO	[%]	0%		0%		13%	8%		
NCA (95, 92, 90, 85)	[%}	25%	6%	0%		19%	16%	19%	
NMCA	[%]	0%	2%	0%			4%		
NMC (96Ni, 955, 721, 811, 622, 532, 111), LMR-NMC	[%]	37%	35%	46%	10%	48% (all NMC 111)	34%	50%	6%
Sodium ion	[%]	0%		0%	0%	0%	2%	0%	
Redox flow	[%]	n/a		n/a	n/a	n/a		0%	
Other	[%}	1%	2%	0%	0%	0%		1%	3%
Sum	**[%}**	**100%**		**100%**				**100%**	**100%**

Source: GPI (2025)[60]

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60 GPI (2025), Batteries in Transition – Innovation, Uncertainty and the Minerals behind them, 11. November 2025, https://www.greenpeace.org/international/batteries-in-transition-report/

5 Key Energy Scenario Assumptions

The basis for the assumptions underlying the analysis of resource requirements consists of two parts:

a) The chosen energy scenario pathways define the overall energy demand and supply structure. Furthermore, they define the requirements for new solar and wind installations as well as the battery electric systems and EVs required. Moreover, consumer pattern – for example the use of public transport and/or individual transport – influence the vehicle size required. For public transport, larger vehicles, such as buses, are required, whereas individual transport could even include small two- or three-wheeler vehicles with significantly smaller batteries and therefore less resources per vehicle. However, the number of vehicles increases significantly when individual transport increases.

b) The calculated resource requirements depend on the assumed material intensities – the required material per vehicle or installed capacity in kilowatt or battery capacity in kWh.

5.1 OECM 1.5°C: Key Assumptions – Energy

The over 40 OECM country scenarios have regionally based assumptions that often differ greatly from one another due to the different circumstances of the local energy demands and supplies. However, there are some common global assumptions and (technical and economic) conventions across all the national OECM scenarios developed to achieve the full decarbonisation of the global energy sector.

5.1.1 Key assumptions to achieve decarbonisation of the energy sector for OECM

- GDP will increase according to World Bank projections (published in 2023) until 2050, and "least-developed countries" will reach middle-income country status (approx. $14,000 per capita; The World Bank Group, 2023).[61]
- Population will grow according to the projections of the United Nations, and the global population will reach around 10 billion by 2050 (United Nations, 2024)[62].
- Decarbonisation pathways are based on immediate actions with currently available technologies, rather than upon radical technologies (e.g., direct air capture) assumed to emerge before 2050.
- Electrification of the transport sector, residential climatisation, and industrial process heat is assumed, with hydrogen-based fuels for all processes that cannot (yet) be electrified.
- New technologies will be implemented in line with historical learning curves and with the fastest-possible technical and economic upscaling of the manufacturing capacity and workforce (educating and training).

Decarbonisation of the electricity supply
- More than 50% of the electricity supply must be from renewable sources by 2035.
- Coal-fired power stations must be fully phased-out by 2030 (OECD) and by 2045 globally.
- Gas-fired power stations must be fully phased-out by 2040 (OECD) and by 2050 globally.
- Globally, 100% of supply must be from renewable electricity sources, primarily wind and solar, by 2050.
- Offshore-wind will be key to increasing the security of supply and reducing the storage technology requirements.

Electrification of transport and mode shifting
- 50% of new vehicle sales must be EVs by 2030.
- The manufacture of vehicles with ICEs will be phased out globally by 2035, and all new vehicles sold must be electric.
- Shifts in different modes of transport are required – passenger transport must shift from both road and aviation to rail if possible.
- Aviation and shipping fuels must switch to sustainable synthetic fuels – mainly hydrogen-based synthetic fuels (e.g., sustainable aviation fuel).

61 The World Bank Group (2023) Middle Income Countries. Available at **https://www.worldbank.org/ext/en/region/mic** (accessed 14 December 2025)

62 United Nations (2024), Department of Economic and Social Affairs, Population Division, World Population Prospects 2024. Available at **https://population.un.org/wpp/** (accessed 14 December 2025)

5.2 Progressive Scenarios (PRO and PRO Accelerated Na-ion): Key Assumptions – Road Transport

Based on the global OECM 1.5°C pathway, two additional scenarios have been developed that focus on accelerated changes in the road transport sector (Progressive, "PRO" and Progressive Accelerated sodium ion, "PRO-Na-ion"). The following parameters (see Table 13) have been changed to reduce the need for vehicles and battery capacity to save mineral resources.

a) **Increased public transport:** This parameter defines the overall share of public transport within all annual passenger-kilometres. The current global share is approximately 16% of all passenger-kilometres on roads. Therefore, 84% of all passenger-kilometres are driven by private vehicles. This number has a high uncertainty because exact statistical data are not available. Furthermore, the passenger-kilometres are calculated based on the average vehicle energy intensity in MJ/km and the fuel demand for road transport. It is assumed that passenger-kilometres on the road will decrease by 1.5% per year, whereas the rail passenger-kilometres will increase by 2.5% per year with the calculated increase in percentages capturing the energy efficiency. For public transport, it is assumed that as the average number of passengers per vehicle increases, fewer vehicles will be required to service the same transport demand. The battery sizes for buses are assumed to be equal to those of freight vehicles – between 250 and 400 kWh/vehicle.

b) **Increased annual vehicle kilometres:** The more passengers that are transported with the same vehicle, the higher the annual vehicle-kilometres. A privately used car has an average annual 'mileage' of around 15,000 km, whereas shared cars reach up to 50,000 km per vehicle. The assumed increase in annual vehicle- kilometres will lead to fewer vehicles to service the same transport demand.

c) **Earlier ICE phase-out:** Global phase-out of the manufacture of vehicles with ICE by 2030 – five years ahead of the OECM; all new vehicles sold must be electric.

d) **Reduced annual global vehicle market volume:** The average annual passenger vehicle market, including (mini)buses, was 75 million vehicles per year over the past 20 years. The OECM assumes this market to be stable over the next 25 years, while additional manufacturing capacity will be required to replace ICE vehicles before the end of their technical lifetimes. The suggested Progressive Scenario goes one step further and assumes a stable 75 million vehicle market per year, including the early retirement of ICEs. This will lead to a smaller overall vehicles fleet in 2050. Under the OECM, the global passenger vehicle fleet will increase from 1.2 billion cars to around 2 billion cars, whereas under the Progressive Scenario, the global fleet plateaus at around 1.6 billion passenger vehicles.

e) **Reduced battery size for private passenger EVs:** To assume smaller vehicles – including two- and three-wheelers – will lead to a reduction in the overall battery capacity that is required. Therefore, manufacturing capacities and mineral demands will decrease compared with those under the OECM.

f) **Increased vehicle efficiency:** Smaller and more-efficient EVs have longer kilometre ranges with smaller battery packs. Therefore, the overall mineral demand is reduced while travel kilometres remain the same as under the OECM. This parameter identifies the average electricity demand per km for each vehicle type.

g) **Vehicle market development favours small vehicles:** This parameter is linked to parameter E (see above). The market share of efficient vehicles defined in parameter E is assumed to increase substantially under the Progressive Scenario relative to the OECM.

The combination of parameters A to G will lead to a significant reduction in the batteries required for EVs – and therefore reduced mineral demands.

Table 13: Assumptions and input data – road transport projection – Progressive Scenario

	Market Share	2030	2040	2050		
Population	[1]	8,563,656,259	9,182,351,894	9,675,975,274		
Share urban	[%]	59%	64%	68%		
Share rural	[%]	41%	37%	32%		
Global ROAD Passenger-km	[million pkm/a]	43,151,931	41,014,000	36,402,981		
Passenger-km per capita – global average	[km/capita]	4,789	4,213	3,762		
Proportion of cars	[%]	81.5%	66.5%	51.5%		
Proportion of public ROAD transport (RAIL NOT INCLUDED)	[%]	18.5%	33.5%	48.5%	High public transport – reduced EV car (Increased E-Buses)	A
Global Rail Passenger-km – development compared with OECM	[%/a]	+2.5%	+2.5%	+2.5%		
Global Road Passenger-km – development compared with OECM	[%/a]	-1.5%	-1.5%	-1.5%		
EV Market Share – Road Transport	**[%]**	**39.2%**	**72.4%**	**100%**		
Annual Kilometres Driven per Vehicle	[km/a]	14,900	30,000	50,000	Increase annual km per vehicles (more shared driving services)	B
Annual manufactured passenger vehicles	[vehicles per year]	75,000,000	75,000,000	75,000,000	Reduced annual manufactured vehicles	C
Annual Manufactured Electric Vehicles	[vehicles per year]	75,000,000	75,000,000	75,000,000		
Average BATTERY size per vehicles type	**Vehicle battery size [kWh/vehicle] | average >**	**67**	**45**	**42**		
Lightweight (LW; 2- & 3-wheelers)	[kWh/vehicle]	1.5	1.5	1.5		
Battery EV (BEV) Light Drive Vehicles (LDVs)	[kWh/vehicle]	30	27.5	25		
Plug-in Hybrid EV (PHEV) LDVs	[kWh/vehicle]	25	25	25	This defines the average size of the battery pack	D
BEV Heavy Drive Vehicles (HDVs)	[kWh/vehicle]	125	110	100		
PHEV HDVs	[kWh/vehicle]	35	60	60		
		11	19	24		
LW (2- & 3-wheelers)	[kWh/100km]	1.5	1.5	1.5		
BEV LDV	[kWh/100km]	15	15	15	This defines the average demand per vehicle and therefore the total electricity demand (that must be generated)	E
PHEV LDVs	[kWh/100km]	25	25	25		
BEV HDV	[kWh/100km]	35	35	35		
PHEV HDV	[kWh/100km]	50	50	50		
Global Fleet Market Share – EV size						
LW (2- & 3-wheelers)	[%]	7.2%	18.4%	31.7%		
BEV LDVs	[%]	14.0%	25.0%	31.0%	This defines the uptake of EV's (and the reduction of CO_2 from road transport)	F
PHEV LDVs	[%]	0%	0.0%	0.0%		
BEV HDVs	[%]	18.0%	29.0%	37.3%		
PHEV HDVs	[%]	0.0%	0.0%	0.0%		

5.2.1 Key assumption for the Accelerated Na-ion scenario

Rationale for passenger vehicles (LDVs)

Aggressive Na-ion uptake scenarios for passenger vehicles exist. This scenario assumes incremental increase of the Na-ion share based on the aggressive Na-ion scenario developed by Bloomberg New Energy Finance in 2023, documented in GPI (2025)[63], which projects a 40% share of Na-ion in 2035 passenger EV sales. In this scenario, battery chemistries for LFP, LMFP, NCA, and NMC are substituted proportionally according to the 2030–2050 battery mix in the Progressive scenario. This approach has been adopted to compensate for the uncertainty related to the types that would be replaced in this Accelerated Na-ion Scenario. LFP is expected to undergo the greatest substitution for the accelerated Na-ion uptake.

Rationale for HDVs

Sodium-ion development for HDVs is less developed than for other mobility segments (LDV, two- and three-wheelers). We assume that it will take longer for Na-ion batteries to develop significant shares in this segment.

The Na-ion technology is assumed to substitute for LFP in this mobility mode because of unique energy density and the range requirements for HDVs. Energy density of Na-ion batteries is assumed to come close to LFP batteries.

Rationale for two- and three-wheeler vehicles

Two-and three-wheeler vehicles with Na-ion batteries are on the market. Their share could ramp up significantly, arguably faster than that of LDVs. In the aggressive Na-ion scenario developed by BNEF (2023), Na-ion batteries take over the whole market share for small vehicles. Because two- and three-wheelers share similar battery needs with small vehicles, a predominant (almost complete) market share for Na-ion batteries by 2050 is assumed under this scenario.

5.3 Key Assumptions for Calculating Resource Requirements

This section provides an overview of the main input assumptions for the calculation of resource requirements. Besides the actual energy scenario, which determines the energy demand including the current and future utilisation of applications and vehicle types and the energy supply technologies, the market shares of the future technologies and their resource intensities define the material requirements.

5.3.1 Interaction between material Intensities and technology market shares

The assumed material intensities for all the energy transition technologies analysed depend upon the assumed market shares of the technology sub-groups. Electric batteries have by far the largest variations regarding the required minerals per energy unit. Based on literature research, which is documented in the following section, three different scenarios for the deployment of various battery technologies with different market shares have been developed. Table 14 shows the assumed mineral requirement for the analysed technologies which have been used for all calculated scenarios.

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63 GPI (2025). Batteries in Transition—Innovation, Uncertainty and the Minerals behind them. 11 November, 2025. https://www.greenpeace.org/international/batteries-in-transition-report/

Table 14 Mineral intensities by technology

		[unit]	Copper	Graphite (pure)	Lithium	Nickel	Manganese	Cobalt	Dysprosium	Neodymium	Vanadium
Batteries											
Lithium-ion phosphate	LFP	[t/GWh]	430[64]	1,090[64]	100[64,65]	0	0	0	0	0	0
Lithium – manganese – Iron phosphate (LMFP)	LMFP	[t/GWh]	430[64]	910[64]	80[64]	0	350[64]	0	0	0	0
Lithium – Nickel – Cobalt – Aluminium Oxide	NCA	[t/GWh]	310[64]	980[64]	100[64,67]	760[64]	0	140[64]	0	0	0
Nickel – Manganese – Cobalt – Aluminium Lithium-Ion	NMC battery types										
	- NMC 111	[t/GWh]	360[64]	990[64]	120[64]	390[64]	330[64]	390[64]	0	0	0
	- NMC 532	[t/GWh]	340[64]	880[64]	120[64,47]	467	261	170	0	0	0
	- NMC 622	[t/GWh]	320[64]	870[64]	120	546	170	182	0	0	0
	- NMC 721	[t/GWh]	305	870	108	575	70	165	0	0	0
	- NMC 811	[t/GWh]	290[64]	870[64]	108	661	80[66]	75[67]	0	0	0
	- NMC 955	[t/GWh]	270[46]	870[46]	80[46]	840[46]	30[46]	50[46]	0	0	0
Redox flow[68]	VRFB	[t/GWh]	0	580	0	0	0	0	0	0	1,995
Sodium-Ion	Na-ion	[t/GWh]	0	0	0	460	612	0	0	0	0
Lithium – sulphur	Li-S	[t/GWh]	0	1,000	161	0	0	0	0	0	0
Solar PV											
Crystalline silicon[69,70]	c-Si	[t/GW]	884	0	0	0	0	0	0	0	0
Copper – indium – gallium – di-selenide solar cell[71]	CIGS	[t/GW]	450	15	0	0	0	0	0	0	0
Cadmium telluride[70]	CdTe	[t/GW]	4,841	0	0	0	0	0	0	0	0
CSP											
Parabolic trough[70]	Parabolic trough	[t/GW]	3,200	0	0	940	2,000	0	0	0	2
Central tower[70]	Central tower	[t/GW]	1,400	0	0	1,800	5,700	0	0	0	2

64 Bobba, S., Latunussa, C., Manni, F.M. and Mathieux, F. (2025) Deep dive on critical raw materials for batteries in the EU, Publications Office of the European Union, Luxembourg, 2025, page 105. Available at https://data.europa.eu/doi/10.2760/3300656, JRC141715 (accessed 15 December 2025)

65 IEA (2018), Global EV Outlook 2018, IEA, Paris https://www.iea.org/reports/global-ev-outlook-2018 p. 84, Table 6.1

66 Li, E., Bieker, G., & Sen, A. (2024). Electrifying road transport with less mining: A global and regional battery material outlook. The International Council on Clean Transportation. https://theicct.org/wp-content/uploads/2024/12/ID-206-%E2%80%93-Battery-outlook_report_final.pdf (Table A4)

67 Davis, K., & Demopoulos, G. P. (2023). Hydrometallurgical recycling technologies for NMC Li-ion battery cathodes: current industrial practice and new R&D trends. RSC Sustainability, 1(8), 1932 – 1951. https://doi.org/10.1039/D3SU00142C

68 Fraunhofer Institute for Solar Energy Systems ISE (2022), MATERIAL REQUIREMENTS FOR THE ENERGY TRANSITION Energy technology profiles and environmental impacts, September 2022, https://publica-rest.fraunhofer.de/server/api/core/bitstreams/6b2d4caa-95af-4356-be9d-eaeb13be54f9/content

69 Frischknecht, R., Stolz, P., Krebs, L., de Wild-Scholten, M., Sinha, P. (2020) Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems

70 Bruce S, Delaval B, Moisi A, Ford J, West J, Loh J, Hayward J (2021) Critical Energy Minerals Roadmap. CSIRO, Australia; http://hdl.handle.net/102.100.100/637751?index=1

71 Carrara, S., Alves Dias, P., Plazzotta, B. and Pavel, C., Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system, EUR 30095 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-16225-4, https://op.europa.eu/en/publication-detail/-/publication/19aae047-7f88-11ea-aea8-01aa75ed71a1/language-en

		[unit]	Copper	Graphite (pure)	Lithium	Nickel	Manganese	Cobalt	Dysprosium	Neodymium	Vanadium
Wind											
Non-permanent-magnet generator (non-PMG)[72]	Direct-drive excited synchronous generator	[t/GW]	3,791	0	0	359	0	0	16	28	0
	Doubly fed induction generator	[t/GW]	2,296	0	3	385	3	0	3	114	0
Permanent-magnet generator (PMG)[71]	Direct-driven permanent synchronous generator	[t/GW]	3,191	0	0	309	0	0	19	175	0
	Permanent magnet synchronous generator	[t/GW]	2,400	0	3	377	3	0	5	44	0

Limitations

It is assumed that the material intensities for the technologies themselves will not change over time; an (LFP) battery for example will require the same amounts of minerals in 2025 as in 2050. This represents a simplification. Literature research has revealed significant variations in the reported material intensities for the same technologies. Therefore, the values are subject to a degree of uncertainty. The selected intensities were discussed and chosen based on the available sources.

5.4 Battery chemistry development and supporting literature

UTS-ISF has developed three scenarios with varying projections for the development of battery chemistries between the base-year 2024 and 2050, using annual data informed by other studies. Two scenarios for each mobility/EVs and grid storage/BESS. The three scenarios per sector include one OECM 1.5°C and two Progressive Scenarios with different development pathway for battery technologies.

First, the OECM Net-Zero pathway has been informed by studies in which future LFP-leaning battery scenarios are developed and NCAs and NMCs were gradually phased out (GPI, 2025[73]). Second, the Progressive Scenario highlights further measures that can be applied until 2050 to reduce mineral demand. Based on the Progressive Scenario, a third pathway has been developed that accelerates the deployment of Na-Ion batteries – the Progressive Accelerated Na-ion Scenario.

