WHERE SHOULD METALS FOR THE GREEN TRANSITION COME FROM?

Comparing Environmental, Social, and Economic Impacts of Supplying Base Metals from Land Ores and Seafloor Polymetallic Nodules

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ACKNOWLEDGEMENTS

Much of the information we would like to have not only about the deep sea but also about terrestrial environments remains unknown. Consequently, our conclusions involve numerous assumptions and estimations. All errors are solely the responsibility of the authors, and we look forward to receiving notice of any that readers may find.

This cross-disciplinary study combines insights and data from the mining and manufacturing sectors, industrial ecology, terrestrial ecology and marine ecology. Few are fluent in all of those areas, including the authors. However, thanks to everyone mentioned above, we have grown in our understanding and we hope that readers of this document will also. Decisions of the scale contemplated here require all of us to learn and collaborate beyond our usual boundaries in seeking paths that best serve people and the planet.

FOREWORD

We have reviewed the paper titled "Where Should Metals for the Green Transition Come From?" by authors D. Paulikas, S. Katona, E. Ilves, G. Stone and A. O'Sullivan (the paper), as well as cited and supporting literature on metal life cycle analyses and the environmental and social impacts of metals.

In our opinion, the paper provides a comprehensive consideration of the environmental, social and economic impacts associated with land and deep-sea mining of metals used in electric vehicles. While we have noted below several caveats and considerations for readers of the paper, we find that the authors have selected an appropriate and objective methodology for analysis of the environmental, social and economic impacts of these metal mining alternatives. We have also found the paper to be transparent with regard to the methods and tools used in the life cycle analysis as well as with the assumptions underlying the analysis.

The authors have clearly and appropriately defined the scope and boundary of the analysis, for example normalizing impacts against economic value of metals (as opposed to normalization to mass), which gives a more decision-useful output by which readers can compare the relative social and environmental impacts of the two sources of metals.

The results are potentially important as they indicate a scenario whereby a low-carbon transition can be globally accelerated with less damage to land and other impacts than would occur in the ocean, with the only concern being relative biodiversity impact. As the encouraging spider chart (Figure 34) and Table 11 indicate, those impacts appear to be not worse than would otherwise occur on land, though further research and analysis would improve confidence. In addition, the apparent lack of plant life on the seafloor in the Clarion-Clipperton Zone suggests that nodule-removal techniques could be developed to encourage mobile forms of life on the ocean floor to relocate, such as through the use of strategic strobe lighting (for one hypothetical example). This might be a useful area of research to consider for minimizing biodiversity loss to even further improve the indicated scenario (Category 3: Biodiversity) of several magnitudes of species lower than land, with no plant life likely to be damaged.

Readers should bear several things in mind when using the results of the analysis to make decisions on the relative impacts and benefits of land-based and deep-sea-based mining:

1) *The life cycle analysis (LCA) results are relative and not absolute.* The authors acknowledge this fact early and often in the paper. The results are meant to compare the relative impacts of the three scenarios (onshore "as-is" mining of land ores, onshore "green" mining of land ores and offshore collection of polymetallic nodules). As an example, all of the scenarios assume that metals are used in the manufacture of batteries for electric vehicles with associated chemical specifications and processing requirements. This assumption is consistent across all three scenarios.

2) *Biodiversity is acknowledged in the paper as the most significant impact of nodule collection and is treated qualitatively in the paper.* Because biodiversity impacts are treated qualitatively, it is difficult to say with certainty that biodiversity and species impacts from deep-sea nodule collection would be less significant than those observed and measured on land. This uncertainty is exacerbated by two assumptions acknowledged by the authors. First, while it is likely that the number of species is more limited in the deep-sea plateau where nodule collection would occur, much remains unknown with regard to the number and type of species that live in or depend on this ecosystem, and where a majority of sea-based animals more generally remain unidentified. Second, the paper does not assess biodiversity impacts on a time-dependent basis. This is particularly important when considering mine remediation. While some land-based mines can be, to some

extent, remediated, resulting in eventual regeneration of ecosystems and species habitats, the time for recovery of deep-sea ecosystems following nodule collection is unknown and likely to be longer than land-based benchmarks.

3) *Potential regulation variability is a likely scenario to further consider.* While the paper makes some effort to incorporate the benefits of social and environmental regulation (or the impacts from lack of regulation), it does not assess the relative stringency of regulations between land-based mining (predominantly governed by national governments) and deep-sea nodule collection (predominantly governed by international treaty) and the associated oversight of mining activities by regulatory authorities to ensure compliance.

4) *While the assumptions of the paper are universally reasonable, some are unsupported by data.* For example, the authors assess relative impacts to ecosystem services from mining activities. The authors acknowledge that there may be some linkages between deep-sea ecosystems and species and ecosystem services and posit that these linkages are likely to be small or very small. Similarly, the authors posit that onshore processing facilities for nodule projects can be sited in locations more conducive to green energy (for example) because of the inherent flexibility of sea-based ore transport. While there is currently no guarantee that a given company will choose to take advantage of green energy or other, more sustainable opportunities, future research could be focused on the incentives to promote these opportunities in processing-facility site selection.

Overall, we find the paper to be a valuable contribution to the literature and groundbreaking in its analysis of the relative environmental, social and economic impacts of land mining and deep-sea nodule collection.

The methodology, including LCA tools employed, scope and boundary setting, and critical assumptions are clearly presented.

While uncertainty remains in some areas that may be relevant for decision-makers, in aggregate, the conclusions seem well supported by the combination of data (greenhouse gas intensity of the analyzed mining scenarios, social capital impacts and nonliving resource system impact estimations) and qualitative analysis (biodiversity and analysis of ecosystem services impacts).

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EXECUTIVE SUMMARY

We make our world by extracting almost a hundred billion tonnes of resources from the planet every year.[1] Our relentless resource extraction has generated negative externalities on a global scale—we have changed our land, our oceans and our atmosphere to a point where the future livability of the planet for humans is now in question.

The impacts of fossil fuel extraction and use—accounting for 16% of annual resource takeout—are now well understood.[2] Burning fossil fuels helped usher in the industrial age and generated unprecedented level of greenhouse gases that tipped the earth out of climate balance. The planet has warmed by more than 1°C since preindustrial levels, global sea levels have risen by 25 centimeters, extreme weather events are on the rise and 7 million people die every year from air pollution.[3] As a global community, we have set a goal to limit global heating to 1.5°,[4] and we hope to achieve this by reducing carbon dioxide equivalent (CO_2e) emissions by 45% below 2010 levels by the year 2030 and reaching net zero by 2050.[5] This plan requires both a radical transformation in how we power and transport our civilization, as well as actively pulling gigatonnes of CO_2 out of the atmosphere. To stay below 1.5°C, every gigatonne of CO_2 matters. The scale of the green transition is monumental, the timeline daunting.

What is less well understood is that the rapid buildout of green technologies will require a massive new injection of metals. Today we produce metals by mining and processing ore bodies—another resource-extraction activity that generates global-scale negative externalities and presents a direct threat to the planet. While burning fossil fuels puts 37 billion tonnes of CO_2e waste into our atmosphere every year,[6] metal production generates over 350 billion tonnes of waste. Some of this waste is toxic, and it ends up in our soil, our rivers, our air, our ocean and our bodies—it is the biggest waste problem on the planet.[7]

Metal production is an energy-intensive process that accounts for 11% of global energy use and a material portion of the annual carbon footprint—a significant contributor to the climate crisis in its own right.[8] Tens of thousands of square kilometers of forests are cleared every year to access metal ore bodies, leading to habitat destruction and biodiversity loss. Mining of metals required for the green transition is increasingly moving to some of the most biodiverse places on the planet (see Biodiversity section). Mining also remains one of the most hazardous occupations in the world, with miner deaths reported on a weekly basis.[9] If we produce metals for the green transition the way we have been producing them so far, we will in effect be shifting the environmental and social burden from fossil fuels to metals.

So, what can we do? To explore the environmental, social and economic impacts of producing metals required for the green transition, we chose to focus on transport. Electrifying the global passenger fleet is a core aspect of the global strategy to tackle the climate crisis, as greenhouse gas emissions from car tailpipes are one of the fastest-growing sources of emissions, now accounting for about 15% of annual global emissions.[10] Some analysts expect the global electric vehicle (EV) fleet to surpass one billion vehicles by 2047 from a low base of about five million EVs today.[11] Compared to conventional vehicles, EVs will require much more copper for electric connectors and much more metals like nickel, manganese and cobalt for battery cathodes. The impacts are material—life cycle assessment shows that the replacement of the internal combustion engine with an EV battery almost triples the CO_2e emissions from vehicle manufacturing, thereby negating the gains from reducing tailpipe emissions.[12]

If the goal is to produce the world's greenest, most ethical EVs, and to reduce the harm imposed by the green transition itself, where should EV manufacturers

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1 See the United Nations International Resource Panel's 2019 Global Resources Outlook - (Oberle, et al., 2019).

2 (Oberle, et al., 2019).

3 See (IPCC, 2018) and (WHO, 2019).

4 See Paris Agreement - (UN, 2015).

5 (IPCC, 2018).

6 (IPCC, 2018).

7 (Blight, 2011).

8 (IPCC, 2014).

9 (Stewart, 2019).

10 (IPCC, 2014).

11 (Morgan Stanley, 2017).

12 (Hausfather, 2019).

source their base metals? All base metals going into EV batteries are currently produced from land ores but there are two alternatives: secondary metals (i.e., recycled metals), and ocean minerals (e.g., polymetallic seafloor nodules).

The first option—recycling metal stocks already in use—is the most promising and responsible solution in the long term as it would help eliminate several categories of environmental and social impacts caused by primary mining. However, it will take decades to build up the primary stock of metals that will make mass-scale EV metal recycling possible. In the meantime, we are forced to revisit the primary sources of metals on land and in the ocean to fill up the stocks with the least environmental, social and economic impact.

Land mining can become greener: equipment and transport could be electrified, more renewables could be brought into the power mix, mechanization and automation could reduce miner deaths, and process innovations could reduce resource use and toxic spills. But the industry is also facing structural challenges: the ore grades are falling; target ore bodies are embedded in hard rock and are increasingly difficult to access; land ores often contain toxic levels of heavy elements.

The oceans are filled with metals, presenting as seafloor massive sulfides (SMS), cobalt crusts, polymetallic nodules and seabed sediments. They have never been mined on a commercial scale, and plans to develop these ocean resources have been met with opposition from ocean-conservation NGOs concerned about disruptions to seabed ecosystems and inhabitants. For the purposes of this report, we chose to focus on polymetallic nodules for several reasons: (1) nodules sit unattached on the ocean floor in the area of the South Pacific international waters known as the Clarion-Clipperton Zone (CCZ), which means they can be collected without the need for destructive rock cutting required for mining SMS and cobalt crusts; (2) nodules are high grade and do not contain toxic levels of heavy elements, and the metal contents of the nodules is uniquely aligned with the base metal needs of EV battery manufacturers; (3) the CCZ nodule resource alone contains enough metals to electrify the global EV fleet several times over.

In this report, we compare the cradle-to-gate impacts of these two imperfect sources—land ores and seafloor polymetallic nodules—to supply the transitional demand for the four base metals used in manufacturing EV battery cathodes and wiring: nickel, cobalt, manganese and copper. For land ores, we explore "as-is" and "green mining" scenarios. For nodules, we look at a basic future production scenario without taking into account further improvements that could be available to future developers of nodule resources in the CCZ.

We leverage several scientific standard methodologies for assessing sustainability impacts, including:

- **Cradle-to-gate life cycle assessments (LCA)** of each metal, considering a scenario of a possible future world of one billion EVs by 2047 to contextualize the environmental impacts.