The Progressive Scenario is based on the OECM pathways, but includes progressive measures such as greater use of public transport, reduced reliance on minerals with large human and environmental impacts, such as cobalt (90% of cobalt is mined in the Democratic Republic of Congo), rare earth elements (REE), and minerals associated with supply risks, including lithium, nickel, and graphite (Shannak et al., 2024)[74]. Finally, the application and deployment of innovative battery technologies (Li-Sulphur, Na-ion) is assumed to take greater shares from currently dominant battery chemistries (LFP, NMCs).

The Progressive Accelerated Na-ion Scenario shows how the accelerated uptake of Na-ion batteries from 2030 onwards can reduce the reliance on Li-ion battery technologies until 2050 and therefore reduce lithium demand.

72 U.S. Department of Energy (2023). Critical Materials Assessment, 2023, https://www.energy.gov/sites/default/files/2023-05/2023-critical-materials-assessment.pdf

73 GPI (2025). Batteries in Transition. Innovation, Uncertainty and the Minerals behind Them. 11 November 2025. https://www.greenpeace.org/international/batteries-in-transition-report/

74 Shannak, S., Cochrane, L., Bobarykina, D. (2024). Strategic analysis of metal dependency in the transition to low-carbon energy: A critical examination of nickel, cobalt, lithium, graphite, and copper scarcity using IEA future scenarios. Energy Research & Social Science 118, Article 103773. https://doi.org/10.1016/j.erss.2024.103773

5.4.1 OECM battery chemistry assumptions

Passenger Electric Vehicles (LDVs)

Based on academic literature and data from GPI (2025), we have developed an OECM-NZS Net-Zero battery chemistry mix for the scenario (see Table 15). In this case, LFP batteries are expected to become the dominant battery chemistry for LDVs and will achieve a share of 67% by 2050. In 2020, LFP batteries had a market share of between 26% and 40% based on the literature (GPI, 2025; ICCT, 2024; Xu et al., 2020)[75,76], and an aggressive uptake of LFP batteries has been projected, with their market share for LDVs reaching between 52% (GPI 2025)[62] and 70% by 2030 (ICCT, 2024). BNEF (2025)[77] projects that LFP battery uptake will decline slightly as LMFP batteries increase (7% in 2030). We will then see a stronger comeback of LFPs in 2040 to over 65%, which will remain stable until 2050, when LFPs reach a 67% share. Overall, NMC-type batteries will decrease from 45% in 2020 to 22% in 2050, and more innovative battery types, such as NMC 955, will be the dominant battery type throughout the transition, making up 17% of the overall 22% of NMC battery types. Sodium-ion batteries are not considered in this scenario.

Table 15: LDV – OECM Scenario, values passenger EV's, in percentages, 2020-2050 (informed by GPI 2025[78], ICCT 2024[79], Xu et al. 2020[80])

	[unit]	2020	2025	2030	2035	2040	2045	2050
LFP	[%]	32%	58%	61%	64%	69%	68%	67%
LMFP	[%]	0%	0%	7%	5%	1%	1%	0%
NCA	[%]	22%	12%	10%	7%	7%	7%	11%
All NMC battery types	[%]	45%	30%	22%	23%	23%	24%	22%
- NMC 111	[%]	4%	1%	1%	1%	1%	1%	1%
- NMC 532	[%]	13%	4%	1%	0%	1%	1%	1%
- NMC 622	[%]	20%	12%	6%	4%	3%	2%	1%
- NMC 721	[%]	1%	0%	0%	0%	0%	0%	0%
- NMC 811	[%]	5%	10%	9%	6%	5%	4%	2%
- NMC 955	[%]	2%	3%	6%	12%	13%	16%	17%
Redox flow	[%]	0%	0%	0%	0%	0%	0%	0%
Na-ion	[%]	1%	0%	0%	1%	0%	0%	0%
Li-S	[%]	0%	0%	0%	0%	0%	0%	0%
Other	[%]	0%	0%	0%	0%	0%	0%	0%
Sum	**[%]**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

75 ICCT (2024). Electrifying road transport with less mining: A global and regional battery material outlook. International Council on Clean Transportation. Available at: https://theicct.org/wp-content/uploads/2024/12/ID-206-%E2%80%93-Battery-outlook_report_final.pdf [accessed: 1 September 2025].

76 Xu, C., Dai, Q., Gaines, L. et al. Future material demand for automotive lithium-based batteries. Communications Materials 2020;1:99. https://doi.org/10.1038/s43246-020-00095-x

77 BNEF (2025) Global Energy Storage Growth Upheld by New Markets, Figure on 'Lithium ion batteries dominate energy storage market'. (BloombergNEF, June 18, 2025). Available at: https://about.bnef.com/insights/clean-energy/global-energy-storage-growth-upheld-by-new-markets/ (Accessed 12 November 2025)

78 GPI (2025). Batteries in Transition. Innovation, Uncertainty and the Minerals behind Them. 11 November 2025. https://www.greenpeace.org/international/batteries-in-transition-report/

79 ICCT (2024). Electrifying road transport with less mining: A global and regional battery material outlook (ID-206). International Council on Clean Transportation. Retrieved from https://theicct.org/wp-content/uploads/2024/12/ID-206-%E2%80%93-Battery-outlook_report_final.pdf

80 Xu, C., Dai, Q., Gaines, L. et al. Future material demand for automotive lithium-based batteries. Communications Materials 2020;1:99. https://doi.org/10.1038/s43246-020-00095-x

Commercial vehicles (HDVs)

LFP batteries will be the main battery type for commercial EVs until 2050, which is similar to the development described above for passenger vehicles (Table 15), with the distinct difference that LMFP battery types will be adopted from 2030 onwards. Considering the projection of improved energy densities and cost reductions (-30%; IEA, 2025) for LFPs, the share of NMC battery types (1%) will become insignificant (Table 16).

Table 16: HDV – Overview of commercial EVs, % (informed by GPI 2025[81], ICCT 2024[82], Xu et al. 2020[83])

	[unit]	2020	2025	2030	2035	2040	2045	2050
LFP	[%]	54%	55%	76%	67%	67%	64%	61%
LMFP	[%]	0%	0%	4%	9%	16%	23%	30%
NCA (NMCA, NCA85,90,92)	[%]	0%	0%	3%	9%	9%	7%	5%
All NMC battery types	[%]	46%	44%	14%	8%	1%	1%	1%
- NMC 111	[%]	0%	0%	0%	0%	0%	0%	0%
- NMC 532	[%]	17%	16%	2%	1%	0%	0%	0%
- NMC 622	[%]	23%	22%	2%	1%	0%	0%	0%
- NMC 721	[%]	0%	0%	1%	1%	0%	0%	0%
- NMC 811	[%]	6%	6%	8%	4%	0%	0%	0%
- NMC 955+96Ni	[%]	0%	0%	1%	1%	1%	1%	1%
Redox flow	[%]	0%	0%	0%	0%	0%	0%	0%
Na-ion	[%]	0%	0%	0%	0%	0%	0%	0%
Li-S	[%]	0%	0%	0%	0%	0%	0%	0%
Other	[%]	0%	0%	3%	7%	7%	5%	3%
Sum	**[%]**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Two-and three-wheelers (2W3Ws)

The battery mixes for two- and three-wheeler vehicles are composed of a mixture of Li-ion-based batteries and the uptake of Na-ion batteries from 2025–2030 onwards. Because LFP batteries will increase over the next decade, peaking in 2035, the share of NMC batteries will decrease from 19% in 2020 to zero in 2050 (see Table 17).

Like the battery mixes for the heavy duty (commercial) mobility mode, the share of LFP batteries will decline as LMFP battery types are introduced from 2025–2030, reaching 34% in 2050. The battery mix in 2050 will be made up of almost equal parts LFP (30%), LMFP, and Na-ion batteries (both with a share of 34%).

81 GPI (2025). Batteries in Transition. Innovation, Uncertainty and the Minerals behind Them. 11 November 2025. https://www.greenpeace.org/international/batteries-in-transition-report/

82 ICCT (2024). Electrifying road transport with less mining: A global and regional battery material outlook (ID-206). International Council on Clean Transportation. Retrieved from https://theicct.org/wp-content/uploads/2024/12/ID-206-%E2%80%93-Battery-outlook_report_final.pdf

83 Xu, C., Dai, Q., Gaines, L. et al. Future material demand for automotive lithium-based batteries. Communications Materials 2020;1:99. https://doi.org/10.1038/s43246-020-00095-x

Table 17: Overview of 2W3W EV, in % (informed by GPI 2025[84], ICCT 2024[85], Xu et al. 2020[86])

	[unit]	2020	2025	2030	2035	2040	2045	2050
LFP	[%]	20%	31%	42%	39%	36%	33%	30%
LMFP	[%]	0%	6%	12%	22%	32%	33%	34%
NCA (NMCA, NCA85,90,92)	[%]	19%	18%	17%	11%	5%	3%	0%
All NMC battery types	[%]	48%	32%	16%	9%	2%	1%	0%
- NMC 111	[%]	48%	24%	0%	0%	0%	0%	0%
- NMC 532	[%]	0%	0%	0%	0%	0%	0%	0%
- NMC 622	[%]	0%	0%	0%	0%	0%	0%	0%
- NMC 721	[%]	0%	0%	0%	0%	0%	0%	0%
- NMC 811	[%]	0%	8%	15%	9%	2%	1%	0%
- NMC 955+96Ni	[%]	0%	1%	1%	0%	0%	0%	0%
Redox flow	[%]	0%	0%	0%	0%	0%	0%	0%
Na-ion	[%]	0%	6%	11%	16%	22%	28%	34%
Li-S	[%]	0%	0%	0%	0%	0%	0%	0%
Other	[%]	13%	8%	2%	3%	3%	3%	2%
Sum	**[%]**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

84 GPI (2025). Batteries in Transition. Innovation, Uncertainty and the Minerals behind Them. 11 November 2025. https://www.greenpeace.org/international/batteries-in-transition-report/

85 ICCT (2024). Electrifying road transport with less mining: A global and regional battery material outlook (ID-206). International Council on Clean Transportation. Retrieved from https://theicct.org/wp-content/uploads/2024/12/ID-206-%E2%80%93-Battery-outlook_report_final.pdf

86 Xu, C., Dai, Q., Gaines, L. et al. Future material demand for automotive lithium-based batteries. Communications Materials 2020;1:99. https://doi.org/10.1038/s43246-020-00095-x

5.4.2 Progressive Scenario (PRO) battery chemistry assumptions

The PRO battery chemistry assumptions are based a LFP-dominated battery mix that applies additional progressive measures to phase out cobalt in battery chemistries by 2050.

The [%] shares for LFP, LMFP, NMCs, and Na-ion batteries are informed by BNEF (2025), ICCT (2024), and IEA Sustainable Development LFP scenario of Xu et al. (2020). To include other scenarios that have considered innovative technologies, particularly a share of Li-S, the Progressive Scenario (PRO) is also informed by Xu et al. (2020)'s IEA Sustainable Development – Lithium-Air Scenario.

Passenger EVs (LDVs)

In 2020, NMC-type batteries dominated the battery mix in passenger vehicles (46%), and LFPs made up the second largest share (32%), whereas NCAs accounted for 22%. By 2030, LFPs (60%) will have outperformed the NMC and NCA battery types. As more innovative battery types enter the market from 2030 onwards, the mix will change. By 2050, Na-ion and Li-S batteries will make up a combined share of 21% and LMFPs will reach 20%, shifting almost half the battery mix away from the LFP, NMC, and NCA battery technologies (Table 18).

Table 18: LDV – Progressive Scenario (PRO), values passenger EV's, by battery chemistry, 2020-2050, in % (informed by GPI 2025[87], ICCT 2024[88], Xu et al. 2020[89])

	[unit]	2020	2025	2030	2035	2040	2045	2050
LFP	[%]	32%	58%	60%	57%	45%	42%	40%
LMFP	[%]	0%	0%	8%	12%	14%	18%	20%
NCA	[%]	22%	12%	10%	7%	6%	4%	4%
All NMC battery types	[%]	46%	30%	17%	15%	19%	16%	15%
- NMC 111	[%]	4%	1%	0%	0%	0%	0%	0%
- NMC 532	[%]	13%	4%	0%	0%	0%	0%	0%
- NMC 622	[%]	20%	12%	6%	6%	5%	4%	4%
- NMC 721	[%]	1%	0%	0%	0%	0%	0%	0%
- NMC 811	[%]	5%	10%	11%	8%	8%	8%	7%
- NMC 955+96Ni	[%]	2%	3%	0%	1%	6%	4%	4%
Redox flow	[%]	0%	0%	0%	0%	0%	0%	0%
Na-ion	[%]	0%	0%	2.5%	4.5%	8.0%	10.0%	10.5%
Li-S	[%]	0%	0%	2.5%	4.5%	8.0%	10.0%	10.5%
Other	[%]	0%	0%	0%	0%	0%	0%	0%
Sum	**[%]**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

87 GPI (2025). Batteries in Transition. Innovation, Uncertainty and the Minerals behind Them. 11 November 2025. https://www.greenpeace.org/international/batteries-in-transition-report/

88 ICCT (2024). Electrifying road transport with less mining: A global and regional battery material outlook (ID-206). International Council on Clean Transportation. Retrieved from https://theicct.org/wp-content/uploads/2024/12/ID-206-%E2%80%93-Battery-outlook_report_final.pdf

89 Xu, C., Dai, Q., Gaines, L. et al. Future material demand for automotive lithium-based batteries. Communications Materials 2020;1:99. https://doi.org/10.1038/s43246-020-00095-x

Commercial EVs (HDVs)

The PRO Scenario assumes the increasing dominance of LFP and LMFP batteries until 2050, marking a shift away from NMC battery types and NCA batteries. Like previous developments, we assume a steep increase in LFPs from 54% in 2020 to almost 90% in 2025, until the uptake of LMFP battery types allows a gradual reduction in the LFP battery chemistry share, reducing it to 64% by 2050 (Table 19). The key progressive measures for the commercial EV mobility sector that influence this scenario will include a shift of freight from road to rail (+2.5% per year to rail between 2025 and 2050) and reduced transport by road (-1.5% per year between 2020 and 2050).

Table 19: HDV – PRO Scenario, commercial EV, in % (informed by GPI 2025[90], ICCT 2024[91], Xu et al. 2020[92])

	[unit]	2020	2025	2030	2035	2040	2045	2050
LFP	[%]	54%	55%	80%	70%	70%	67%	64%
LMFP	[%]	0%	0%	4%	9%	17%	24%	32%
NCA (NMCA, NCA85,90,92)	[%]	0%	0%	3%	8%	7%	5%	2%
All NMC battery types		46%	44%	11%	7%	1%	1%	0%
- NMC 111	[%]	0%	0%	0%	0%	0%	0%	0%
- NMC 532	[%]	17%	16%	2%	1%	0%	0%	0%
- NMC 622	[%]	23%	22%	2%	1%	0%	0%	0%
- NMC 721	[%]	0%	0%	1%	1%	0%	0%	0%
- NMC 811	[%]	6%	6%	5%	3%	0%	0%	0%
- NMC 955+96Ni	[%]	0%	0%	1%	1%	1%	1%	0%
Redox flow	[%]	0%	0%	0%	0%	0%	0%	0%
Na-ion	[%]	0%	0%	0%	0%	0%	0%	0%
Li-S	[%]	0%	0%	0%	0%	0%	0%	0%
Other*	[%]	0%	0%	2%	6%	5%	3%	1%
Sum	**[%]**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Two-and three-Wheeler vehicles (2W3Ws)

The battery chemistry development for two- and three-wheelers is already highly innovative in 2025, with sodium-ion batteries currently applied. However, NMC and LFP batteries remain major players, with each technology making up about one third of the market share in 2025. As LMFP and sodium-ion batteries are further commercialised after 2030, the share of NMC batteries will decline, and we assume a complete phase-out of NMC batteries by 2050. In 2050, the battery market for two- and three-wheelers will be shared almost equally by LFP, LMFP, and sodium-ion batteries (Table 20).

90 GPI (2025). Batteries in Transition. Innovation, Uncertainty and the Minerals behind Them. 11 November 2025. https://www.greenpeace.org/international/batteries-in-transition-report/

91 ICCT (2024). Electrifying road transport with less mining: A global and regional battery material outlook (ID-206). International Council on Clean Transportation. Retrieved from https://theicct.org/wp-content/uploads/2024/12/ID-206-%E2%80%93-Battery-outlook_report_final.pdf

92 Xu, C., Dai, Q., Gaines, L. et al. Future material demand for automotive lithium-based batteries. Communications Materials 2020;1:99. https://doi.org/10.1038/s43246-020-00095-x

Table 20: PRO Scenario, 2W3W EV, in % (informed by GPI 2025[93], ICCT 2024[94], Xu et al. 2020[95])

	[unit]	2020	2025	2030	2035	2040	2045	2050
LFP	[%]	20%	32%	43%	41%	38%	36%	34%
LMFP	[%]	0%	7%	13%	23%	34%	32%	30%
NCA (NMCA, NCA85,90,92)	[%]	19%	17%	15%	9%	3%	0%	0%
All NMC battery types		48%	32%	15%	8%	1%	1%	0%
- NMC 111	[%]	48%	24%	0%	0%	0%	0%	0%
- NMC 532	[%]	0%	0%	0%	0%	0%	0%	0%
- NMC 622	[%]	0%	0%	0%	0%	0%	0%	0%
- NMC 721	[%]	0%	0%	0%	0%	0%	0%	0%
- NMC 811	[%]	0%	8%	15%	8%	1%	1%	0%
- NMC 955+96Ni	[%]	0%	0%	0%	0%	0%	0%	0%
Redox flow	[%]	0%	0%	0%	0%	0%	0%	0%
Na-ion	[%]	0%	6%	12%	17%	23%	30%	36%
Li-S	[%]	0%	0%	0%	0%	0%	0%	0%
Other *	[%]	13%	8%	2%	2%	1%	1%	0%
Sum	**[%]**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

5.4.3 Progressive Scenario – Accelerated Na-ion (PRO-Na-ion) battery chemistry assumptions

The PRO Scenario with the accelerated Na-ion pathway is based on PRO, and builds on a scenario published in BNEF (2023)[96], which assumes a more aggressive uptake of Na-ion batteries between 2030 and 2050, to reduce the reliance on Li-ion batteries (LFP, NMC).

Passenger EVs (LDVs)

In the scenario for passenger EVs, the battery mix will change substantially from 2030, as Na-ion batteries are introduced (15%) as a commercial battery type for passenger EVs. The share of Na-ion batteries will increase rapidly, reaching 40% in 2035 and 50% by 2050. Because half the market share will be supplied by Na-ion batteries, the demand for LFPs, NMCs, and LMFPs will be reduced by a large margin (Table 21).