- **A life cycle sustainability assessment (LCSA)** that broadens the LCA to include future supply-and-demand projections as well as economic and social impacts.

- **Ecosystem services (ES) analysis** of impacts to ecosystems' abilities to directly and indirectly contribute to sustained operation of natural systems and their continued flow of benefits to humans.

Using these methods in combination with extensive literature review and analysis, the paper compares the impacts of producing metals for one billion EVs across climate change, nonliving resources, biodiversity, and social and economic impacts.

Notably, high-fidelity models were created to quantify the global warming potential (GWP) and several other important indicators. For land ores, results were derived from models documented in existing literature. For nodules, results were derived from a new LCA model developed for the purpose of enabling like-for-like comparisons. Data for the nodules model was sourced from detailed operating concepts, engineering models, CCZ survey data, preliminary economic assessments, comparables from literature and industry benchmarks.

To help the reader understand the drivers behind the models, this paper also provides a comparative overview of processes involved in mining and processing of these four metals on land and collecting them from the CCZ seabed, along with a discussion of key drivers of environmental, social and economic impacts.

Environmental, social and economic impacts

	Cradle-to-gate production of nickel sulfate, manganese sulfate, cobalt sulfate and copper cathode Serving size **1 billion electric cars**		
	Land	**Nodules**	**% change**
Climate change			
GWP - CO_2 equivalent emissions, Gt	1.5	0.4	**-70%**
Stored carbon at risk, Gt	9.3	0.6	**-94%**
Nonliving resources			
Ore use, Gt	25	6	**-75%**
Land use, km^2	156,000	9,800	**-94%**
Incl. Forest use, km^2	66,000	5,200	**-92%**
Seabed use, km^2	2,000*	508,000	**+99.6%**
Water use, km^3	45	5	**-89%**
Primary and secondary energy extracted, PJ	24,500	25,300	**+3%**
Waste streams			
Solid waste, Gt	64	0	**-100%**
Terrestrial ecotoxicity, 1,4-DCB equivalent Mt	33	0.5	**-98%**
Freshwater ecotoxicity, 1,4-DCB equivalent Gt	21	0.1	**-99%**
Eutrophication potential, PO4 equivalent Mt	80	0.6	**-99%**
Human & wildlife health			
Human toxicity, 1,4-DCB equivalent Mt	37,000	286	**-99%**
SOx and NOx emissions, Mt	180	18	**-90%**
Human lives at risk, number	1,800	47	**-97%**
Megafauna wildlife at risk, trillion organisms	47	3	**-93%**
Biomass at risk, Mt	568	42	**-93%**
Biodiversity loss risk	Present	Present	
Economic impact			
Nickel sulfate production cost, USD per tonne Ni	14,500	7,700	**-47%**
Jobs created (non-artisanal), worker-years	600,000	150,000	**-75%**

As summarized in the figure above, our analysis produced the following results:

- **Climate change** impacts would be significantly reduced by producing metals from polymetallic nodules. GWP is much higher when producing metals from land ores, even in the green mining scenario. Carbon sequestration is greatly impacted by land mining, while models of potential ocean-based mechanisms show expected nodule-collection impacts to be low.

- **Nonliving resource** impacts such as use and pollution of land, forests, water and soil would be far more substantial with land-ore mining. Producing metals from nodules would eliminate solid waste generation and would significantly reduce ecotoxicity, eutrophication potential as well as SOx and NOx emissions. A notable exception is seafloor use where nodules would impact a much larger area than what would be impacted by land mining through deep-sea placement of tailings. Due to the two-dimensional

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nature of the nodule resource, producing metals from nodules would impact an area of seabed more than three times larger than the land area that would be impacted by metal production from land ores. It is important to keep in mind that there are many competing uses and pressures for land (e.g., carbon sinks, agriculture, natural reserves) while disruption from nodule collection would likely be the only disruptive use of the CCZ seabed.

- **Biodiversity** impact lacks a single, established, unifying metric for comparison. As with mining on land, the risk of biodiversity loss will likely remain present in case of nodule collection. Given the CCZ seabed is a food-poor and sparsely populated environment, the megafauna population at risk from nodule collection—a key metric usually assessed for new mining projects on land—is expected to be much lower compared to megafauna populations that would be impacted by mining on land. However, not enough is currently understood about the functioning of the CCZ seabed ecosystems and the role played by different species to make definitive statements about biodiversity impacts.

- **Social impact** would be significantly lower in case of metal production from nodules—with substantially lower expected fatalities, injuries, illnesses, impacts to vulnerable populations and human toxicity potential.

- **Economic impact** outcomes are expected to be overall better when producing metals from nodules. Nickel, manganese and copper produced from nodules are expected to sit in the bottom quartile of their respective production cost curves. Metal production from nodules would create fewer but safer jobs. The effect of a broadened supply of manganese may be significant, and outcomes will depend on reactions from industry players, states, international authorities and product innovators.

As with planning and modeling for any scenario, these results are based on a specific set of assumptions that can and should be challenged and developed further. At a minimum, we hope that our analysis serves to:

- Spotlight the need to carefully consider the global impacts of resource extraction in general and the impacts of the green transition in particular, so we avoid merely shifting the environmental, social and economic burdens from one type of resource to another.

- Create awareness of how base metals are produced today from land ores and how they could be produced from polymetallic seafloor nodules in the near future.

- Provide a framework for discussion around the impacts of metal production that is productive and comprehensive.

- Contribute to LCA literature with an impact study of producing four base metals from polymetallic nodules.

We also hope our work helps frame the conversation and the difficult choices ahead for society to source metals for the green transition responsibly, ethically and with minimal extra emissions load on the planet. The impacts of our relentless resource extraction are global and systemic. To minimize and avoid further impacts on the planet, wildlife and humans, our thinking about future resource development needs to become global and systemic as well.

ACRONYMS

AUV	Autonomous underwater vehicle
CCZ	Clarion-Clipperton Zone
Cd	Cadmium
CED	Cumulative energy demand
CIF	Cost, infrastructure, and freight
Co	Cobalt
CML	Centrum voor Milieuwetenschappen (Institute of Environmental Sciences)
CO$_2$	Carbon dioxide
CO$_2$e	CO$_2$ equivalent
Cu	Copper
DALY	Disability-adjusted life year
DB	Dichlorobenzene
DMTU	Dry metric tonne unit
DRC	Democratic Republic of the Congo
DSTP	Deep sea tailings placement
EMM	Electrolytic manganese metal
EMSA	European Marine Safety Agency
ES	Ecosystem services
EV	Electric vehicle
GEO	Global environment outlook
GHG	Greenhouse gas
Gt	Gigaton
GWP	Global warming potential
HPAL	High-pressure acid leaching
ICE	Internal combustion engine
IEA	International Energy Agency
ILO	International Labour Organization
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
ISA	International Seabed Authority
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LCO	Lithium-cobalt-oxide
LCSA	Life cycle sustainability assessment
Mn	Manganese
MPA	Marine protected area
Mt	Megaton
Ni	Nickel
NMC	Nickel-manganese-cobalt
NOx	Nitrogen oxides
Pb	Lead
PGE	Platinum-group elements
PO4	Phosphate
SMS	Seafloor Massive Sulfides
SO$_2$	Sulfur dioxide
SO$_4$	Sulfate
SOx	Sulfur oxide
TEEB	The Economics of Ecosystems and Biodiversity
UN	United Nations
UNEP	United Nations Environment Programme
USGS	United States Geological Survey
UN	United Nations
USES	Uniform System for the Evaluation of Substances
VSL	Value of statistical life
WEF	World Economic Forum
WEO	World Energy Outlook
Zn	Zinc

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I. MOTIVATING THE ANALYSIS

CLIMATE AND WILDLIFE CRISES

In May 2019, the measurement of carbon dioxide (CO_2) in the atmosphere surpassed 415 parts per million. This is higher than at any point in at least the past 800,000 years (see Figure 1).[13]

CO_2 molecules trap thermal infrared energy continuously radiated by earth's land and ocean surfaces as they are warmed by sunlight in a process similar to a greenhouse: light enters through the glass, is degraded to infrared heat, and the heat is trapped by the glass, allowing plants to grow in a warmer environment than outside. Another analogy is fireplace bricks that continue to emit heat after the fire goes out. A certain level of carbon dioxide and other greenhouse gases is critical for maintaining planetary temperatures that can sustain life—

without greenhouse gases, earth's average annual temperature would drop below freezing.

But unprecedented levels of greenhouse gases generated by humans burning fossil fuels "have tipped the Earth's energy budget out of balance, trapping additional heat and raising Earth's average temperature."[14] The consequences are here for everyone to experience: the planet has warmed by over 1°C since preindustrial levels, and global sea levels have risen by 25 centimeters. We are experiencing more extreme weather events, more extreme flooding, coral bleaching and die-offs, and collapsing fish populations. (See Figure 2 and Figure 3 for data and visualizations of recent changes in global surface temperatures.)

Figure 1. Atmospheric CO_2 Concentration: Historical Through August 13, 2019 (parts per million)[15]
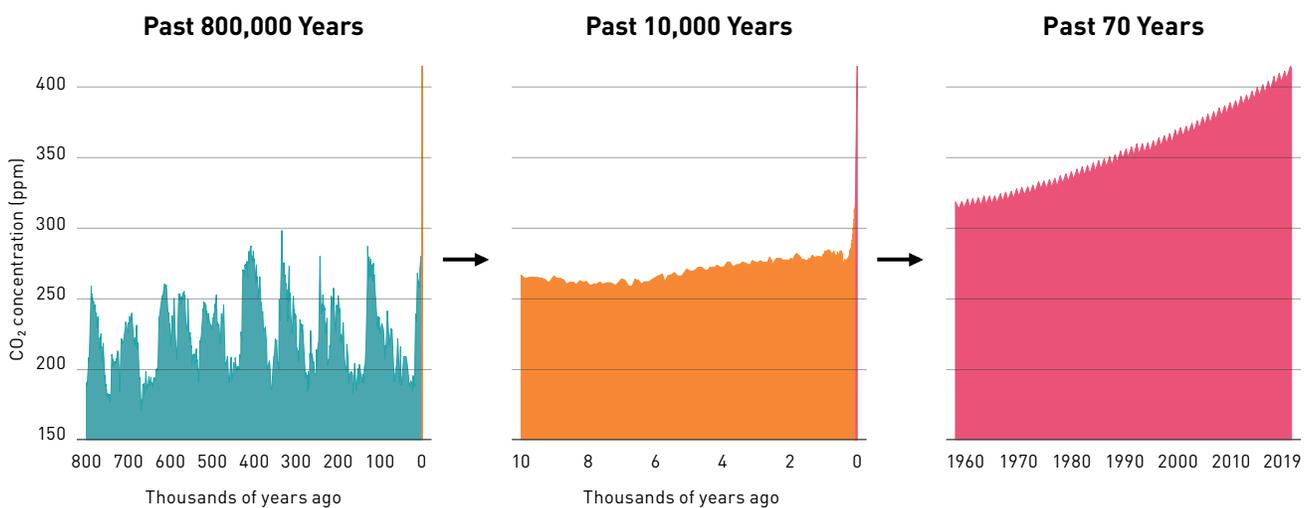
Increases in atmospheric carbon dioxide are responsible for about two-thirds of the total energy imbalance causing global warming (see Figure 4). To put human CO_2 additions into context: each day,

each person on earth puts one pound of solid trash into a landfill and 31 pounds of CO_2 trash into the atmosphere.[16] We have essentially turned the thin sliver of earth's atmosphere into a landfill for CO_2.

13 (The Keeling Curve, 2019).

14 (Lindsey, 2018).