93 GPI (2025). Batteries in Transition. Innovation, Uncertainty and the Minerals behind Them. 11 November 2025. https://www.greenpeace.org/international/batteries-in-transition-report/

94 ICCT (2024). Electrifying road transport with less mining: A global and regional battery material outlook (ID-206). International Council on Clean Transportation. Retrieved from https://theicct.org/wp-content/uploads/2024/12/ID-206-%E2%80%93-Battery-outlook_report_final.pdf

95 Xu, C., Dai, Q., Gaines, L. et al. Future material demand for automotive lithium-based batteries. Communications Materials 2020;1:99. https://doi.org/10.1038/s43246-020-00095-x

96 BNEF (2023) 1H 2023 Energy Storage Market Outlook, Blomberg NEF, March 21, 2023, https://about.bnef.com/insights/commodities/1h-2023-energy-storage-market-outlook/

Table 21: LDV – *Progressive* Accelerated Na-ion Scenario, values passenger EV's, by battery chemistry, 2020–2050 (informed by GPI 2025, ICCT 2024, Xu et al. 2020) [97,98,99]

	[unit]	2020	2025	2030	2035	2040	2045	2050
LFP	[%]	32.0%	58.0%	52%	34.8%	27.9%	23.6%	20.0%
LMFP	[%]	0.0%	0.0%	7%	7.3%	8.7%	10.1%	10.0%
NCA	[%]	22.0%	12.0%	9%	4.3%	3.7%	2.3%	2.0%
All NMC battery types	[%]	45.5%	30.0%	15%	9.1%	11.8%	9.0%	7.5%
- NMC 111	[%]	4.2%	1.0%	0%	0.0%	0.0%	0.0%	0.0%
- NMC 532	[%]	13.3%	4.0%	0%	0.0%	0.0%	0.0%	0.0%
- NMC 622	[%]	20.0%	12.0%	5%	3.7%	3.1%	2.3%	2.0%
- NMC 721	[%]	1.0%	0.0%	0%	0.0%	0.0%	0.0%	0.0%
- NMC 811	[%]	5.0%	10.0%	10%	4.9%	5.0%	4.5%	3.5%
- NMC 955+96Ni	[%]	2.0%	3.0%	0%	0.6%	3.7%	2.3%	2.0%
Redox flow	[%]	0.0%	0.0%	0%	0.0%	0.0%	0.0%	0.0%
Na-ion	[%]	0.0%	0.0%	15.0%	40.0%	40.0%	45.0%	50.0%
Li-S	[%]	0.0%	0.0%	2.5%	4.5%	8.0%	10.0%	10.5%
Other	[%]	0.0%	0.0%	0%	0.0%	0.0%	0.0%	0.0%
Sum	**[%]**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Commercial EVs (HDVs)

Compared with passenger EVs, heavy-duty EVs show a stronger reliance on high-density and long-range batteries. As a result, the uptake of Na-ion batteries will be less pronounced in this category. We assume a phase-out of NMC batteries (< 10% from 2035 onwards to nearly zero in 2050), an overall reduction in LFP batteries (two thirds decline from 2025 to 2050), and an increase in LMFP batteries from 2035 onwards, resulting in equal shares of battery types provided by LFP (32.5%), LMFP (31.5%), and Na-ion batteries (32%) by 2050 (Table 22).

97 GPI (2025). Batteries in Transition. Innovation, Uncertainty and the Minerals behind Them. 11 November 2025. https://www.greenpeace.org/international/batteries-in-transition-report/

98 ICCT (2024). Electrifying road transport with less mining: A global and regional battery material outlook (ID-206). International Council on Clean Transportation. Retrieved from https://theicct.org/wp-content/uploads/2024/12/ID-206-%E2%80%93-Battery-outlook_report_final.pdf

99 Xu, C., Dai, Q., Gaines, L. et al. (2020) Future material demand for automotive lithium-based batteries. Communications Materials 2020;1:99. https://doi.org/10.1038/s43246-020-00095-x

Table 22: HDV – Progressive Accelerated Na-ion Scenario, commercial EV's, by battery chemistry, 2020–2050 (informed by [97, 98, 99])

	[unit]	2020	2025	2030	2035	2040	2045	2050
LFP	[%]	54.0%	55%	80.0%	66.0%	62.0%	51.3%	32.5%
LMFP	[%]	0.0%	0%	4.0%	9.0%	17.0%	24.3%	31.5%
NCA (NMCA, NCA85,90,92)	[%]	0.0%	0%	3.0%	8.0%	7.0%	4.7%	2.5%
All NMC battery types	[%]	46.0%	44%	11.0%	7.0%	1.0%	0.7%	0.5%
- NMC 111	[%]	0.0%	0%	0.0%	0.0%	0.0%	0.0%	0.0%
- NMC 532	[%]	17.0%	16%	2.0%	1.0%	0.0%	0.0%	0.0%
- NMC 622	[%]	23.0%	22%	2.0%	1.0%	0.0%	0.0%	0.0%
- NMC 721	[%]	0.0%	0%	1.0%	1.0%	0.0%	0.0%	0.0%
- NMC 811	[%]	6.0%	6%	5.0%	3.0%	0.0%	0.0%	0.0%
- NMC 955+96Ni	[%]	0.0%	0%	1.0%	1.0%	1.0%	0.7%	0.5%
Redox flow	[%]	0.0%	0%	0.0%	0.0%	0.0%	0.0%	0.0%
Na-ion	[%]	0.0%	0%	0.0%	4.0%	8.0%	16.0%	32.0%
Li-S	[%]	0.0%	0%	0.0%	0.0%	0.0%	0.0%	0.0%
Other	[%]	0.0%	0%	2.0%	6.0%	5.0%	3.0%	1.0%
Sum	**[%]**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Two-and three-wheelers (2W3Ws)

As highlighted in the assumptions section (Section 5) the mobility mode of two- and three-wheeler vehicles will adopt Na-ion batteries earlier than other modes because these batteries are best suited to lighter-weight and shorter-range vehicles. Under the PRO Accelerated Na-ion Scenario, the share of Na-ion batteries will increase steadily from 2025 onwards, reaching a large share of 85% by 2050, and leaving only small shares of LFPs (8%) and LMFPs (7%) to cover the remaining battery market share (Table 23).

Table 23: 2W3W EV, Progressive Accelerated Na-ion Scenario, in % (informed by GPI 2025, ICCT 2024, Xu et al. 2020)[100,101,102]

	[unit]	2020	2025	2030	2035	2040	2045	2050
LFP	[%]	20.0%	32%	36.5%	29.4%	19.5%	9.7%	8.0%
LMFP	[%]	0.0%	7%	11.0%	16.5%	17.4%	8.6%	7.0%
NCA (NMCA, NCA85,90,92)	[%]	19.0%	17%	12.7%	6.4%	1.5%	0.0%	0.0%
All NMC	[%]	48.0%	32%	12.7%	5.7%	0.5%	0.1%	0.0%
- NMC 111	[%]	48.0%	24%	0.0%	0.0%	0.0%	0.0%	0.0%
- NMC 532	[%]	0.0%	0%	0.0%	0.0%	0.0%	0.0%	0.0%
- NMC 622	[%]	0.0%	0%	0.0%	0.0%	0.0%	0.0%	0.0%
- NMC 721	[%]	0.0%	0%	0.0%	0.0%	0.0%	0.0%	0.0%
- NMC 811	[%]	0.0%	8%	12.7%	5.7%	0.5%	0.1%	0.0%
- NMC 955+96Ni	[%]	0.0%	0%	0.0%	0.0%	0.0%	0.0%	0.0%
Redox flow	[%]	0.0%	0%	0.0%	0.0%	0.0%	0.0%	0.0%
Na-ion	[%]	0.0%	6%	25.0%	40.0%	60.0%	80.0%	85.0%
Li-S	[%]	0.0%	0%	0.0%	0.0%	0.0%	0.0%	0.0%
Other *	[%]	13.0%	8%	2.0%	2.0%	1.0%	1.0%	0.0%
Sum	**[%]**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

100 GPI (2025). Batteries in Transition. Innovation, Uncertainty and the Minerals behind Them. 11 November 2025. https://www.greenpeace.org/international/batteries-in-transition-report/

101 ICCT (2024). Electrifying road transport with less mining: A global and regional battery material outlook (ID-206). International Council on Clean Transportation. Retrieved from https://theicct.org/wp-content/uploads/2024/12/ID-206-%E2%80%93-Battery-outlook_report_final.pdf

102 Xu, C., Dai, Q., Gaines, L. et al. Future material demand for automotive lithium-based batteries. Communications Materials 2020;1:99. https://doi.org/10.1038/s43246-020-00095-x

5.5 Battery Chemistry Scenario for Battery Energy Storage Systems (BESS)

The scenarios presented in this section cover battery chemistries for global BESSs, including grid or utility-scale battery storage systems and home battery storage systems. Three scenarios for future battery chemistries have been developed to demonstrate how future batteries for BESSs could evolve: the OECM-Net Zero Scenario (BESS OECM-NZS) – a moderately Progressive scenario; the highly PRO scenario (BESS Progressive), which includes Progressive measures; and the Accelerated Na-ion Scenario highlighting the increased application of Na-ion technology for stationary battery storage. Compared with the EV battery scenarios, the key battery chemistries for BESSs included fewer battery types (LFP, NMC, and NCA) in 2020. From 2030 onwards, some of these chemistries will gradually be replaced with innovative technologies, including the Na-ion technology, whereas LFP will remain dominant in the OECM-NZS and Progressive Scenarios. This analysis does not include any further differentiation of the various NMC battery types.

Table 24: Overview of literature sources on the current and future BESS technology shares [%]

Battery type	Data source	[unit]	2020	2025	2030	2040	2050
LFP	Aquila,2024 [103]	[%]	33%	93%	87%	--	--
LFP	BNEF, 2025[104]	[%]	30%	91%	88%	--	--
NMC	Aquila,2024[103]	[%]	49%	6%	0%	--	--
NMC	BNEF, 2025[104]	[%]	50%	6%	2%	--	--
NCA	Aquila,2024[103]	[%]	18%	0%	0%	--	--
NCA	BNEF, 2025[104]	[%]	19%	0%	0%	--	--
Sodium-ion	Aquila,2024[103]	[%]	0%	1%	12%	--	--
Sodium-ion	BNEF, 2025[104]	[%]	0%	1%	5%	--	--
Sodium-ion	ICCT, 2024 [105]	[%]	0%	0%	15%	--	--
Other	BNEF, 2025[104]	[%]	1%	2%	5%	--	--

5.5.1 OECM Assumptions for Battery Energy Storage Systems (BESS)

The future BESS battery mix for the OECM scenario has been developed on the following assumptions:

● Lithium-ion battery chemistries (LFP) will dominate battery storage in the foreseeable future (Aquila, 2024, p.3; BNEF, 2025). LFPs batteries will continue to decrease at a rate of 1% from 2031 per year until 2035, as projected by BNEF (2025). From 2036 onwards, the annual decline rate will double to 2% as more LFPs are required for EV batteries. By 2050, LFP batteries will contribute 61% of stationary battery storage.

● From 2035 onwards, NMC batteries will be phased out for BESS.

● Sodium-ion batteries will start to play a more significant role and are assumed to be cost-competitive with LFP batteries by 2040, because lithium prices are likely to increase by a factor of 3 (IEA, 2025) due to the increased demand for mobile batteries. Moreover, Na-ion batteries will play a greater role in cold climates (Bai et al., 2025) [106]. As demonstrated in the previous section on EV mobility, Na-ion batteries are used in more Progressive scenarios, but minimal in the OECM. Because stationary batteries can be larger and have a lower battery density than batteries for EVs, larger volume and weight batteries are suitable. Based on this, it is assumed that the Na-ion share will reach 25% for BESS applications in 2050.

103 Aquila Clean Energy. (2024). Battery Energy Storage Systems (BESS) — Enhancing System Stability and Efficiency. Aquila Group. Available at: https://www.aquila-clean-energy.com/wp-content/uploads/2024-06-24_Aquila-Clean-Energy_Whitepaper_BESS_EN.pdf (accessed 12 November 2025)

104 BNEF (2025) Global Energy Storage Growth Upheld by New Markets, Figure on 'Lithium ion batteries dominate energy storage market'. (BloombergNEF, June 18, 2025). Available at: https://about.bnef.com/insights/clean-energy/global-energy-storage-growth-upheld-by-new-markets/ (Accessed 12 November 2025)

105 ICCT (2024). Electrifying road transport with less mining: A global and regional battery material outlook (ID-206). International Council on Clean Transportation. Retrieved from https://theicct.org/wp-content/uploads/2024/12/ID-206-%E2%80%93-Battery-outlook_report_final.pdf

106 Bai, H., Zhu, X., Ao, H., He, G., Xiao, H., Chen, Y. Advances in sodium-ion batteries at low-temperature: Challenges and strategies. Journal of Energy Chemistry 2024;90:518 – 539. https://doi.org/10.1016/j.jechem.2023.11.004

● Redox flow batteries complement LFP and sodium-ion batteries for battery storage systems, showing similar trends and increasing shares as Na-ion batteries.

Table 25: Overview of BESS assumptions for the OECM scenario, 2020-2050 (informed by GPI 2025[107],Aquila 2024[108])

Battery type	Unit	2020	2025	2030	2035	2040	2045	2050
LFP	[%]	31%	91%	88%	81%	71%	66%	61%
NMC	[%]	50%	6%	1%	1%	0%	0%	0%
NCA	[%]	19%	0%	0%	0%	0%	0%	0%
Sodium-ion	[%]	0%	1%	6%	10%	15%	20%	25%
Redox flow	[%]	0%	2%	5%	8%	14%	14%	14%
Sum	**[%]**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

By 2050, NMCs and NCAs, which made up almost 70% of the battery storage mix in 2020, will be phased out, over half of the battery capacity will be covered by LFPs, one quarter will be provided by Na-ion and another 14% by redox flow batteries.

5.5.2 Progressive Scenario Assumptions for Battery Energy Storage Systems (BESS)

The BESS assumptions for the Progressive Scenario are:

● LFP batteries will dominate the BESS battery storage market until 2040, a shorter time frame than predicted by Aquila (2024, p.3). In the Progressive Scenario, LFPs will continue to decrease at a rate of 1% per year from 2031 until 2035, as projected by GPI (2025). From 2035 to 2040, the annual decline rate will accelerate to 2% and double again to 4% from 2045 to 2050. By 2050, LFPs will contribute 51% of stationary battery storage.

● From 2025 onwards, NMCs will be phased out for BESS. The phase out is initiated 5 years earlier in the Progressive Scenario than in the OECM Scenario.

● The share of Na-ion batteries will gradually grow at 1% annually from 2035, increasing the annual rate from 14% in 2040 to 34% in 2050. This development (2040–2050) assumes an improvement in energy density.

● Redox flow batteries will show a similar trend to Na-ion batteries, increasing gradually from 2025 (2%) onwards and reaching 15% by 2045.

Table 26: Overview of BESS assumptions for the Progressive Scenario, 2020-2050 (informed by Aquila, 2024[109], BNEF, 2025[110], ICCT, 2024[111])

Battery type	Unit	2020	2025	2030	2035	2040	2045	2050
LFP	[%]	31%	91%	88%	83%	73%	61%	51%
NMC	[%]	50%	6%	0%	0%	0%	0%	0%
NCA	[%]	19%	0%	0%	0%	0%	0%	0%
Sodium-ion	[%]	0%	1%	6%	9%	14%	24%	34%
Redox flow	[%]	0%	2%	6%	8%	13%	15%	15%
Sum	**[%]**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

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107 GPI (2025). Batteries in Transition. Innovation, Uncertainty and the Minerals behind Them. 11 November 2025. https://www.greenpeace.org/international/batteries-in-transition-report/

108 Aquila Clean Energy. (2024). Battery Energy Storage Systems (BESS) — Enhancing System Stability and Efficiency. Aquila Group. Available at: https://www.aquila-clean-energy.com/wp-content/uploads/2024-06-24_Aquila-Clean-Energy_Whitepaper_BESS_EN.pdf (accessed 12 November 2025)

109 Aquila Clean Energy. (2024). Battery Energy Storage Systems (BESS) — Enhancing System Stability and Efficiency. Aquila Group. Available at: https://www.aquila-clean-energy.com/wp-content/uploads/2024-06-24_Aquila-Clean-Energy_Whitepaper_BESS_EN.pdf (accessed 12 November 2025)

110 BNEF (2025) Global Energy Storage Growth Upheld by New Markets, Figure on 'Lithium ion batteries dominate energy storage market'. (BloombergNEF, June 18, 2025). Available at: https://about.bnef.com/insights/clean-energy/global-energy-storage-growth-upheld-by-new-markets/ (Accessed 12 November 2025)

111 ICCT (2024). Electrifying road transport with less mining: A global and regional battery material outlook (ID-206). International Council on Clean Transportation. Retrieved from https://theicct.org/wp-content/uploads/2024/12/ID-206-%E2%80%93-Battery-outlook_report_final.pdf

By 2030, NMCs and NCAs, which made almost 70% of the battery storage mix by 2020, will be phased out. The share of LFPs in the battery mix will increase, reaching around 90% in 2025–2030 and will decrease after 2030, reaching 51% in 2050. From 2035 onwards, Na-ion and redox flow batteries will increase at a greater rate and contribute 34% and 15%, respectively, by 2050.

The greatest difference between the OECM and the Progressive Scenarios for battery storage systems is the shift from LFP towards Na-ion and redox flow batteries in the latter, which we expect will be largely driven by the motivation to reduce material supply pressures on high-demand minerals, such as lithium and cobalt, and the ability of the battery storage sector to use batteries with lower energy densities. Energy storage use allows more physical space for battery storage systems, relative to the physical restrictions associated with all types of EVs.

5.5.3 Progressive Accelerated Na-ion Scenario Assumptions for Battery Energy Storage Systems (BESS)

In the Accelerated Na-ion Scenario for BESS, the Na-ion technology will be introduced to the market from 2025 onwards. The uptake of sodium-ion will accelerate due to the less strict technological requirements for BESS, because energy density will be a less limiting factor relative to its role in the transport and mobility sectors. There are other benefits of Na-ion batteries over Li-ion batteries, including their lower mineral demand and lower costs, which support the argument that BESS could adopt higher Na-ion shares than LDVs in an aggressive scenario. Therefore, the uptake of Na-ion batteries is shifting shares away from LFP batteries in this scenario. Another development that favours Na-ion batteries over Li-ion batteries is the improvement in energy density, which is nearing that of LFPs.

In 2020, the BESS battery mix was dominated by NMC-type batteries (50%), LFPs (31%), and NCAs (19%). Until 2030, the share of LFP batteries increased rapidly and reached > 91% by 2025, shifting shares away from NMC battery types. The main driver is their cost competitiveness and lack of spatial restrictions in achieving higher energy density. As soon as the shares of Na-ion and redox flow batteries increase from 2030 onwards, the LFPs share in BESS will decrease, and NMCs and NCAs will be phased out. By 2050, LFPs will retain a small share of 10% and the market will be dominated by Na-ion batteries (75%), complemented by redox flow batteries (15%), (see Table 27).

Table 27: Overview of BESS assumption for the Progressive Accelerated Sodium-ion uptake pathway, 2020-2050 (informed by Aquila, 2024[112], BNEF, 2025[113] ,ICCT, 2024[114])

Battery type	Unit	2020	2025	2030	2035	2040	2045	2050
LFP	[%]	31%	91%	84%	67%	47%	25%	10%
NMC	[%]	50%	6%	0%	0%	0%	0%	0%
NCA	[%]	19%	0%	0%	0%	0%	0%	0%
Sodium-ion	[%]	0%	1%	10%	25%	40%	60%	75%
Redox flow	[%]	0%	2%	6%	8%	13%	15%	15%
Sum	**[%]**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

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112 Aquila Clean Energy. (2024). Battery Energy Storage Systems (BESS) — Enhancing System Stability and Efficiency. Aquila Group. Available at: https://www.aquila-clean-energy.com/wp-content/uploads/2024-06-24_Aquila-Clean-Energy_Whitepaper_BESS_EN.pdf (accessed 12 November 2025)

113 BNEF (2025) Global Energy Storage Growth Upheld by New Markets, Figure on 'Lithium ion batteries dominate energy storage market'. (BloombergNEF, June 18, 2025). Available at: https://about.bnef.com/insights/clean-energy/global-energy-storage-growth-upheld-by-new-markets/ (Accessed 12 November 2025)

114 ICCT (2024). Electrifying road transport with less mining: A global and regional battery material outlook (ID-206). International Council on Clean Transportation. Retrieved from https://theicct.org/wp-content/uploads/2024/12/ID-206-%E2%80%93-Battery-outlook_report_final.pdf

6 Methodology – Mapping
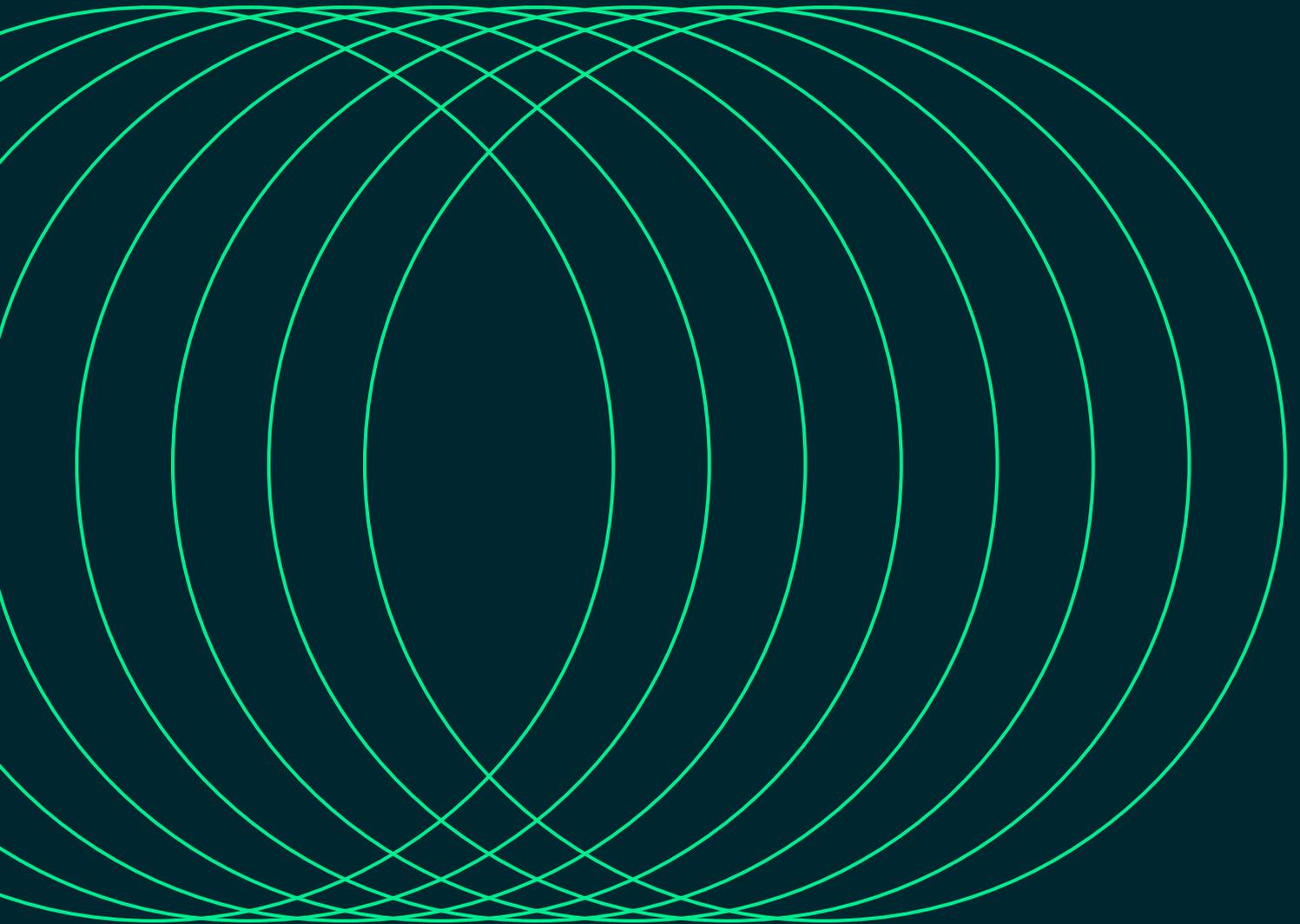
6.1 Mapping Objectives

This study aims to inform global debates on the sourcing of minerals for energy transitions, while at the same time, safeguarding biodiversity, natural ecosystems, climate stability, and the rights of Indigenous Peoples and Local Communities (IP&LC). To this end, mapping is required to evaluate how the transition to renewable energy and the mineral demands of the related scenario intersect with areas of critical environmental value and IP&LC rights.

The approach brings together two components:

1. The delineation of a global map of Restricted Areas (RAs), including areas that should remain off-limits to mineral extraction ("RA1") due to their critical ecological, environmental, or cultural importance for a habitable Earth; and

2. The identification of Reserve Proxy Areas (RPAs) at the country level, representing an approximation of the potential spatial footprint of key transition minerals, in this case nickel, lithium, and cobalt.

The combined analysis provides a global perspective on where development pressures for transition minerals could emerge, and the extent to which these pressures overlap with protected or otherwise sensitive landscapes. Numeric estimates were compared against the demands estimated with scenario analyses to identify potential reserve constraints.

6.2 Contributions

The Restricted Areas mapping approach and methodology was developed by Greenpeace with input from experts from other non-governmental organisations (NGOs) working on minerals, and the ISF team. The map itself was produced by the Global Mapping Hub of Greenpeace International, and included the gathering and processing of data sources, compilation, interpretation, and webtool functionality.

Mapping the RPAs was a collaboration between ISF and Greenpeace. ISF led the initial research and gathered the data on mineral occurrences and reserve information, ultimately collecting an extensive list of regional and global data sources in the countries of interest, and combining these into mineral-focused point data. Greenpeace International gathered additional data, including mineral permit data and other global point data, and developed the RPA mapping methodology. Greenpeace then conducted the analysis to spatially identify RPAs and calculate the proportion of RPAs that intersect with RAs that should be off-limits to mining. Greenpeace's team leveraged input from experts in the ISF team to improve the method and results at key points in the study.

6.3 Restricted Areas Mapping

The global RA mapping system identifies key 'sensitive' areas that should be off-limits to mineral-extraction-related activities ("RA1"). These include areas considered off-limits by default, such as protected areas, intact forest landscapes, oceans, the territories of uncontacted Indigenous peoples, and areas with very high natural values, such as key biodiversity areas, significant natural ecosystems, critical water bodies, and areas of high carbon stock. Spatial datasets were compiled from credible, publicly accessible sources and screened for data quality, reliability and resolution.

6.3.1 Criteria for mapping Restricted Areas

The criteria for defining RAs are drawn from Greenpeace's Minerals for Energy Transition: Guiding Principles (2025), and identify zones of sensitive ecological, cultural or social value. These include:

- Areas protected under international conventions (IUCN, UNESCO, Ramsar, etc.);
- Areas of high conservation value, such as intact forest landscapes and key biodiversity areas;
- Areas of high carbon stocks – forests, peatlands, and wetlands critical for carbon sequestration;
- Significant natural ecosystems, including marine, deep-sea, and coastal habitats;
- Critical water bodies, such as rivers, lakes, and glaciers with protective buffer zones; and
- Territories of Indigenous Peoples and Local Communities, including those of uncontacted or voluntarily isolated tribes.

6.3.2 Mapping Data for Restricted Areas

Protected areas
Spatial data representing protected areas (PAs), including World Heritage Sites and Ramsar Sites, were obtained from the World Database on Protected Areas and Other Effective Area-Based Conservation Measures (WDPA/WDOECM) via the Google Earth Engine platform. This dataset provides the most comprehensive global coverage of both terrestrial and marine PAs, encompassing all six management categories of the International Union for Conservation of Nature, as well as areas without assigned classifications, such as Terras Indígenas in Brazil. Although certain types of protected or conserved areas are under-represented (e.g., Indigenous PAs and community-conserved areas), the WDPA/WDOECM was used to ensure global consistency and comparability across all designation types.

High conservation values and high carbon stocks
To complement the PAs, data on areas of high conservation value (HCV) and high carbon stocks (HCS) were incorporated to capture regions of exceptional biodiversity and carbon importance. HCV datasets include key biodiversity areas (over 16,000 sites, which safeguard key populations of more than 13,000 species), and intact forest landscapes, representing large unfragmented forest mosaics. The HCS datasets include aboveground and below ground biomass carbon density, peatland carbon stocks, and marine carbon stock, which collectively characterise key terrestrial and marine carbon reservoirs.

Significant natural ecosystems and critical water bodies
The variables defining significant natural ecosystems include peatlands, mangroves, wetlands, grasslands, reefs, deep-sea areas, small islands, steep slopes, and oceans, capturing globally important ecosystems and natural features. Critical waterbodies (CWB) encompass water dynamics and change, the distributions of global lakes and wetlands, water risk, and the extent of glaciers, providing information on freshwater systems and water-related vulnerabilities.

Territories of Indigenous Peoples and Local Communities

'Indigenous Peoples and Local Communities' (IP&LC) territories include traditional and customary lands, waters, and natural resources where Free, Prior, and Informed Consent (FPIC) applies. Due to incomplete global data, these areas were generally not included in this study's analyses, except for existing datasets on protected IP&LC territories and the lands of uncontacted or voluntarily isolated Indigenous Peoples (included in RA1). For countries where the boundaries of IP&LC lands are not known or fully mapped, based on taking a precautionary approach, all lands are assumed and considered as a 'Restricted Area requiring FPIC' (RA-FPIC)' or as 'Areas requiring free prior informed consent (FPIC) of Indigenous Peoples and Local Communities'. Where reliable data exists and after consultation with Indigenous organisations, such areas were specifically mapped as RA-FPIC (e.g., Sámi lands in Sweden)."

Table 28: Variables for mapping global Restricted Areas. A full reference list can be found in Supplementary, Development of Restricted Areas Map for Transition Minerals Mining at a Global Scale

Variables	Source	RA Element
Protected Areas	UNEP-WCMC and IUCN, 2025[115]	1.Protected areas
World Heritage Sites	UNEP-WCMC and IUCN, 2025[116]	1.Protected areas
Ramsar Sites	UNEP-WCMC and IUCN, 2025[116]	1.Protected areas
Key Biodiversity Areas	BirdLife International, 2025[116]	2.High conservation value areas
Important Bird and Biodiversity Areas	Waliczky et al., 2019[117]	2.High conservation value areas
Relative Species Richness	UNEP-WCMC, 2025[118]	2.High conservation value areas
Plants Species Richness	Sabatini et al., 2022[119]	2.High conservation value areas
Intact Forest Landscapes	Potapov et al., 2008[120]	2.High conservation value areas
Forest Integrity Index	Grantham et al., 2020[121]	2.High conservation value areas
Aboveground Live Woody Biomass	Xu et al., 2021[122]	3.High carbon stock areas
Aboveground and Belowground Biomass Carbon Density	Spawn et al., 2020[123]	3.High carbon stock areas

115 UNEP-WCMC and IUCN, 2025. Protected Planet: [The World Database on Protected Areas (WDPA)/The World Database on Other Effective Area-based Conservation Measures (WD-OECM)/The Global Database on Protected Areas Management Effectiveness (GD-PAME)] [On-line], 05/2025, Cambridge, UK: UNEP-WCMC and IUCN. Available at https://developers.google.com/earth-engine/datasets/catalog/WCMC_WDPA_current_polygons

116 BirdLife International, 2025. The World Database of Key Biodiversity Areas. Developed by the KBA Partnership: BirdLife International, International Union for the Conservation of Nature, Amphibian Survival Alliance, Conservation International, Critical Ecosystem Partnership Fund, Global Environment Facility, Re:wild, NatureServe, Rainforest Trust, Royal Society for the Protection of Birds, Wildlife Conservation Society and World Wildlife Fund. Available at https://www.keybiodiversityareas.org/sites/search

117 Waliczky, Z., Fishpool, L.D.C., Butchart, S.H.M., Thomas, D., Heath, M.F., Hazin, C., Donald, P.F., Kowalska, A., Dias, M.P., Allinson, T.S.M., 2019. Important Bird and Biodiversity Areas (IBAs): their impact on conservation policy, advocacy and action. Bird Conservation International 29, 199 – 215.

118 UNEP-WCMC, 2025. Species richness. Derived from Areas of Habitat maps created from data from the IUCN Red List, BirdLife International, the Global Assessment of Reptile Distributions (GARD), the Botanical Information and Ecology Network (BIEN) database and additional vascular plant species ranges were created from point data from the IUCN Red List, Botanic Gardens Conservation International (BGCI), the Global Biodiversity Information Facility (GBIF) and iNaturalist. Cambridge, UK. Available at https://data-gis.unep-wcmc.org/server/rest/services/NatureMap/Species_richness/MapServer

119 Sabatini, F.M., Jiménez-Alfaro, B., Jandt, U., Chytrý, M., Bruelheide, H., the sPlot Consortium, 2022. Global patterns of vascular plant alpha-diversity. https://doi.org/10.1038/s41467-022-32063-z. Available at https://idata.idiv.de/ddm/Data/ShowData/3506?version=70

120 Potapov, P., Yaroshenko, A., Turubanova, S., Dubinin, M., Laestadius, L., Thies, C., Aksenov, D., Egorov, A., Yesipova, Y., Glushkov, I., Karpachevskiy, M., Kostikova, A., Manisha, A., Tsybikova, E., Zhuravleva, I., 2008. Mapping the World's Intact Forest Landscapes by Remote Sensing. Ecology and Society 13. https://www.ecologyandsociety.org/vol13/iss2/art51. Available at https://intactforests.org/data.ifl.html

121 Grantham, H.S., Duncan, A., Evans, T.D., Jones, K.R., Beyer, H.L., Schuster, R., Walston, J., Ray, J.C., Robinson, J.G., Callow, M., Clements, T., Costa, H.M., DeGemmis, A., Elsen, P.R., Ervin, J., Franco, P., Goldman, E., Goetz, S., Hansen, A., Hofsvang, E., Jantz, P., Jupiter, S., Kang, A., Langhammer, P., Laurance, W.F., Lieberman, S., Linkie, M., Malhi, Y., Maxwell, S., Mendez, M., Mittermeier, R., Murray, N.J., Possingham, H., Radachowsky, J., Saatchi, S., Samper, C., Silverman, J., Shapiro, A., Strassburg, B., Stevens, T., Stokes, E., Taylor, R., Tear, T., Tizard, R., Venter, O., Visconti, P., Wang, S., Watson, J.E.M., 2020. Anthropogenic modification of forests means only 40% of remaining forests have high ecosystem integrity. Nat Commun 11, 5978. https://doi.org/10.1038/s41467-020-19493-3. Available at https://www.forestintegrity.com

122 Xu, L., Saatchi, S.S., Yang, Y., Yu, Y., Pongratz, J., Bloom, A.A., Bowman, K., Worden, J., Liu, J., Yin, Y., Domke, G., McRoberts, R.E., Woodall, C., Nabuurs, G.-J., de-Miguel, S., Keller, M., Harris, N., Maxwell, S., Schimel, D., 2021. Changes in global terrestrial live biomass over the 21st century. Sci. Adv. 7, eabe9829. https://doi.org/10.1126/sciadv.abe9829. Available at https://data.globalforestwatch.org/datasets/gfw::aboveground-live-woody-biomass-density/about

123 Spawn, S.A., Sullivan, C.C., Lark, T.J., Gibbs, H.K., 2020. Harmonized global maps of above and belowground biomass carbon density in the year 2010. Sci Data 7, 112. https://doi.org/10.1038/s41597-020-0444-4. Available at https://developers.google.com/earth-engine/datasets/catalog/NASA_ORNL_biomass_carbon_density_v1

Variables	Source	RA Element
Peatlands Carbon Stock	Widyastuti et al., 2025[124]	3.High carbon stock areas
Peatlands Thickness	Widyastuti et al., 2025[125]	4.Significant natural ecosystems
Mangroves	Mazur et al., 2025[125]	4.Significant natural ecosystems
Wetlands	Zhang et al., 2023[126]	4.Significant natural ecosystems
Grasslands	Parente et al., 2024[127]	4.Significant natural ecosystems
Small Islands	Sayre R., 2022[128]	4.Significant natural ecosystems
Steep Slopes	Jarvis et al., 2008[129]	4.Significant natural ecosystems
Permanent and Natural Waters	Potapov et al., 2022[130], Pekel et al., 2016[131]	5.Critical water bodies
Inland Waters Surface Density	Lehner et al., 2024[132]	5.Critical water bodies
River Basins Physical Risks	WWF, 2024[133]	5.Critical water bodies
Glaciers	GLIMS Consortium, 2005[134]	5.Critical water bodies
Global Ocean	Mikelsons et al., 2021[135]	5.Critical water bodies
Hongana-Manyawa uncontacted tribal territory	Survival International, 2024[136]	6. IP&LC territories – uncontacted

124 Widyastuti, M.T., Minasny, B., Padarian, J., Maggi, F., Aitkenhead, M., Beucher, A., Connolly, J., Fiantis, D., Kidd, D., Ma, Y., Macfarlane, F., Robb, C., Rudiyanto, Setiawan, B.I., Taufik, M., 2025. Digital mapping of peat thickness and carbon stock of global peatlands. CATENA 258, 109243. https://doi.org/10.1016/j.catena.2025.109243. Available at https://zenodo.org/records/12559239 World Wide Fund for Nature, 2024. WWF Water Risk Filter Methodology Documentation.