15 Source: The Keeling Curve from Scripps Institution of Oceanography (The Keeling Curve, 2019). Provides 800,000 years' analysis, 10,000 years' analysis, and full record since 1958. Latest CO_2 readings as of May 18, 2019. Green line indicates 415.02 parts per million. Left and middle: ice core data before 1958, Mauna Loa data after 1958. Right: CO_2 concentration at Mauna Loa Observatory.

16 (Innovations in Energy Storage, 2019).

Figure 2. Human Activity, Global Surface Temperatures, and Sea-Level Increase[17]

Global GDP
A hundred-fold increase

Global energy use
A twenty-fold increase

Global surface temperature
A 1°C increase

Global sea level
A 25 cm increase
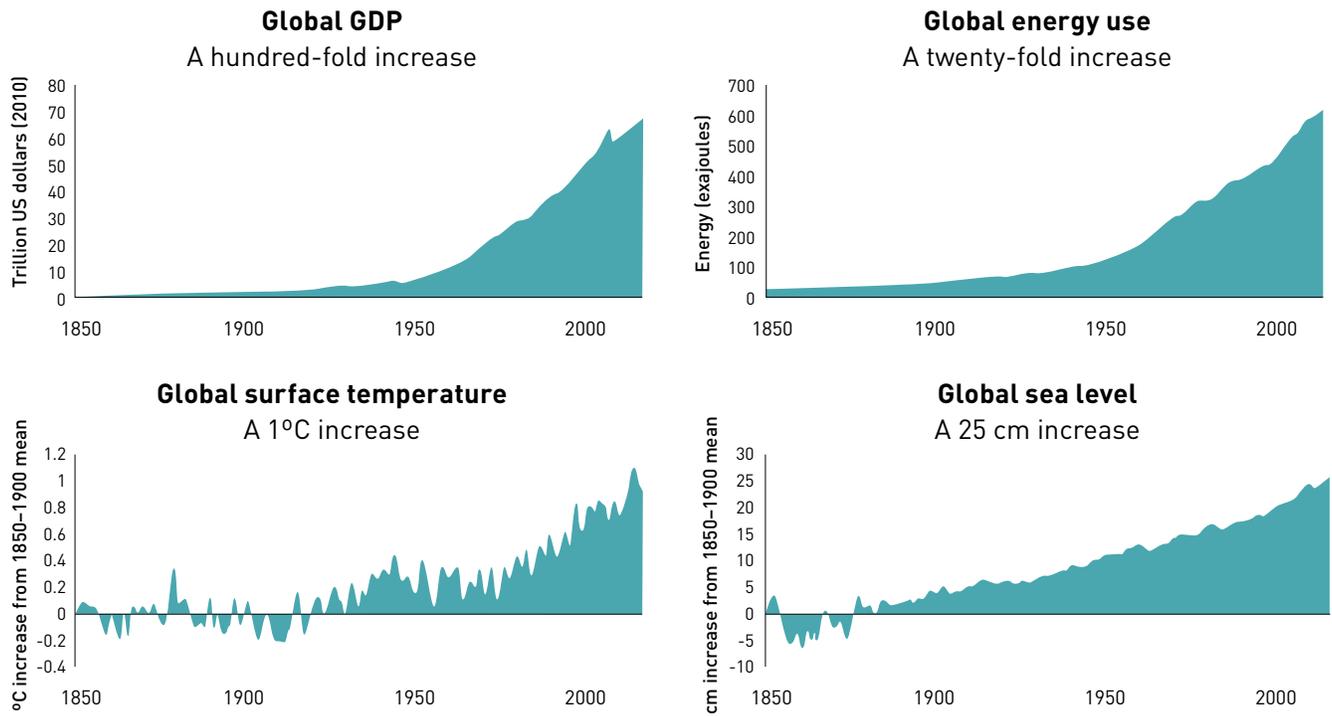
Figure 3. Annual Global Temperatures, 1850-2017[18]
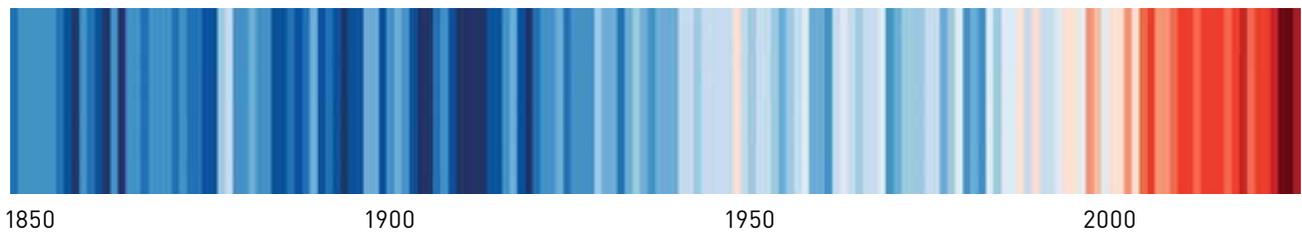
The scale represents the change in global temperatures, covering 1.35°C, with the color of each stripe representing a single year.

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17 Source: (Azhar, 2019).

18 The graphic shows relative changes in average global temperatures from 1850 to 2017, compared to a pre-industrial baseline. Each stripe represents average global temperatures for a single year. Darkest blue indicates the baseline value, while darkest red represents the largest relative increase of 1.35°C with respect to that baseline. See (Climate Lab Book, 2018) for more images; dataset is available at (Met Office, 2016).