125 Mazur, E., Sims, M., Goldman, E., Schneider, M., 2025. SBTN Natural Lands Map – Technical Documentation. https://sciencebasedtargetsnetwork.org/wp-content/uploads/2025/02/Technical-Guidance-2025-Step3-Land-v1_1-Natural-Lands-Map.pdf. Available at https://developers.google.com/earth-engine/datasets/catalog/WRI_SBTN_naturalLands_v1

126 Zhang, X., Liu, L., Zhao, T., Chen, X., Lin, S., Wang, J., Mi, J., Liu, W., 2023. GWL_FCS30: a global 30 m wetland map with a fine classification system using multi-sourced and time-series remote sensing imagery in 2020. Earth Syst. Sci. Data 15, 265 – 293. https://doi.org/10.5194/essd-15-265-2023. Available at https://zenodo.org/records/7340516

127 Parente, L., Sloat, L., Mesquita, V., Consoli, D., Stanimirova, R., Hengl, T., Bonannella, C., Teles, N., Wheeler, I., Hunter, M., Ehrmann, S., Ferreira, L., Mattos, A.P., Oliveira, B., Meyer, C., Şahin, M., Witjes, M., Fritz, S., Malek, Z., Stolle, F., 2024. Annual 30-m maps of global grassland class and extent (2000 – 2022) based on spatiotemporal Machine Learning. Sci Data 11, 1303. https://doi.org/10.1038/s41597-024-04139-6. Available at https://developers.google.com/earth-engine/datasets/publisher/global-pasture-watch

128 Sayre, R., 2022. Global Islands – Public Domain Data [Data set]. GEO Knowledge Hub. Available at https://doi.org/10.60566/7yjze-2g558

129 Jarvis A., H.I. Reuter, A. Nelson, E. Guevara, 2008. Hole-filled seamless SRTM data V4, International Centre for Tropical Agriculture (CIAT). Available at https://developers.google.com/earth-engine/datasets/catalog/CGIAR_SRTM90_V4

130 Potapov, P., Hansen, M.C., Pickens, A., Hernandez-Serna, A., Tyukavina, A., Turubanova, S., Zalles, V., Li, X., Khan, A., Stolle, F., Harris, N., Song, X.-P., Baggett, A., Kommareddy, I., Kommareddy, A., 2022. The Global 2000-2020 Land Cover and Land Use Change Dataset Derived From the Landsat Archive: First Results. Front. Remote Sens. 3, 856903. https://doi.org/10.3389/frsen.2022.856903. Available at https://glad.umd.edu/dataset/GLCLUC2020

131 Pekel, J.-F., Cottam, A., Gorelick, N., Belward, A.S., 2016. High-resolution mapping of global surface water and its long-term changes. Nature 540, 418 – 422. https://doi.org/10.1038/nature20584. Available at https://developers.google.com/earth-engine/datasets/catalog/JRC_GSW1_4_GlobalSurfaceWater

132 Lehner, B., Anand, M., Fluet-Chouinard, E., Tan, F., Aires, F., Allen, G.H., Bousquet, P., Canadell, J.G., Davidson, N., Finlayson, C.M., Gumbricht, T., Hilarides, L., Hugelius, G., Jackson, R.B., Korver, M.C., McIntyre, P.B., Nagy, S., Olefeldt, D., Pavelsky, T.M., Pekel, J.-F., Poulter, B., Prigent, C., Wang, J., Worthington, T.A., Yamazaki, D., Thieme, M., 2024. Mapping the world's inland surface waters: an update to the Global Lakes and Wetlands Database (GLWD v2). https://doi.org/10.5194/essd-2024-204. Available at https://www.hydrosheds.org/products/glwd

133 World Wide Fund for Nature, 2024. WWF Water Risk Filter Methodology Documentation. https://doi.org/10.5281/ZENODO.13768279. Available at https://riskfilter.org/water/explore/map

134 GLIMS Consortium, 2005. GLIMS Glacier Database. (NSIDC-0272, Version 1). [Data Set]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. https://doi.org/10.7265/N5V98602. Available at https://www.glims.org/maps/glims

135 Mikelsons, K., Wang, M., Wang, X.-L., Jiang, L., 2021. Global land mask for satellite ocean color remote sensing. Remote Sensing of Environment 257, 112356. https://doi.org/10.1016/j.rse.2021.112356. Available at https://data.mendeley.com/datasets/9r93m9s7cw/1

136 Survival International 2024. Driven to the edge: How the demand for electric cars is destroying uncontacted Indigenous people's lives and lands in Indonesia. P24-28. https://www.survivalinternational.org/documents/DrivenToTheEdge

6.3.3 Mapping method for Restricted Areas

All spatial datasets were converted into global raster layers in geographic coordinates (EPSG:4326, WGS84) with a uniform spatial resolution of 0.0025 degrees (approximately 300 m at the equator). Vector reference maps were reprojected and converted to the same raster format to ensure consistency, and all computations were conducted with these raster datasets. The preprocessing steps included metric extraction and class selection from source data – for example, generating a steep slope layer using a ≥ 21° threshold from a global digital elevation model, or isolating mangrove areas from a landcover dataset. Detailed preprocessing methods for each layer are provided in Supplementary – "Development of Restricted Areas Map for Transition Minerals Mining at a Global Scale". To ensure comparability, all datasets were reclassified into three ranking levels (medium = 1, high = 2, very high = 3). Continuous variables were normalised into three classes based on the 1st and 95th percentiles to reduce the influence of extreme values. Binary datasets were ranked according to expert-assigned importance values, and discrete datasets were manually reclassified based on expert judgement of class relevance and converted into ranked layers.

These datasets were uploaded to Google Earth Engine (GEE) for dynamic visualisation, comparative analysis, and spatial processing (e.g., conversion, reclassification, and integration). With iterative expert consultation, a final set of data layers was selected to produce a comprehensive map of global RAs. Some layers (e.g., PAs, intact forest landscapes, and territories of uncontacted indigenous peoples) were fully included (i.e., off-limits by 'default'), whereas others were weighted across 1–3 importance classes based on natural values. In total, four weighted aggregated layers were included: HCV areas, HCS areas, significant natural ecosystems, and critical water bodies (CWBs).

Areas that should be off-limits to mining due to their critical natural values or significance for IP&LC rights are identified by either the presence of default restriction criteria (e.g., PAs) or because they surpassed the threshold value for weighted elements. The threshold value seven was selected to represent areas that contain at least one very high and one high value, or three or more high value. The resulting main layer is called Restricted Areas 1 (RA1) and this layer is used for a comparative analysis with the mineral RPAs.

6.3.4 Application at a local scale

Although the Restricted Areas Map offers a valuable global overview, its limited resolution renders it insufficient for local applications or decision-making (see Figure 2). To address this, the same methodology can be applied to higher-resolution local datasets, including those resulting from local assessments, to create more-precise national, regional, or local maps. These localised versions can refine the boundaries of RAs with locally verified high-resolution data and with input from local experts, ensuring the accuracy required for policy making, advocacy, and operational decision-making. Validation in countries such as Indonesia and Sweden was undertaken to confirm the map's accuracy and identify potential data gaps at the national level. It is important to note that the regional or national application of the RA map requires additional consultation with local stakeholders and additional assessments.

Figure 2: Global Restricted Areas web map, showing off-limits areas by Default on land (green), in the ocean (dark green) and by Values (blue), all of which combine to form Restricted Areas 1, "RA1". The web map can be found at https://maps.greenpeace.org/maps/gpint/restricted-areas/
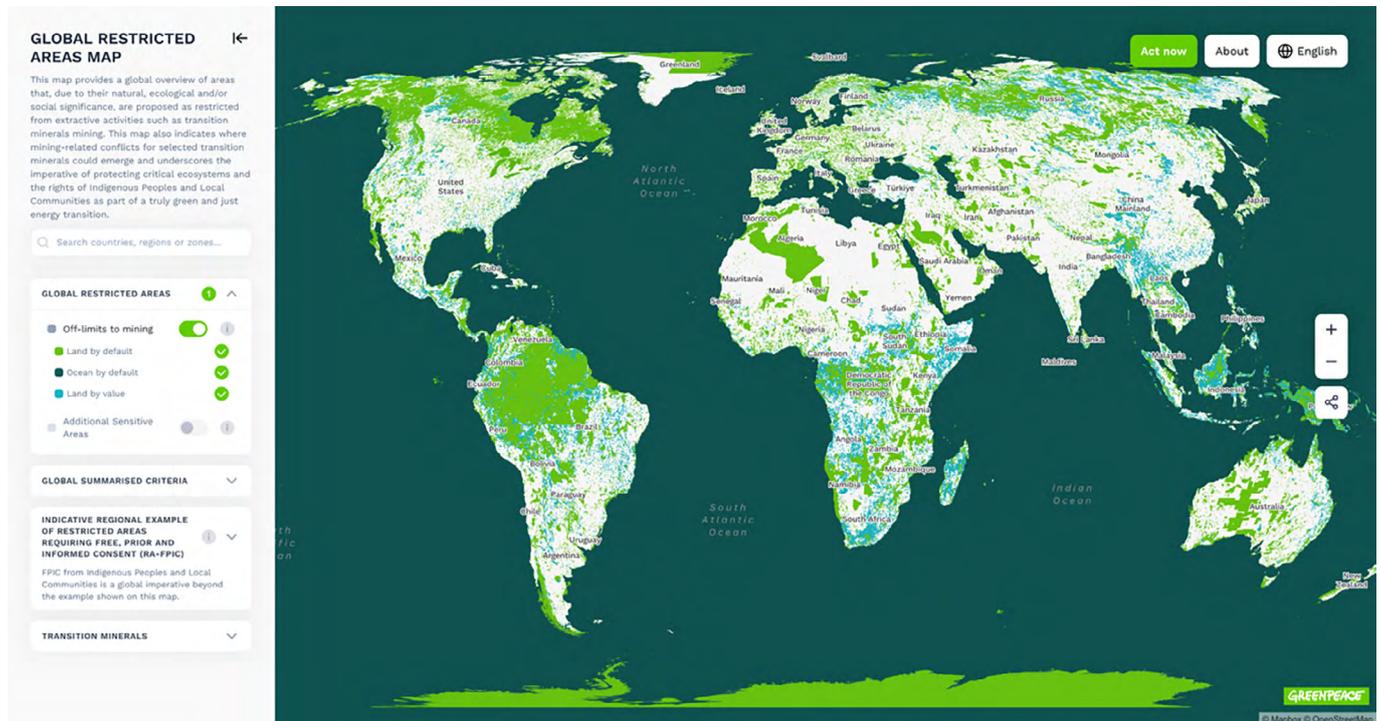
6.3.5 Limitations

The RA mapping approach is subject to several methodological limitations that warrant careful consideration. The reliability of outputs is contingent upon the quality, completeness and spatial resolution of the underlying global datasets, which can display regional variability and, in some cases, temporal obsolescence. The process of harmonising heterogeneous datasets through percentile-based reclassification and expert-informed simplification, although necessary for comparability, introduces an element of subjectivity and inevitably reduces the thematic richness of the original data. Although ecological stratification by biome was used to enhance representativeness and mitigate ecological bias, this adjustment cannot fully account for fine-scale environmental heterogeneity or ecotonal transitions. Furthermore, the classification thresholds and decision rules applied within the analysis are indicative rather than definitive, positioning the resulting maps as heuristic tools for preliminary assessment rather than instruments for definitive decision-making. Consequently, although the RAs map provides valuable insight into potential spatial conflicts between mineral extraction and critical environmental, ecological and natural values, as well as IP&LC rights, its outputs should be complemented by high-resolution, site-specific analyses and participatory stakeholder engagement to inform robust land-use and policy decisions.

6.4 Reserves Proxy Areas

Reserves Proxy Areas (RPAs) are spatial approximations of likely mineral reserves derived from the overlap of various mining data. These can be interpreted as areas in which development pressures could emerge.

6.4.1 Mineral mapping data

Publicly available information was compiled to estimate the Reserves Proxy Areas (RPAs), focusing on the following data categories:

- Mineral point data suggesting the presence of that mineral at various stages of development (ranging from occurrences, to mining, and post-closure)
- Mineral permit data, as it can serve as a useful proxy for identifying potential areas of mineral reserves, particularly when metadata can be filtered by the specific commodity of interest; and
- Mapped areas of mining globally.

Data was available at the global and regional level from various sources:

1. Local Government Data Sets (national, regional, provincial or territorial). These datasets typically include 1) mineral commodity-specific, geospatially referenced data on mineral-related occurrences within national or territorial borders; and 2) mining permit or concession data (also called tenements), a subset of which contain searchable metadata on the mineral commodities of interest.

2. Global Government Data Sets (global or region-specific). Data from the Government of Canada and the U.S. Geological Survey (USGS) contains geospatially referenced information on mineral-related occurrences and infrastructure across many countries and regions. The U.S. Geological Survey (USGS) also provides a comprehensive dataset on country-level mineral reserves through its annual Mineral Commodity Summaries and Minerals Yearbook. This dataset includes estimates of the quantity and distribution of mineral reserves including those of nickel, cobalt, copper, lithium, rare earth elements, and others across various countries. These data do not include a spatial analysis of where reserves are located within countries.

3. Academic Publications & Related Supplemental Data (global). These datasets typically provide geospatially referenced data on mineral-related occurrences or mining activities. The data may be specific to certain minerals of interest or may relate to non-commodity-specific mining activities.

For a detailed list of the data sources included, please see Supplementary 2 – "Minerals Mapping Approach and Integration with a Global Restricted Areas Map".

6.4.2 Minerals and areas of focus

The Reserves Proxy Area (RPA) analysis focused on nickel, lithium, and cobalt – minerals currently central to batteries and renewable energy infrastructure.

The mapping also focused on countries that dominate the global reserves of these minerals, those collectively holding over 80% of known global reserves according to the U.S. Geological Survey including: Argentina, Australia, Brazil, Canada, Chile, China, the Democratic Republic of the Congo, Indonesia, New Caledonia, the Philippines, and the United States.

6.4.3 Method – approximating reserve locations

Identifying the precise locations and quantities of mineral reserves on a global scale is complex and resource intensive. Accurate delineation requires detailed and often proprietary geological data, detailed sub-surface modelling, and expert interpretation. This information is not consistently available across all countries and mineral commodities. Given these limitations, in this study, we adopt a spatial approximation approach using publicly available Geographic Information System (GIS) data to estimate the likely locations and areal extents of current and future reserves. While not intended to define exact reserve boundaries or volumes, this method offers a scalable framework for the spatial estimation of reserves that supports comparative analyses across countries and commodities. For clarity, this process aims to estimate reserve locations, but not resource locations (USGS, 2025).[137]

137 USGS (2025). USGS Mineral Commodity Summaries 2025. See Appendix

This methodology consists of the following sequential steps:

I.   Data Compilation. Spatial datasets were collected and standardised, including:

   a)   Mineral point data representing mineral occurrences or deposits for lithium, nickel and cobalt (global and regional data sets),

   b)   Mining polygons or industrial areas delineating the footprints of active or historical mines, and

   c)   Mineral permit (also called tenement or concession) polygons indicating areas authorised for exploration or development (regional data from governments).

II.   Buffer Application. To account for positional inaccuracies and spatial uncertainty, a uniform 5-kilometer buffer was applied to the mineral point data, and a 1-kilometer buffer was applied to the mining polygons. Buffers increase the likelihood of capturing relevant spatial relationships while accounting for data uncertainty, and potential reserve expansion or development not reflected in the original datasets.

III.   Identification of Reserves Proxy Areas. Intersections between multiple spatial datasets were used to infer potential mineral reserve locations. The approach is based on the premise that co-located data increase the likelihood of reserves. For example, if a known mineral occurrence (mineral point data) is found within or near a mining polygon (representing active or historic mining activity), it is reasonable to infer that the mine may be extracting that commodity. Similarly, if permits have been granted for exploration or development for a specific commodity in an area with active mining, this strengthens the inference of the potential presence of a reserve.

   Although not definitive, these classifications provide useful proxies for identifying areas with likely reserve concentrations and therefore potential development pressure. This method offers a consistent and repeatable way to approximate reserve locations across different geographies and commodities. Reserves Proxy Areas should be regarded as a screening tool. They are useful for identifying potential reserves and development pressures but should not be interpreted as definitive reserve boundaries.

6.4.4 Method – spatial allocation of reserves

It is assumed for the purpose of this global analysis only that reserves are uniformly distributed over the total area of the identified polygons. This simplification does not reflect the true heterogeneity of mineral deposits and reserves delineation, as there was no feasible way to account for these variables at the scale and scope of this study.

It is assumed that the total share of Reserves Proxy Areas within Restricted Areas (based on estimates from countries that contain at least 80% of global reserves) also applies to the other countries that were not evaluated. This approximation is suitable for high-level spatial analysis and risk identification globally, however finer-scale or site-specific assessments will require more detailed geological and operational data.

6.4.5 Testing and verification

Case studies were carried out in Sweden (copper) and Indonesia (nickel) – two major mineral-producing countries in distinct geographies. These case studies informed adjustments to the method and confirmed the method validity.

Reserves Proxy Area selections underwent a manual quality control process for each mineral commodity and country. Where the spot check revealed minimal errors, the analysis was considered adequate. In regions where multiple errors were identified, each polygon was manually reviewed for accuracy. To help address missing data in known high-priority mining zones, additional verification was carried out for known reserve areas using Planet Mosaic satellite imagery. Cross-checking strengthened the reliability of the analysis, particularly for regions undergoing rapid development.

6.5 Comparison of Reserves Proxy Areas with Restricted Areas

The Reserves Proxy Areas were systematically compared against the Restricted Areas mapping at the country level to evaluate potential constraints on mineral availability. This comparison identified the proportion of Reserves Proxy Areas that are situated inside and outside Restricted Areas that should be off-limits to mining (RA1), offering an initial estimate of the spatial overlap between mineral opportunities and areas of critical environmental, ecological or natural values.

This analysis includes the following steps:

1. Overlay of Reserves Proxy Areas with the Restricted Areas 1 (RA1) map to identify overlap

2. Quantification of Reserves Proxy Areas inside and outside RA1

3. Derive an estimate of the reserves located outside of RA1

6.5.1 Interpretation and Implications

When substantial shares of Reserves Proxy Areas are located within Restricted Areas (RA1, or others), this signals a constraint on future mineral development locations. In the case of the RA1 areas, they should be considered as off limits to mining for transition minerals. In remaining areas, extraction of critical transition minerals is subject to further detailed expert assessments and local consultation to gather higher resolution and quality data, and still subject to strict environmental, social, and governance safeguards, and in particular FPIC from Indigenous People & local communities.

This comparison should be treated as a screening-level assessment tool. It is intended to provide directional insights with indicative information on what areas should be off limits and the potential global mineral availability under critical environmental and development constraints, rather than definitive boundaries at an operational level of where mining may or may not occur.

6.5.2 Limitations

While the method provides a consistent and scalable proxy for identifying reserve locations, it has limitations. There are presumed errors in the mineral point data when it plots in unlikely locations. In some regions, permit data is incomplete or lacks sufficient detail, particularly the ability to filter by specific mineral commodity. Also, recent or smaller scale mining operations may not yet appear in the available datasets, particularly in regions where permit data is incomplete or outdated, which can result in under-representation of newly developed areas. These factors limit the precision of identifying potential reserves based on data intersections.

In the absence of permit data, or limited point data, the analysis is less likely to identify fewer Reserves Proxy Areas. Additionally, recognising that Reserves Proxy Areas and Restricted Areas are derived from heterogeneous datasets with varying resolution, there is inherent spatial uncertainty in the analysis, with Restricted Areas data sets converted into uniform layers with a spatial resolution at approximately 300m resolution and Reserves Proxy Areas at approximately 30m resolution.

Ultimately, the Reserves Proxy Areas and Restricted Areas identified through these methods should be interpreted as indicative rather than definitive. This can provide a valuable first step in highlighting areas of potential overlap between mineral development and essential environmental protection and respect for IP&LC rights, but they require further validation through local datasets, ground-truthing, and consultation with Indigenous Peoples, local communities, and regional experts to ensure accuracy and applicability in decision-making.

It is important to note that this mapping gives an indication of the fraction of estimated reserve area that is inside Restricted Areas that should be off-limits to mining. The fraction of mineral quantity that is within or outside these areas has been estimated based on area, not geological characteristics such as orebody geometry or ore grades. RPAs are intentionally described as a proxy – the method cannot precisely define reserve locations.

6.5.3 Additional Data, Methodology, and Results

This chapter provides a high-level overview of the mapping methods and data used. For detailed information, including a full list of references, please refer to Supplementary 1, "Development of a Restricted Areas Map for Transition Minerals Mining at a Global Scale" and 2, "Minerals Mapping Approach and Integration with a Global Restricted Areas Map". The web map is available here: https://maps.greenpeace.org/maps/gpint/restricted-areas/
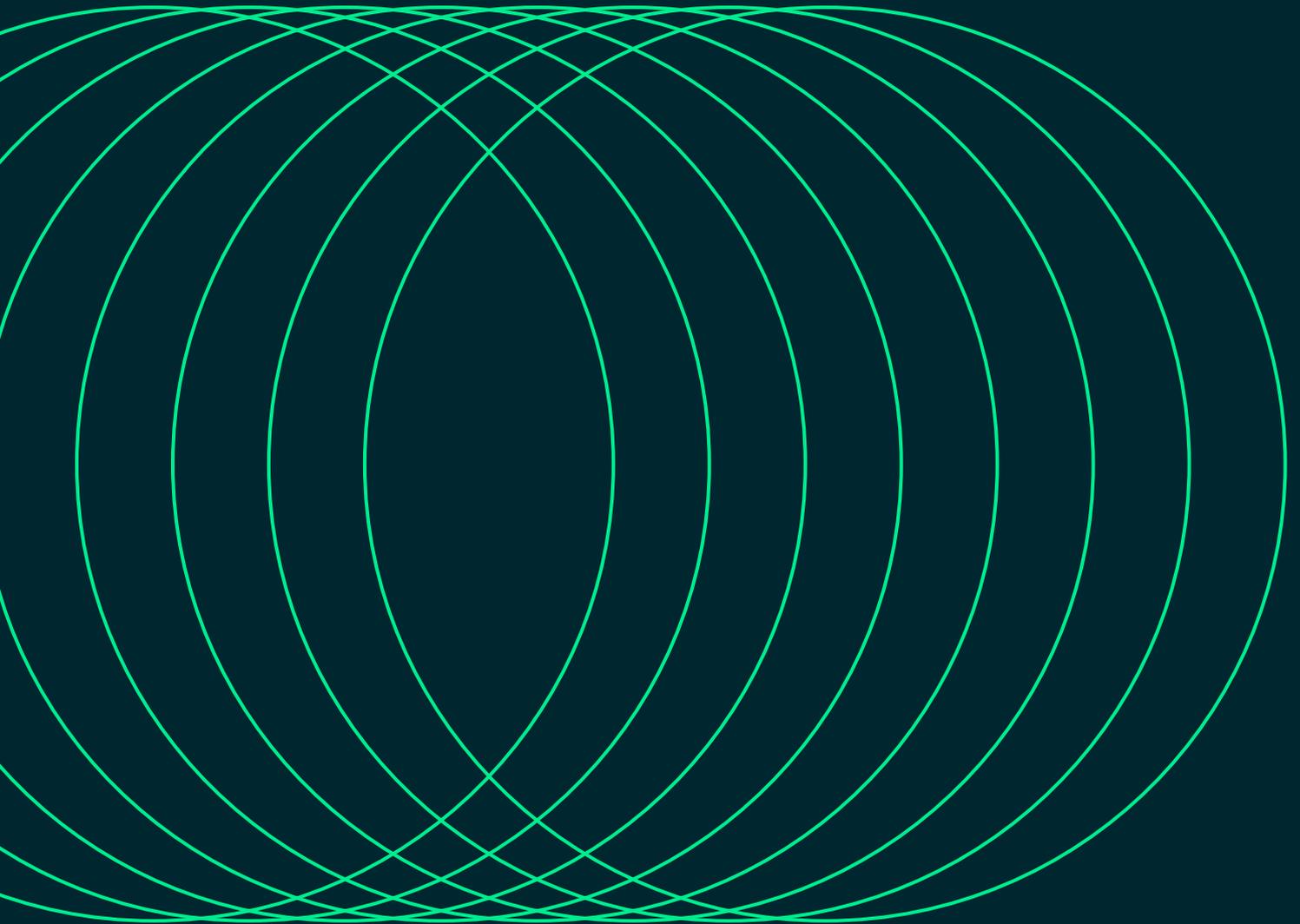
7 Key Results

Based on the methodology documented in the previous chapters, the resource requirements for nine important minerals were calculated. The selected minerals are key to the leading energy transition technologies in the following sectors:

- Power generation, solar PV, and onshore and offshore wind are assumed to dominate the market for new power generation. The significant cost benefits compared with all other power generation technologies, combined with the relatively short installation times and low operation costs because no fuel is required, will very likely make these technologies the backbone of future power generation.

- Storage adapts the variable power generated by solar and wind power plants to the temporal needs of different consumers. Batteries – together with pumped hydro and molten salt – are the key technology for the energy transition and electrification. Batteries are urgently required for sector coupling in sectors currently dominated by oil (vehicles) and gas (space heating). Please note the mineral intensity of pumped hydro and molten salt were not considered in this study.

The extent to which stationary BESSs are required on a global scale is still subject to research. The battery capacity required is largely dependent upon the generation mix, the extent to which demand-side management and flexible demand measures are implemented, and whether pumped hydro or other technologies are available. In turn, these factors depend on the geography of each country implementing BESS.

Therefore, the capacity used for this analysis is estimated as a share of the installed capacity for solar photovoltaics. For the OECM it is assumed that 10% of the new installed solar PV capacity in GW will include storage batteries by 2030, and 33% by 2050. The assumption for the Progressive scenarios is that the battery share will increase to only 25% of the new installed capacity by 2050 while other measures – like flexible demand and other non-battery storage technologies – will play a larger role in comparison to the OECM.

Furthermore, batteries are the 'core' of any EV. The mining activities for minerals that are required for electric mobility will replace the extraction of oil. Unlike oil, which is simply burned, the battery minerals store the energy required for driving and can be recharged.

The analysed minerals in this study are:
- Cobalt
- Copper
- Graphite
- Dysprosium ('rare earth')
- Lithium
- Manganese
- Neodymium ('rare earth')
- Nickel
- Vanadium

Comparison of scenarios

The calculated mineral requirements for the OECM 1.5°C Scenario, the Progressive Scenario (PRO), and the Progressive Accelerated Na-ion (PRO-Na-ion) Scenario are compared with the results of the IEA analysis 'Global Critical Mineral Outlook 2025' (IEA, 2025).[138]

There are significant differences between the five scenarios that are compared in this section, not only regarding the assumed parameters for mineral requirements, but also in terms of the assumed energy demand and supply infrastructures. The transport demand under both IEA scenarios is significantly higher than under the OECM and both PRO scenarios. This leads to different battery market volumes. Furthermore, the assumed recycling rates and yield rate – the material that is re-used from the recycling collection – are considered under the IEA scenarios, but not under the OECM and PRO scenarios (see also 4.3.1). Therefore, there are significant uncertainties due to methodological differences.

Although the IEA included the copper demand for power generation and storage technologies and electric grids in their assessment, the assessments of the OECM and PRO focus on power generation [and storage] only. Therefore, the copper demand for power grids is deducted from the IEA results.

Figure 3 shows the results of the IEA scenarios 'Stated Policies Scenario' (STEPS) and Net-Zero Emissions by 2050' (NZE) compared with those of the OECM and PRO Scenarios.

Figure 3: Comparison of scenarios
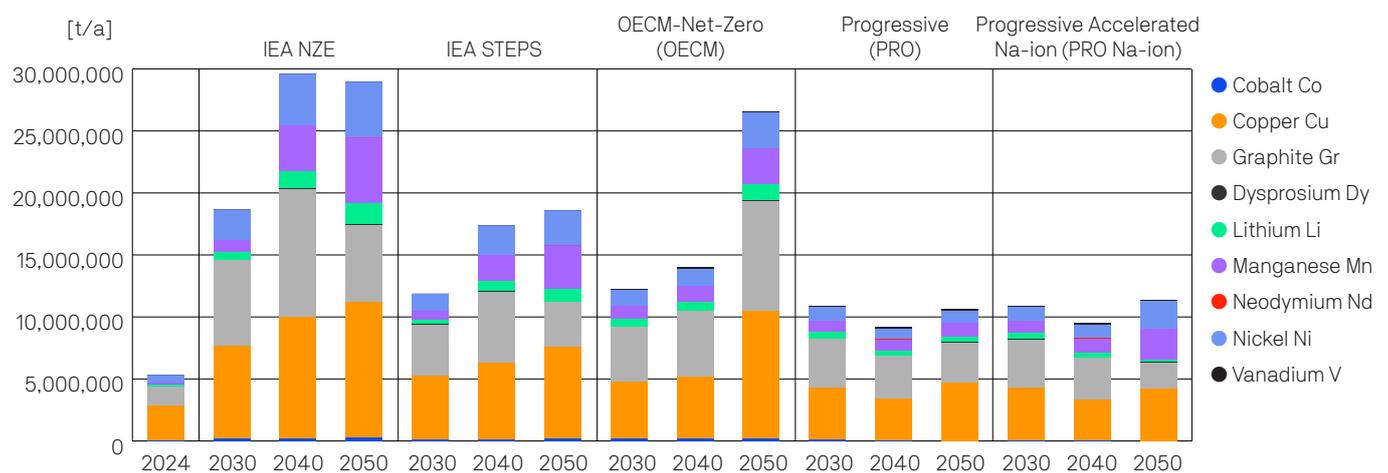
The demand for the minerals analysed in IEA Net-Zero is higher than under the OECM and PRO scenarios (including recycling). Besides the different methodologies applied, the difference is also due to the lower overall energy demand in the latter. The OECM and PRO Scenarios are based on more-ambitious efficiency measures combined with an assumed lower number of vehicles and increased public transport services.

However, the trajectories in all scenarios show the same trends. The PRO Scenario has a lower resource demand than the IEA and OECM Scenarios because of the smaller global vehicle fleet and larger role of public transport (road and rail). Moreover, faster change toward new battery technologies reduces the total demand even further under PRO.

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138 IEA (2025). Global Critical Mineral Outlook 2025. Available at https://www.iea.org/reports/global-critical-minerals-outlook-2025

7.1 Global 1.5°C One Earth Climate Model – Mineral Requirements without Recycling

Table 29 shows the annual mineral resource demand under the OECM scenario. By 2030, the mineral demand of most of the minerals analysed will increase significantly. By 2030, Nickel demand would increase by a factor of 2.6, cobalt by 2.9 and copper by 2.4, lithium and manganese will increase by factor 5 to 6 compared to 2024. Vanadium will increase significantly, because redox flow batteries for stationary storage systems are assumed to increase significantly for BESS, although the overall mineral volume is small relative to the other analysed minerals. In 2050, graphite and lithium – both key ingredients of electric batteries – will increase in demand to about 9 and 16 times of the 2024 demand respectively.

In the following tables, demand projections are compared with 2024 energy transition demand as reported by IEA (2025),[139] and 2024 global mine production as reported by USGS (2025)[140]. It is important to note, that the calculated mineral demands in Table 29 does not consider any recycling measures. The effect of recycling is significant, and the results are shown in Table 31.

Table 29: OECM – Development of annual mineral demand without recycling

Material Demand Without Recycling		Material Demand for Energy Transition Technologies in 2024	Global Mining 2024	Share Energy Transition Materials	Annual Material Demand in 2030 Compared with 2024	Annual Material Demand in 2050 Compared with 2024	Annual Material Demand from Mining (Zero if material is sourced entirely from recycling)				
							2030	2035	2040	2045	2050
		[t/a]	[t/a]	[%]	[1]	[1]	[t/a]	[t/a]	[t/a]	[t/a]	[t/a]
Cobalt	Co	70,600	290,000	24%	2.9	5.5	205,000	328,000	313,000	347,000	386,000
Copper	Cu	2,808,000	23,000,000	12%	2.4	5.4	6,671,000	9,354,000	10,042,000	11,793,000	15,191,000
Graphite	Gr	1,505,000	1,600,000	94%	3.0	9.4	4,557,000	6,721,000	8,139,000	10,421,000	14,088,000
Dysprosium	Dy	1,530	1,800	85%	2.1	4.8	3,200	6,940	8,470	5,950	7,280
Lithium	Li	128,000	240,000	53%	5.1	15.9	654,000	929,000	1,150,000	1,499,000	2,032,000
Manganese	Mn	186,000	20,000,000	1%	6.1	21.8	1,137,000	1,749,000	2,262,000	2,998,000	4,062,000
Neodymium	Nd	14,600	16,000	91%	1.1	1.8	15,500	43,400	52,400	24,600	26,900
Nickel	Ni	562,000	3,700,000	15%	2.6	7.5	1,455,000	2,178,000	2,581,000	3,237,000	4,211,000
Vanadium	V	892	100,000	1%	50.6	55.6	45,100	130,000	137,000	101,000	49,600

Table 30 shows the cumulative mineral demand between 2024 and 2050 for the minerals analysed. The total demands are compared with the currently known reserves and resources of these minerals. None of the nine minerals will exceed the known resources. Cobalt shows the highest resource utilisation at 34%, followed by lithium and graphite at 25%. The utilisation of lithium is equivalent to 97% of the reserves in this scenario. These projections would entail a significant increase in mining.

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139 IEA (2025). Critical Minerals Dataset. Updated May 2025. CC BY 4.0. https://www.iea.org/data-and-statistics/data-product/critical-minerals-dataset (accessed 19 December 2025, Cu demand from electric grid deducted)

140 USGS (2025) Mineral Commodity Summaries 2025, values are estimates of 2024 global mine production based on 2023 data. U.S. Geological Survey (USGS). Available at https://doi.org/10.3133/mcs2025 (accessed 16 December 2025)

Table 30: OECM – Development of annual mineral demand without recycling

Material Demand Without Recycling		Total Material Demand in comparison with global reserves & resources				
		Current Global Reserves (Statistic 2024)	Current Global Resources (Statistic 2024)	Total 2024–2050	Cumulative Material Demand (Scenario) in [t] 2024–2050 versus Reserves	Cumulative Material Demand (Scenario) in [t] 2024–2050 versus Resources
		[t]	[t]	[t]	[%]	[%]
Cobalt	Co	11,000,000	25,000,000	8,541,600	78%	34%
Copper	Cu	980,000,000	3,500,000,000	254,621,000	26%	7%
Graphite	Gr	290,000,000	800,000,000	201,663,000	70%	25%
Dysprosium	Dy	1,100,000	1,980,000	167,000	15%	8%
Lithium	Li	30,000,000	115,000,000	29,151,000	97%	25%
Manganese	Mn	1,700,000,000	UNKNOWN	56,486,000	3%	UNKNOWN
Neodymium	Nd	12,800,000	23,040,000	908,000	7%	4%
Nickel	Ni	130,000,000	350,000,000	66,497,000	51%	19%
Vanadium	V	18,000,000	63,000,000	1,881,000	10%	3%

7.2 Global 1.5°C One Earth Climate Model – Mineral Requirements with Recycling

Table 31 shows the annual OECM mineral requirements after the assumed recycling rates (see 4.3) are implemented. The annual mining requirements for the minerals analysed decrease throughout all analysed minerals:

Compared to 2024, the Cobalt demand in 2030 will increase by factor 2.5 (2.9 without recycling) and copper by 1.7 and 2.4 without recycling. The mineral demand in the OECM with recycling for cobalt in 2050 is 51% of the demand without recycling. For the other analysed minerals, the demand decreases by around 10% for vanadium and between 20–40% for all other minerals. This is only possible when all the minerals are recycled at the assumed rates. However, by 2050, all mineral demands will be significantly higher than in 2024. Recycling can and must play an important role in the mineral sourcing strategy but still will not preclude increased extractive mining.

Table 31: OECM – Development of annual mineral demand with recycling

Material Demand With Recycling		Material Demand for Energy Transition Technologies in 2024	Global Mining 2024	Share Energy Transition Materials	Annual Material Demand in 2030 Compared with 2024	Annual Material Demand in 2050 Compared with 2024	Annual Material Demand from Mining (Zero if material is sourced entirely from recycling)				
							2030	2035	2040	2045	2050
		[t/a]	[t/a]	[%]	[1]	[1]	[t/a]	[t/a]	[t/a]	[t/a]	[t/a]
Cobalt	Co	70,600	290,000	24%	2.5	2.8	177,000	184,000	165,000	103,000	197,000
Copper	Cu	2,808,000	23,000,000	12%	1.7	3.7	4,636,000	5,509,000	5,065,000	6,384,000	10,357,000
Graphite	Gr	1,505,000	1,600,000	94%	2.9	5.9	4,436,000	5,722,000	5,298,000	5,946,000	8,863,000
Dysprosium	Dy	1,530	1,800	85%	1.1	3.5	1,620	2,030	1,960	3,150	5,310
Lithium	Li	128,000	240,000	53%	4.8	10.6	617,000	708,000	680,000	788,000	1,353,000
Manganese	Mn	186,000	20,000,000	1%	5.6	15.3	1,037,000	1,243,000	1,346,000	1,546,000	2,838,000
Neodymium	Nd	14,600	16,000	91%	0.2	1.5	3,140	6,540	5,280	15,800	21,200
Nickel	Ni	562,000	3,700,000	15%	2.3	5.1	1,299,000	1,406,000	1,320,000	1,517,000	2,848,000
Vanadium	V	892	100,000	1%	50.6	51.0	45,100	129,000	135,000	94,500	45,500

Table 32 shows the cumulative mineral requirements for the OECM scenario with ambitious recycling rates. Compared to OECM without recycling, the total demand until 2050 for the analysed minerals is lowered. This means that recycling can significantly decrease pressures on reserves. In this scenario, lithium will still have the highest reserve utilisation of 66%, equivalent to 17% of total known resources.