Human activities producing this CO_2 increase, including mining and the burning of fossil fuels, present direct threats to the planet's biodiversity. According to a landmark global assessment of biodiversity and ecosystem services (ES) compiled by 145 authors from 50 countries, out of an estimated 8.7 million to 20 million species on earth (only 1.8 million of which have been scientifically described), 1 million species are now at risk of extinction due to these activities. With 75% of land environments altered by human actions, the average abundance of native land-based species has fallen by around 20% since 1900, and 9% of terrestrial species have insufficient habitats for long-term survival without habitat restoration. Climate change is impacting nature from ecosystems to genetics. According to the co-chair of the landmark assessment, "Humanity's most important life-supporting safety net [is] stretched almost to breaking point."[19]

Increases in carbon dioxide and temperature have hit the oceans disproportionately hard. First, the temperature increase itself impacts both marine life and human civilization. Over 90% of excess heat in the earth's system is absorbed by the ocean.[20] Increased ocean heat resulting from increased CO_2 naturally contributes to sea-level rise, and for low-lying island nations that rely on the oceans for survival this is an existential threat. The heat change furthermore impacts the natural habitat of marine life. Ocean heat content is therefore essential for understanding and modeling global climate (see Figure 5). Second, there is impact from the carbon dioxide itself as it interacts with the ocean. Carbon dioxide dissolves into the ocean like the fizz in a can of soda, reacting with water molecules to produce carbonic acid and thereby lowering the ocean's pH, leading to ocean acidification. Since the start of the Industrial Revolution, the pH of the ocean's surface waters has dropped from 8.21 to 8.10. This may seem small, but the pH scale is logarithmic, so a one-unit drop in pH means a tenfold increase in acidity; the 0.1 change we have observed means acidity has increased roughly 30%. This increased ocean acidity has directly affected marine ecosystems, for instance, in the ability of marine life to extract calcium from the water to build shells and skeletons (see Figure 6).[21]

Figure 4. Influence of All Major Human-Produced GHGs (1979–2018); 43% Increase Since 1990[22]
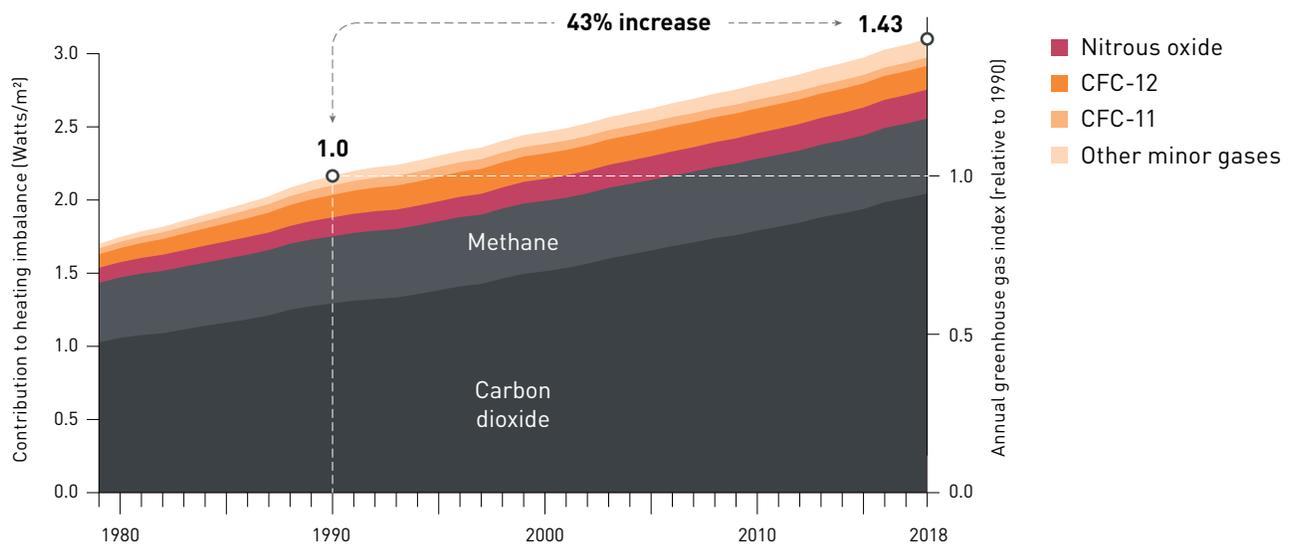
19 (IPBES, 2019).

20 (NOAA, 2019).

21 (Lindsey, 2018).

22 Source: (Lindsey, 2018).

Figure 5. Global Ocean Heat Content (Left) and Total Steric Sea-Level Anomaly (Right)[23]
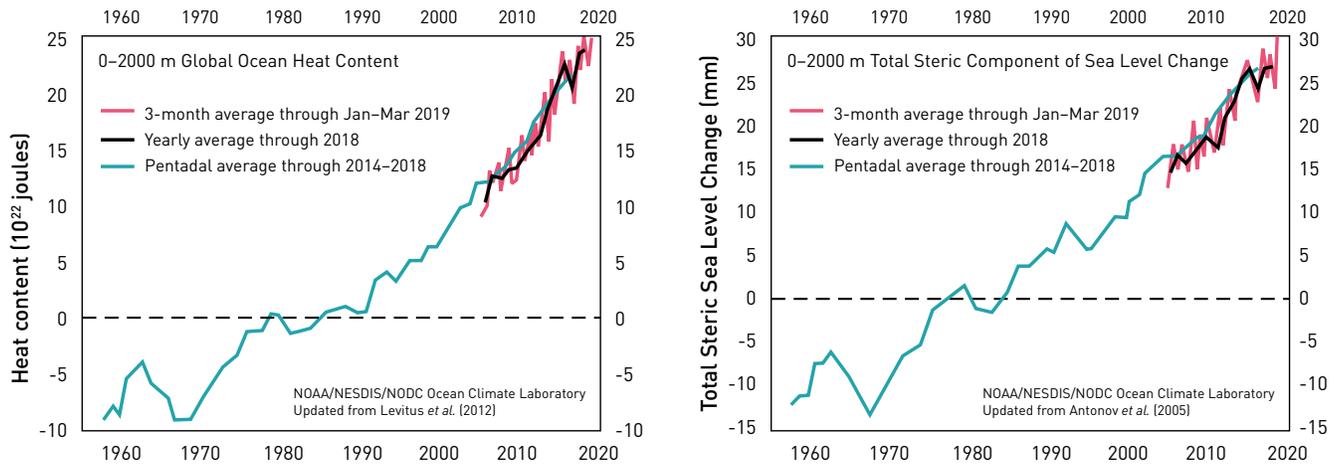
Figure 6. Effects of Marine Acidity (pH) on Shell Development[24]