Table 32: OECM – Development of annual mineral demand with recycling

		Total Material Demand in comparison with global reserves & resources				
Material Demand With recycling		**Current Global Reserves (Statistic 2024)**	**Current Global Resources (Statistic 2024)**	**Total 2024–2050**	**Cumulative Material Demand (Scenario) in [t] 2024–2050 versus Reserves**	**Cumulative Material Demand (Scenario) in [t] 2024–2050 versus Resources**
		[t]	**[t]**	**[t]**	**[%]**	**[%]**
Cobalt	Co	11,000,000	25,000,000	5,091,000	46%	20%
Copper	Cu	980,000,000	3,500,000,000	150,306,000	15%	4%
Graphite	Gr	290,000,000	800,000,000	143,974,000	50%	18%
Dysprosium	Dy	1,100,000	1,980,000	71,000	6%	4%
Lithium	Li	30,000,000	115,000,000	19,673,000	66%	17%
Manganese	Mn	1,700,000,000	UNKNOWN	37,107,000	2%	UNKNOWN
Neodymium	Nd	12,800,000	23,040,000	292,000	2%	1%
Nickel	Ni	130,000,000	350,000,000	41,573,000	32%	12%
Vanadium	V	18,000,000	63,000,000	1,838,000	10%	3%

7.3 Global Progressive Scenario – Mineral Requirements without Recycling

The Progressive Scenario combines the ambitious energy efficiency measures of the OECM with a shift towards high shares of public transport, fewer private vehicles and a faster shift toward newer battery technologies. The PRO scenario has higher recycling rates than the OECM Scenario (see 4.3.1), however, the smaller global vehicle fleet is the most significant factor in reducing the mineral demand.

The reduced resource requirement of the PRO Scenario is for a large part due to an assumed lower total number of vehicles produced until 2050, compared to the OECM. The OECM leads to an accumulated global vehicle fleet of 2 billion passenger cars, an increase of about 800 million from the currently estimated 1.2 billion cars in 2022, whereas the increase in vehicles under the PRO is halved, to 400 million, leading to 1.6 billion passenger vehicles in 2050. Furthermore, the different battery technology mix and increased uptake of emerging battery technology also contribute to a reduction in mineral demand under this scenario.

Table 33 shows the annual mineral requirements without recycling and Table 34 shows the cumulative requirements until 2050. Compared to the OECM without recycling, the annual mineral demand in 2030 in the PRO is around 10% lower, except for neodymium (same as OECM), cobalt (-29%) and vanadium (+20%).

This is a very significant achievement, which requires that the focus be shifted from individual transport to public transport systems and global reductions in the overall EVs produced and battery capacities. The highest-impact measures for mineral resource efficiency are a combination of less demand and high recycling.

Table 33: Progressive Scenario – Development of annual mineral demand without recycling

Material Demand Without Recycling		Material Demand for Energy Transition Technologies in 2024	Global Mining 2024	Share Energy Transition Materials	Annual Material Demand in 2030 Compared with 2024	Annual Material Demand in 2050 Compared with 2024	Annual Material Demand from Mining (Zero if material is sourced entirely from recycling)				
							2030	2035	2040	2045	2050
		[t/a]	[t/a]	[%]	[1]	[1]	[t/a]	[t/a]	[t/a]	[t/a]	[t/a]
Cobalt	Co	70,600	290,000	24%	2.2	2.5	153,000	237,000	210,000	192,000	179,000
Copper	Cu	2,808,000	23,000,000	12%	2.2	3.6	6,230,000	8,191,000	7,974,000	8,352,000	9,972,000
Graphite	Gr	1,505,000	1,600,000	94%	2.7	5.5	4,051,000	5,441,000	5,893,000	6,629,000	8,206,000
Dysprosium	Dy	1,530	1,800	85%	2.0	3.7	3,070	6,480	7,700	4,880	5,730
Lithium	Li	128,000	240,000	53%	4.6	9.6	583,000	761,000	855,000	987,000	1,229,000
Manganese	Mn	186,000	20,000,000	1%	5.5	14.7	1,014,000	1,469,000	1,792,000	2,165,000	2,738,000
Neodymium	Nd	14,600	16,000	91%	1.1	1.8	15,500	41,900	50,400	23,700	26,700
Nickel	Ni	562,000	3,700,000	15%	2.3	4.8	1,282,000	1,850,000	2,057,000	2,282,000	2,702,000
Vanadium	V	892	100,000	1%	60.5	111.2	54,000	123,000	108,000	110,000	99,200

Table 34: Progressive Scenario – Development of annual mineral demand without recycling

Material Demand Without Recycling		Total Material Demand in comparison with global reserves & resources				
		Current Global Reserves (Statistic 2024)	Current Global Resources (Statistic 2024)	Total 2024–2050	Cumulative Material Demand (Scenario) in [t] 2024–2050 versus Reserves	Cumulative Material Demand (Scenario) in [t] 2024–2050 versus Resources
		[t]	[t]	[t]	[%]	[%]
Cobalt	Co	11,000,000	25,000,000	5,233,000	48%	21%
Copper	Cu	980,000,000	3,500,000,000	205,299,000	21%	6%
Graphite	Gr	290,000,000	800,000,000	146,744,000	51%	18%
Dysprosium	Dy	1,100,000	1,980,000	150,000	14%	8%
Lithium	Li	30,000,000	115,000,000	21,691,000	72%	19%
Manganese	Mn	1,700,000,000	UNKNOWN	44,255,000	3%	UNKNOWN
Neodymium	Nd	12,800,000	23,040,000	884,000	7%	4%
Nickel	Ni	130,000,000	350,000,000	51,099,000	39%	15%
Vanadium	V	18,000,000	63,000,000	2,107,000	12%	3%

7.4 Global Progressive Scenario – Mineral requirements including Recycling

As under the OECM pathway, the high recycling rates under the PRO will reduce the pressure on the resource requirement, by even further. Table 35 shows the results of the PRO scenario with recycling. Compared to the PRO without recycling, the difference in annual mineral demand between 2024 and 2050 decreased from factor 2.5 to zero for cobalt (all remaining demand can be supplied from recycled materials), from factor 3.6 to 1.7 for copper, 5.5 to 2.2 for graphite and a decrease factor 9.6 to 3.6 for lithium. The demand for all analysed minerals decreased – except for vanadium which will have a slightly higher annual demand in 2030 and 2050 under the PRO Scenario than under OECM due to the increased deployment of redox flow storage systems for the stabilisation of power grids and storage services.

Table 35: Progressive Scenario – Development of annual mineral demand with recycling

Material Demand With Recycling		Material Demand for Energy Transition Technologies in 2024	Global Mining 2024	Share of Energy Transition Materials	Annual Material Demand in 2030 Compared with 2024	Annual Material Demand in 2050 Compared with 2024	Annual Material Demand from Mining (Zero if material is sourced entirely from mining)				
							2030	2035	2040	2045	2050
		[t/a]	[t/a]	[%]	[1]	[1]	[t/a]	[t/a]	[t/a]	[t/a]	[t/a]
Cobalt	Co	70,600	290,000	24%	1.8	0.0	124,000	173,000	98,400	0	394
Copper	Cu	2,808,000	23,000,000	12%	1.5	1.7	4,197,000	4,190,000	3,330,000	3,219,000	4,690,000
Graphite	Gr	1,505,000	1,600,000	94%	2.6	2.2	3,931,000	4,221,000	3,472,000	2,315,000	3,277,000
Dysprosium	Dy	1,530	1,800	85%	1.0	2.1	1,490	1,640	1,370	2,270	3,140
Lithium	Li	128,000	240,000	53%	4.3	3.6	545,000	514,000	421,000	329,000	465,000
Manganese	Mn	186,000	20,000,000	1%	4.9	6.0	914,000	939,000	894,000	836,000	1,107,000
Neodymium	Nd	14,600	16,000	91%	0.2	1.4	3,130	6,310	5,060	14,900	20,700
Nickel	Ni	562,000	3,700,000	15%	2.0	1.7	1,126,000	1,111,000	865,000	695,000	952,000
Vanadium	V	892	100,000	1%	60.4	102.4	53,900	112,000	104,000	93,600	91,300

The overall mineral resource requirements relative to the known mineral reserves and resources under the PRO Scenario are shown in Table 36. The cumulative material demand for all minerals relative to the reserves with recycling will be 12% lower for cobalt, 5% lower for copper, minus 19% for graphite, 1% lower for dysprosium and 15% lower for lithium. Also, the cumulative nickel share is reduced from 39% under the PRO without recycling to 21% under the PRO with recycling scenario.

Table 36: Progressive Scenario – Development of annual mineral demand with recycling

Material Demand With Recycling		Total Material Demand Compared with Global Reserves & Resources				
		Current Global Reserves (Statistic 2024)	Current Global Resources (Statistic 2024)	Total 2024–2050	Cumulative Material Demand (Scenario) in [t] 2024–2050 versus Reserves	Cumulative Material Demand (Scenario) in [t] 2024–2050 versus Resources
		[t]	[t]	[t]	[%]	[%]
Cobalt	Co	11,000,000	25,000,000	2,617,000	24%	10%
Copper	Cu	980,000,000	3,500,000,000	102,437,000	10%	3%
Graphite	Gr	290,000,000	800,000,000	90,464,000	31%	11%
Dysprosium	Dy	1,100,000	1,980,000	56,000	5%	3%
Lithium	Li	30,000,000	115,000,000	12,317,000	41%	11%
Manganese	Mn	1,700,000,000	UNKNOWN	24,809,000	1%	UNKNOWN
Neodymium	Nd	12,800,000	23,040,000	281,000	2%	1%
Nickel	Ni	130,000,000	350,000,000	26,697,000	21%	8%
Vanadium	V	18,000,000	63,000,000	1,929,000	11%	3%

7.5 Global Progressive Scenario Accelerated Na-ion – Mineral Requirements with Recycling

The PRO Scenario with the accelerated Na-Ion technology aims to reduce the global lithium demand further by assuming a different battery mix. The implementation of Na-ion batteries is significantly accelerated as document in section 5.4.3.

Table 37 shows, that the adjusted battery mix would reduce the mineral demand even further in certain cases. The direct comparison drawn in Table 38 shows the demand for lithium will decrease from 3.6 times the volume in 2024 in the PRO scenario to only 1.2 under the PRO-Na-ion. This scenario is achievable, if the Na-ion battery technology dominates the market from around 2040 onwards. Also, the demand of all other analysed minerals will decrease except manganese, nickel, cobalt, neodymium, and dysprosium. However, this calculated increase has a high uncertainty. The Na-ion battery technology is still under development and has multiple different chemistry mixes. As a matter of precaution, we used the average mineral intensities for Na-ion batteries. Thus, the demand for manganese and nickel could be lower than calculated under the PRO Na-ion scenario.

Table 37: Progressive Accelerated Na-ion Scenario – Development of annual mineral demand with recycling

Material Demand With Recycling		Material Demand for Energy Transition Technologies in 2024	Global Mining 2024	Share of Energy Transition Materials	Annual Material Demand in 2030 Compared with 2024	Annual Material Demand in 2050 Compared with 2024	Annual Material Demand from Mining (Zero if material is sourced entirely from mining)				
							2030	2035	2040	2045	2050
		[t/a]	[t/a]	[%]	[1]	[1]	[t/a]	[t/a]	[t/a]	[t/a]	[t/a]
Cobalt	Co	70,600	290,000	24%	1.5	0.3	103,000	112,000	36,600	0	24,300
Copper	Cu	2,808,000	23,000,000	12%	1.5	1.5	4,197,000	4,182,000	3,320,000	2,669,000	4,190,000
Graphite	Gr	1,505,000	1,600,000	94%	2.6	1.4	3,922,000	4,158,000	3,393,000	1,372,000	2,163,000
Dysprosium	Dy	1,530	1,800	85%	1.0	2.1	1,490	1,640	1,370	2,270	3,140
Lithium	Li	128,000	240,000	53%	4.2	1.2	540,000	476,000	373,000	205,000	152,000
Manganese	Mn	186,000	20,000,000	1%	5.1	13.7	951,000	1,177,000	1,183,000	1,072,000	2,547,000
Neodymium	Nd	14,600	16,000	91%	0.2	1.4	3,130	6,310	5,060	14,900	20,700
Nickel	Ni	562,000	3,700,000	15%	2.0	3.9	1,150,000	1,291,000	1,092,000	848,000	2,205,000
Vanadium	V	892	100,000	1%	60.4	47.2	53,900	112,000	104,000	70,600	42,100

Table 38: Annual mineral demand in 2050 compared with 2024 under the PRO and PRO Accelerated Na-Ion Scenario, including recycling"

	2024–2050	
	PRO	PRO-Na-ion
Cobalt	0.0	0.3
Copper	1.7	1.5
Graphite	2.2	1.4
Dysprosium	2.1	2.1
Lithium	3.6	1.2
Manganese	6.0	13.7
Neodymium	1.4	1.4
Nickel	1.7	3.9
Vanadium	102.4	47.2

The overall mineral resource requirement relative to the known mineral reserves and resources under the PRO Accelerated Na-Ion Scenario is shown in Table 39. The utilisation rate for all minerals relative to known resources is at or below 10%, whereas all currently known reserves of the analysed minerals are at or below 35%.

Table 39: Progressive Scenario – Accelerated Na-ion – development of annual mineral demand with recycling

Material Demand With Recycling		Total Material Demand Compared with Global Reserves & Resources				
		Current Global Reserves (Statistic 2024)	Current Global Resources (Statistic 2024)	Total 2024–2050	Cumulative Material Demand (Scenario) in [t] 2024–2050 versus Reserves	Cumulative Material Demand (Scenario) in [t] 2024–2050 versus Resources
		[t]	[t]	[t]	[%]	[%]
Cobalt	Co	11,000,000	25,000,000	1,907,000	17%	8%
Copper	Cu	980,000,000	3,500,000,000	99,144,000	10%	3%
Graphite	Gr	290,000,000	800,000,000	81,894,000	28%	10%
Dysprosium	Dy	1,100,000	1,980,000	57,000	5%	3%
Lithium	Li	30,000,000	115,000,000	10,462,000	35%	9%
Manganese	Mn	1,700,000,000	UNKNOWN	33,402,000	2%	UNKNOWN
Neodymium	Nd	12,800,000	23,040,000	283,000	2%	1%
Nickel	Ni	130,000,000	350,000,000	33,631,000	26%	10%
Vanadium	V	18,000,000	63,000,000	1,695,000	9%	3%

7.6 Comparison of OECM and Progressive Scenarios

The annual mineral demands under the OECM and PRO pathways are compared for the years 2030–2050 in five-year intervals. Figure 4 compares the annual mineral demand without recycling and Figure 5 includes the assumed recycling measures. The successful implementation of the PRO assumptions in the transport sector will lead to significant resource savings and will ease the pressure on the volume of total mineral extraction required between 2025 and 2050 by about a third compared to the OECM.

Finally, Figure 6 compares the lithium demand for the OECM and both Progressive scenarios with the two IEA scenarios.

The results clearly show that the recycling of materials is a necessity to reduce mineral demand to limit the mining requirement for energy transition technologies.

The significant material demand reduction between the OECM and the PRO-Na-ion Scenario – both with recycling – (see Figure 5 and Figure 6) shows that material reduction does not end with recycling. A progressive transport policy that prioritises public transport and reduces individual transport leads to less vehicles and therefore less material demand for EVs. Both Progressive scenarios successfully reduced the peak mineral demand from around 27 million tonnes under the OECM to just over 10 million tonnes.

In comparison with the PRO Scenario, the PRO-Na-ion Scenario reduced the demand for lithium even further by shifting battery technologies towards sodium ion (Na-ion) batteries.

Reducing minerals for the required energy transition to decarbonise the global economy must follow a three-step approach:

1. Maximise recycling of materials (circular economy)
2. Reduce the production volume of electric vehicles by implementing public transport and shared vehicles
3. Prioritise battery technologies with high material efficiencies and abundant minerals to reduce mining to rare or difficult-to-obtain materials.

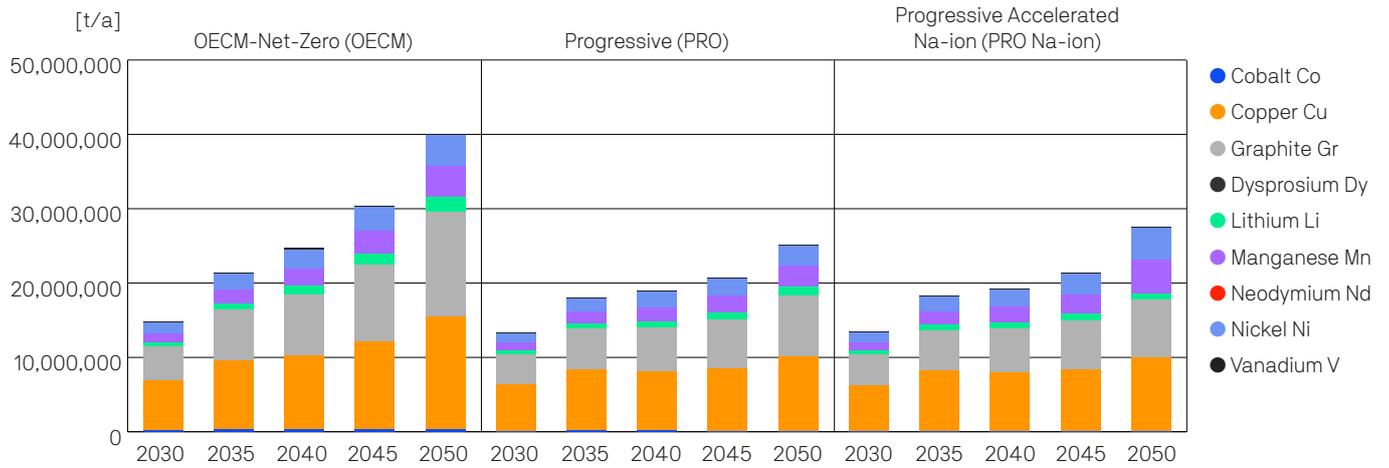**Figure 4: Annual mineral demand without recycling – comparison of scenarios**

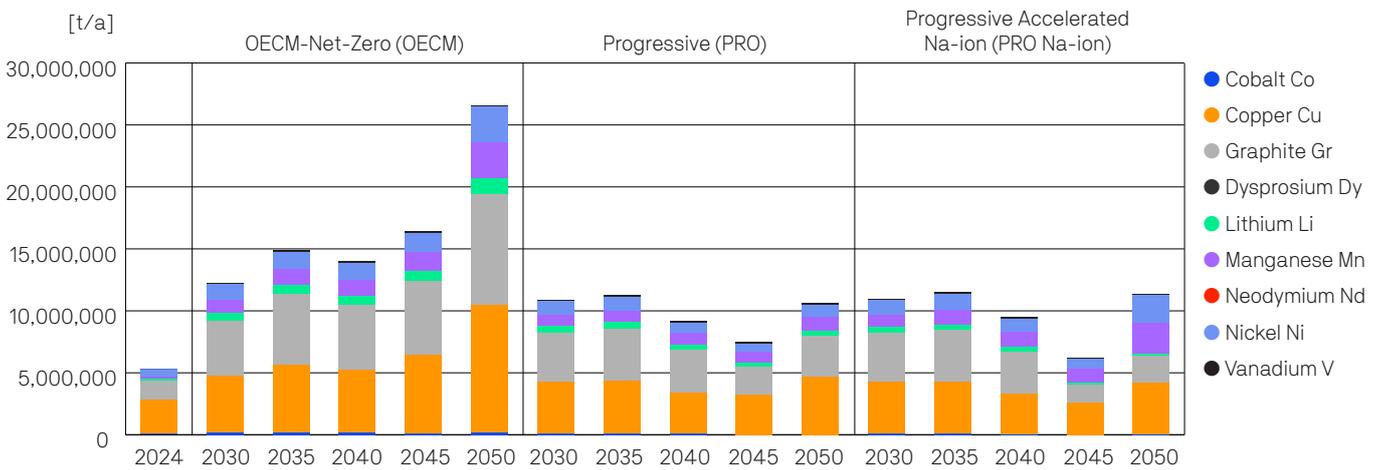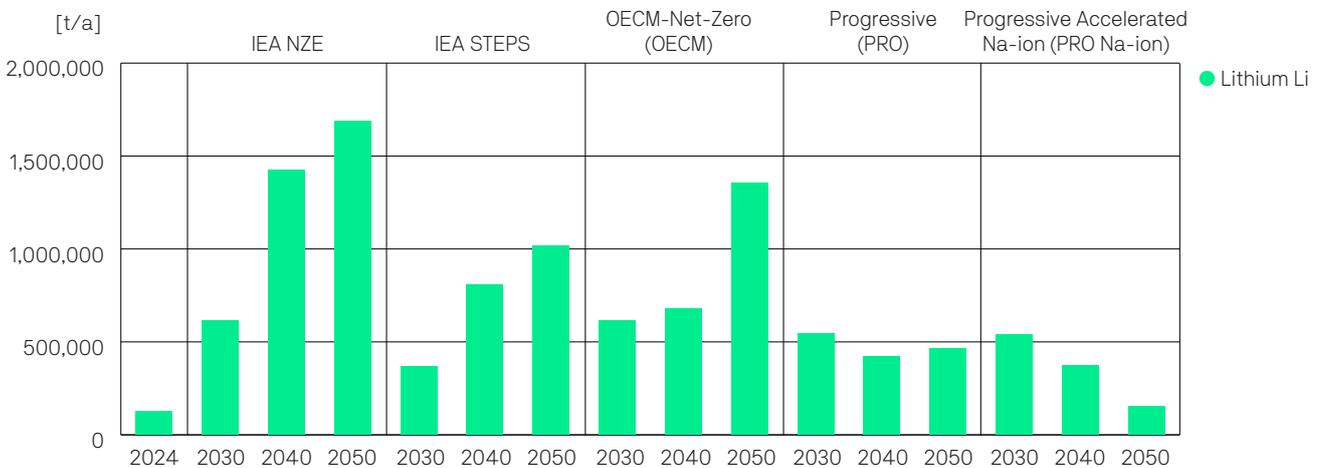**Figure 5: Annual mineral demand including recycling – comparison of scenarios**

Figure 6: Comparison of lithium demand under five different scenarios

8 Mapping Results and Discussion

Preliminary results show substantial overlap between potential mineral reserves and Restricted Areas that should be off-limits to mining. Approximately 45% of global nickel, 58% of lithium, and 27% of cobalt reserve areas may lie within such areas. Numerical details are outlined in Table 40, Table 41 and Table 42. These findings serve as a directional, high-level screening tool to inform strategic planning and policy discussions. Known limitations include incomplete datasets, variable spatial resolution, and the assumption of uniform reserve distribution across RPAs.

Despite these uncertainties, the combined methodology provides an important foundation for understanding potential conflict between the extraction of minerals for the global energy transition, and biodiversity, natural ecosystem values and nature protection as well as IP&LC rights, highlighting the urgent need to reduce mineral demand and prioritise sustainable alternatives, as shown in the scenario analysis results in this report.

Table 40: Analysis of nickel Reserve Proxy Areas located in Restricted Areas that should be off-limits to mining ("RA1")

Country	Nickel Reserve Proxy Area (RPA), total [ha]	Portion of Nickel RPA located in "RA1" [ha]	Portion of Nickel RPA located in "RA1" [%]	Nickel Reserves (Tonnes) USGS, 2025[141]	Estimated Nickel Reserves (by area) outside "RA1" [tonnes]
Indonesia	280,975	163,520	58%	55,000,000	22,991,405
Australia	179,045	32,361	18%	24,000,000	19,662,130
Brazil	49,589	13,555	27%	16,000,000	11,626,644
New Caledonia	119,320	68,956	58%	7,100,000	2,996,845
Philippines	80,987	54,134	66%	4,800,000	1,591,546
Total				**106,900,000**	**58,868,571**
Total Global Reserves				131,000,000	rounded
Portion of Total Global Reserves Represented (%)				81%	
Estimated Portion of Global Reserves Area inside RA1 (%)				45%	
Estimated Portion of Global Reserves Area outside RA1 (%)				55%	
Estimated Reserves, by area, outside RA1 (tonnes)				72,140,157	
Estimated demand for transition, Accelerated Na-ion Scenario (tonnes)				33,630,758	
Transition demand as a portion of estimated reserves outside RA1 (%)				47%	

141 USGS (2025). USGS Mineral Commodity Summaries 2025. Available at https://pubs.usgs.gov/periodicals/mcs2025/mcs2025.pdf

Table 41: Analysis of lithium Reserve Proxy Areas located in Restricted Areas that should be off-limits to mining ("RA1")

Country	Lithium Reserve Proxy Area (RPA), total [ha]	Portion of Lithium RPA located in "RA1" [ha]	Portion of Lithium RPA located in "RA1" [%]	Lithium Reserves (Tonnes) USGS, 2025[141]	Estimated Lithium Reserves (by area) outside RA1[tonnes]
Australia	38,270	7,495	20%	7,000,000	5,629,086
USA	163,914	38,278	23%	1,800,000	1,379,660
Chile	180,744	161,600	89%	9,300,000	985,032
Argentina	230,040	202,498	88%	4,000,000	478,903
China	709,798	286,325	40%	3,000,000	1,890,000
Canada	26,718	5,283	20%	1,200,000	962,715
Total				**26,300,000**	**11,325,396**
Total Global Reserves				30,000,000	rounded
Portion of Total Global Reserves Represented (%)				88%	
Estimated Portion of Global Reserves Area inside RA1 (%)				57%	
Estimated Portion of Global Reserves Area outside RA1 (%)				43%	
Estimated Reserves, by area, outside RA1 (tonnes)				12,918,702	
Estimated demand for transition, Accelerated Na-ion Scenario (tonnes)				10,461,881	
Transition demand as a portion of estimated reserves outside RA1 (%)				81%	

Table 42: Analysis of Cobalt Reserves Proxy Areas located in Restricted Areas that should be off-limits to mining ("RA1")

| Country	Cobalt Reserves Proxy Area (RPA), total [ha]	Portion of Cobalt RPA located in "RA1" [ha]	Portion of Cobalt RPA located in "RA1" [%]	Cobalt Reserves (tonnes) USGS, 2025[142]	Estimated Cobalt Reserves (by area) outside RA1 [tonnes]
Indonesia	265,780	157,208	58%	640,000	265,974
Australia	180,819	30,717	17%	1,700,000	1,411,208
DRC*	249,694	60,772	24%	6,000,000	4,539,695
Philippines	73,872	48,514	66%	260,000	89,248
Total				**8,600,000**	**6,301,593**
Total Global Reserves				11,000,000	rounded
Portion of Total Global Reserves Represented (%)				80%	
Estimated Portion of Global Reserves Area inside [RA1] (%)				73%	
Estimated Portion of Global Reserves Area outside [RA1] (%)				27%	
Estimated Reserves, by area, outside [RA1] (Tonnes)				8,065,973	
Estimated demand for transition, Accelerated Na-ion Scenario (Tonnes)				1,906,515	
Transition demand as a portion of estimated reserves outside [RA1] (%)				24%	

*The USGS Commodity Summaries refers to this area as Congo (Kinshasa)

As noted earlier in this chapter, the analysis of local and regional contexts necessitates a more detailed examination of the available data, because the current findings are only applicable in aggregate, at the global level. For illustrative purposes, the mapping in Indonesia, one of the case study areas, is shown in Figure 7. In this region, approximately 58% of the nickel and cobalt Reserves Proxy Areas are in Restricted Areas (RA1).

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142 USGS (2025). USGS Mineral Commodity Summaries 2025. Available at https://pubs.usgs.gov/periodicals/mcs2025/mcs2025.pdf (accessed December 2025)

Figure 7: Example of mapping results in Indonesia showing Restricted Areas "RA1" (green = includes Restricted Areas, including by Default and by Values) and Reserve Proxy Areas (blue = cobalt, grey = nickel)
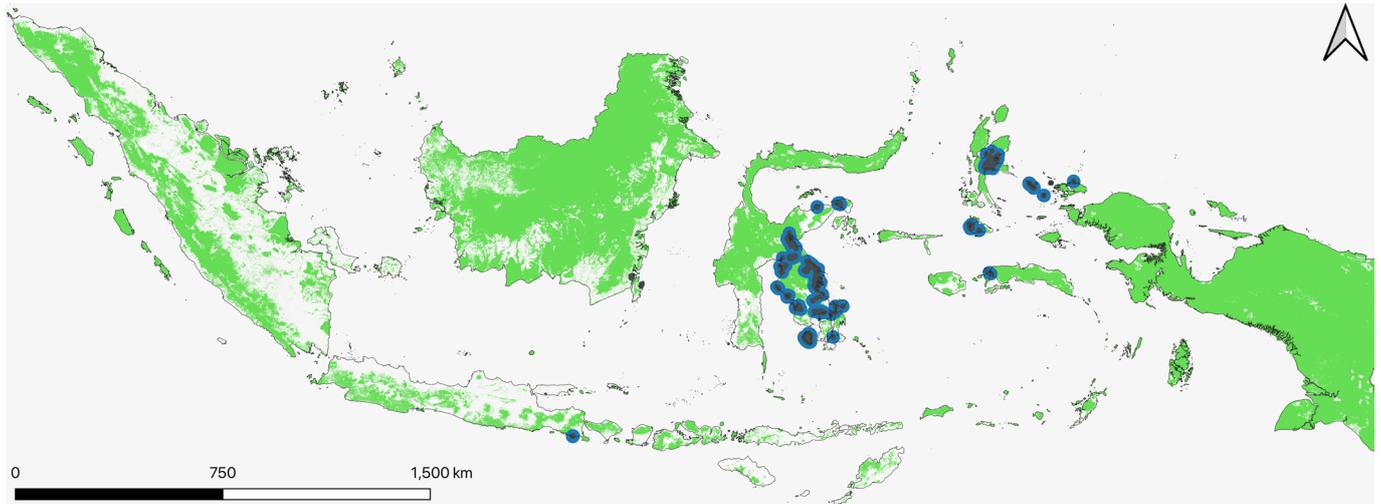
9 Policy recommendations
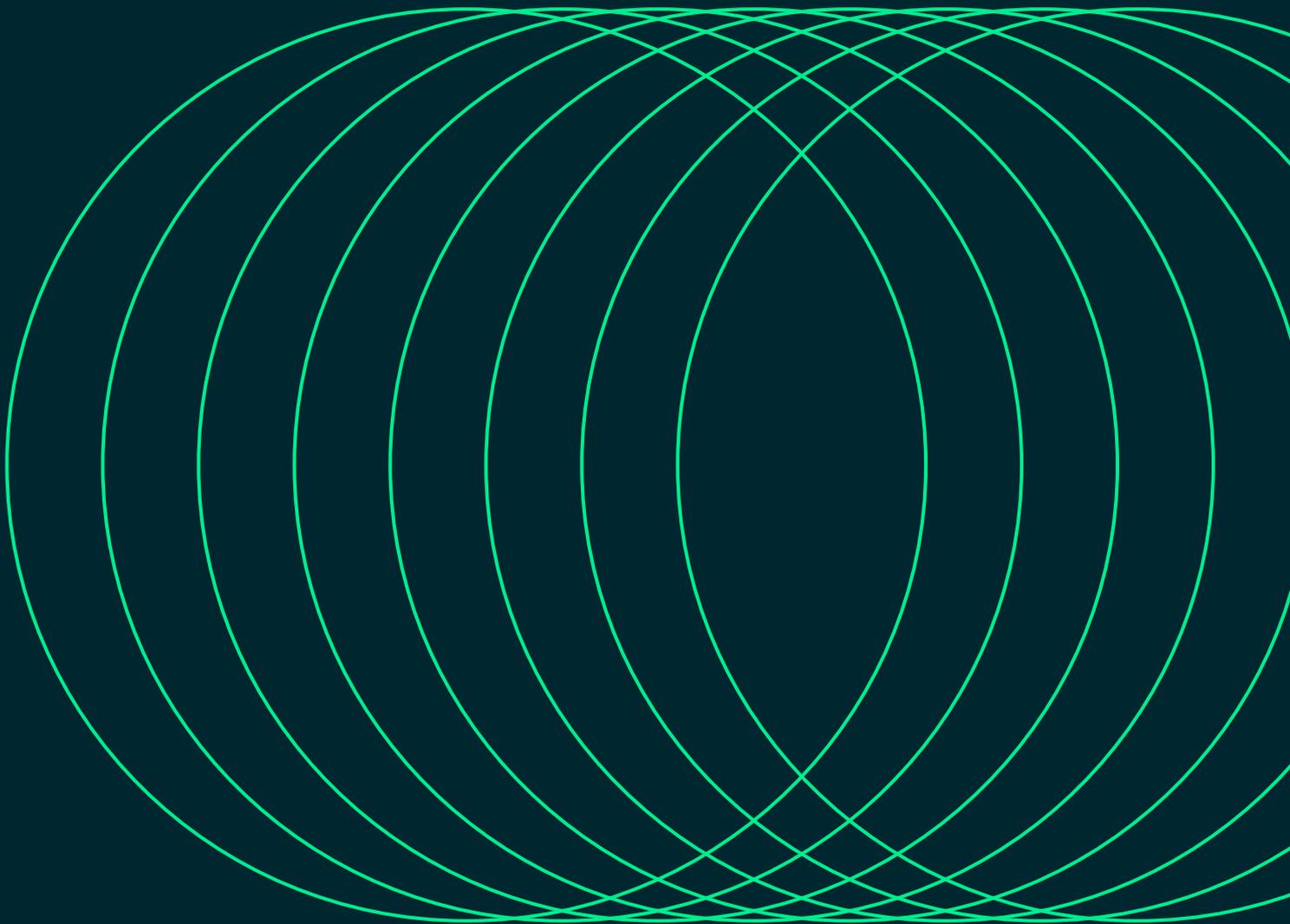
As this study shows, demand for transition minerals, even among 1.5-degree aligned scenarios, varies significantly depending on assumed future choices made.

In other words, future demand is not fixed: the decisions governments, industries, and communities make, both now and in the coming decades, can meaningfully reduce mineral demand for energy transition minerals. This would limit the amount of future mining required to deliver an energy transition and help to avoid the need to mine in areas of critical environmental importance. Based on the findings of this research, five key interventions are required for a green and just energy transition with less minerals:

1. Reduce mineral demand through investment and delivery of shared mobility systems like improved public transport and smaller, more efficient cars

Shifting towards shared mobility systems is one of the most effective ways to reduce the need for mineral-intensive electric vehicles and the batteries that power them. Expanding high-quality public transport, car-sharing schemes and other forms of convenient mobility can significantly decrease reliance on individual car ownership. Complementary measures such as right-sizing batteries, avoiding unnecessarily large vehicles (e.g. SUVs in cities) and improving vehicle efficiency, also contribute to reduced mineral demand.

2. Incentivise battery technology substitution towards alternatives requiring less lithium, cobalt, or nickel

Technological innovation over the last decade has transformed the mobility and energy storage battery markets. Lithium iron phosphate (LFP) batteries, now widely commercialised, eliminate the need for cobalt and nickel, reducing pressure on these supply chains. At the same time, sodium-ion (Na-ion) batteries are advancing rapidly, and because they do not require lithium or cobalt, they offer a pathway to significantly reduce mineral demand for lithium. Further market growth of these and other emerging chemistries (e.g. redox flow batteries) in the coming years, as outlined in the Progressive- Battery scenarios, can significantly reduce supply gaps and ease potential development pressures for new mines. Innovative energy storage systems that do not require these key minerals, could further reduce the need for batteries in the electricity grid.

3. Design for circularity and scale up recycling

By maximising collection and the recovery of transition minerals from end-of-life renewable technologies, recycling can significantly reduce the need for new extraction. Investing in advanced recycling technologies and collection systems, alongside policy incentives that reward high recycled mineral content, can ensure that transition minerals re-enter the supply chain. All scenarios in the study show significant reductions in primary demand when ambitious recycling assumptions are included. Additional circularity measures like extending technologies' lifespans, improving repairability, incentivising reuse, designing products for easy disassembly, standardising components, and enforcing extended producer responsibility (EPR), while not part of the mineral resources calculation model, could also contribute to reducing overall mineral demands.

4. Prioritise mineral use for essential energy transition needs

Minerals are finite resources, and mining for them carries significant social and environmental risks. Therefore, the use of mineral resources should be prioritised where they matter most - with renewable energy applications to phase out fossil fuels being a major part of that. This study focuses on the mineral demands for energy transition, however demand from other uses often compete for the same limited supply. Governments and industries must steer minerals toward critical energy transition infrastructure and other vital uses. Coupled with supply chain transparency, prioritising minerals for energy transition ensures finite minerals are used to advance climate goals that benefit all people and the planet.

5. Protect key 'Restricted Areas' from mining development

Protecting human rights and ecological integrity is a non-negotiable foundation of a just and green transition. Restricted Areas (RA) have critical environmental, ecological and natural values, and Indigenous Peoples and Local Community (IP&LC) territories. Defining and protecting these RAs is a crucial step in ensuring that mining of transition minerals does not compromise the safeguarding of biodiversity, ecosystem services, natural carbon storage, freshwater systems, oceans and respecting the rights of IP&LC. Protecting these areas is essential to staying within the Earth's planetary boundaries[143] and to prevent the energy transition from repeating the injustices of past extractive models, with Free, Prior and Informed Consent from IP&LC as a key prerequisite of any mining development.

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143 Planetary Boundaries Science (PBScience). 2025. Planetary Health Check 2025. Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany. https://publications.pik-potsdam.de/rest/items/item_32589_5/component/file_33151/content

Institute for Sustainable Futures

University of Technology Sydney
PO Box 123 Broadway, NSW 2007

www.isf.uts.edu.au