Healthy shell (normal pH)

Damaged shell (lower pH)
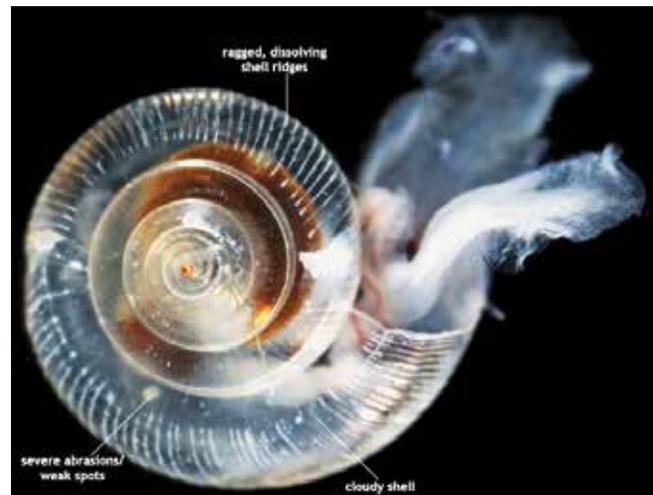
Climate scientists, the UN, politicians, and media outlets are notably starting to shift their language to more accurately describe the environmental crises facing the world. Rather than neutral and gentle terms like "climate change" and "global warming," they are using "global heating" and climate "emergency," "crisis," or "breakdown."[25] Other terms shifting in public discourse include the use of "wildlife" rather than "biodiversity" and "fish populations" instead of "fish stocks."[26] This language indicates growing acknowledgement of the severity of these crises.

23 The change in ocean heat content is calculated from the difference of observed temperature profiles from the long-term mean. Source: (NOAA, 2019).

24 https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide

25 (UN Secretary-General, 2018)

26 (The Guardian, 2019).

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CLIMATE ACTION AND GREEN, ETHICAL CARS

The Intergovernmental Panel on Climate Change (IPCC) recommends limiting global heating to 1.5°C compared to preindustrial levels.[27] Because we are already most of the way to that 1.5°C change, the total remaining carbon budget we can emit is small: we can put no more than 420 gigatonnes of CO_2 into the atmosphere between now and 2050.[28,29] In 2018 alone, we emitted 37 gigatonnes—nearly 10% of our total remaining budget (see Figure 7). If we simply keep going at our current emissions rate, we will exceed our carbon budget by 2030 and reach a 3°C temperature rise by 2100.[30] We would then have a very different planet than the one on which our species evolved.

The stakes for staying within our remaining carbon budget are high. At a 3°C increase, expected global sea-level rise would be 10 centimeters higher than what is projected for a 1.5°C rise. Instead of a 70%–90% decline in coral reefs, we would lose virtually all of them—a habitat for 25% of all marine life. Even the difference between 1.5°C and 2°C is dramatic.[31]

No credible pathways exist to get to *absolute* zero emissions by 2050. The IPCC's current recommended climate-action pathway involves reducing CO_2 by 45% below 2010 levels by the year 2030 and reaching net zero by 2050, whereby global greenhouse gas (GHG) emissions are offset by actively pulling gigatonnes of emitted CO_2 out of the atmosphere (see Figure 7).

Figure 7. Global CO₂ Emissions from Human Activity (L); Emissions Pathway to Limit Rise to 1.5°C (R)[32]

Global fossil CO_2 emissions

1990–2000 +1.1%/yr
2000–10 +3.1%/yr
2010–17 +1.0%/yr

Projection 2018 37.1 Gt CO_2 ▲ 2.7% (1.8%–3.7%)

Global Carbon Project • Data: CDIAC/GCP/BP/USGS

Global CO_2 emissions

Pathways limiting temperature rise to 1.5°C

Net negative emissions

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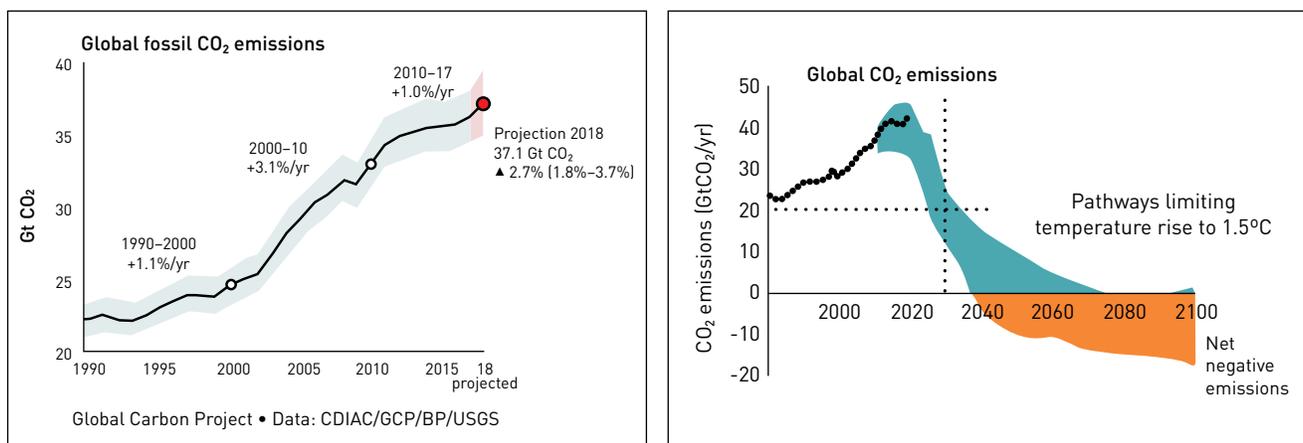
27 (IPCC 2018).

28 (IPCC, 2018). A 420-gigatonne carbon budget gives a 66% probability that we would not exceed 1.5°C heating.

29 Throughout this document, the 'tonne' spelling is used, referring to 1 'metric ton' or precisely 1,000 kilograms.

30 (Azhar, 2019)

31 (IPCC, 2018).

32 Figures taken from (Azhar, 2019).

The scale of the challenge is monumental. It requires a dramatic reversal in our currently still-growing emissions—by frontloading rapid and far-reaching transitions in land use, energy, industry, buildings, transport, and cities, as well as rapid development and deployment of carbon sequestration and storage technologies. Every gigatonne of CO_2 matters to stay below 1.5°C.

To make the already monumental task more challenging, our current CO_2 emissions rate doesn't include the extra CO_2 burden that must be incurred to transition to a zero-emissions world. The new green infrastructure is more metal-intensive than its fossil-fueled predecessor, and a rapid buildout of green technologies will require a massive new injection of base metals.[33] Base metal production itself is a carbon-intensive process.[34] Some have even argued that we would be simply shifting the environmental burden from fossil fuels to metals.[35]

To help illuminate the choices we need to make as a civilization when it comes to sourcing raw materials to enable a fast-paced green transition, we focus on the example of the electrification of the global passenger fleet.

Figure 8. GHG Emissions from Transport, 1970–2010 (Gigatonnes CO_2 Equivalent/Year)[36]

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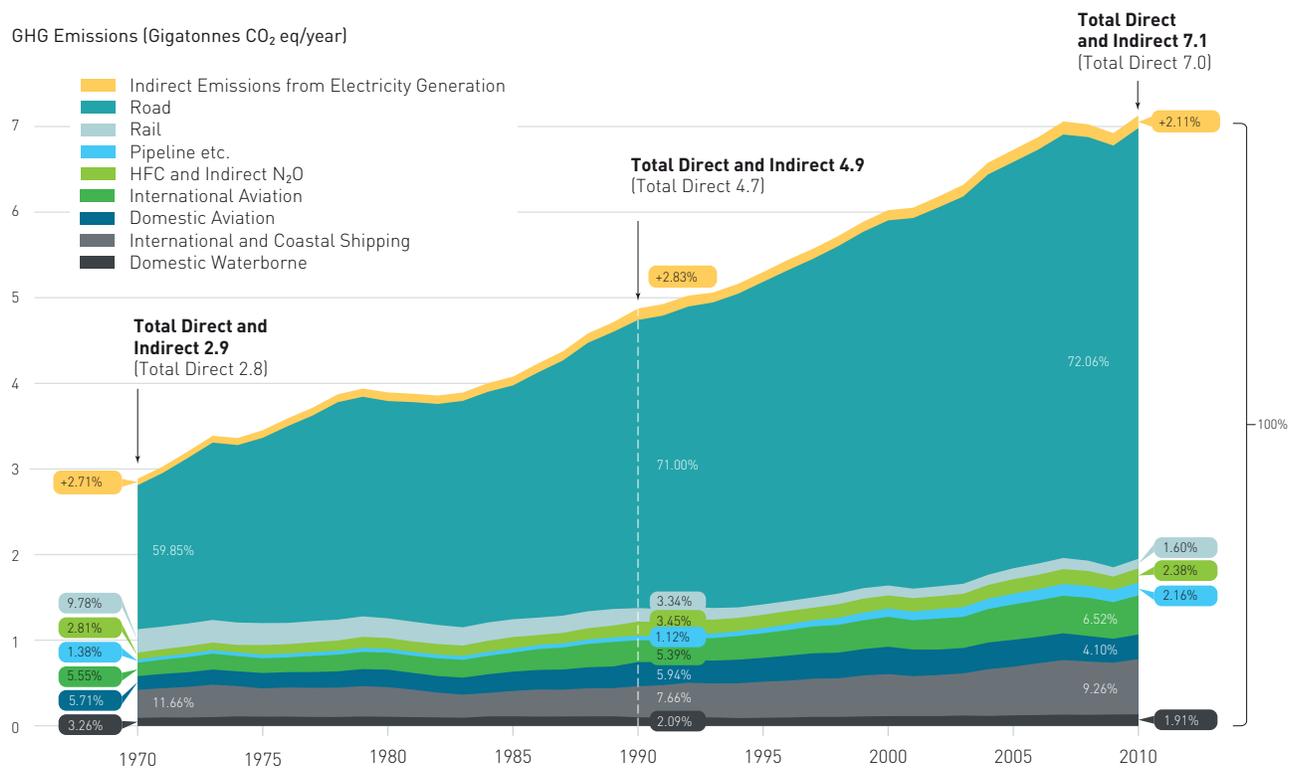
33 (Arrobas, Hund, McCormick, Ningthoujam, & Drexhage, 2017).

34 See literature on life cycle assessments of metals, e.g., (Nuss & Eckelman, 2014) and (van der Voet, van Oers, Verboon, & Kuipers, 2018).

35 (White & Grantham, 2019).

36 See chapter on "Transport" in IPCC Fifth Report (IPCC, 2014).

19

Today, about 1.3 billion fossil-fuel-burning conventional passenger cars drive on the roads around the globe. Driven by global population growth in general and the growth of the car-driving middle class, GHG emissions from car tailpipes have been one of the fastest-growing sources of emissions globally, now accounting for about 15% of global annual emissions (see Figure 8).[37]

Electrifying the global passenger fleet is a core strategy in the global effort to tackle the climate crisis. Today an estimated 5.4 million EVs drive quietly on roads worldwide.[38] A growing number of governments around the world have announced plans to limit or ban sales of gasoline and diesel vehicles.[39] We could be at the very beginning of the exponential growth curve in EVs, with some analysts expecting EV sales to surpass those of conventional vehicles by 2038, and the global EV fleet to surpass one billion by 2047 (see Figure 9).[40] Going from about 5 million to one billion EVs in less than 30 years is ambitious. With every new gigatonne of CO_2 already accounted for in the remaining carbon budget, it's both important and urgent to track the full life cycle impact of this electrification. We must ensure we take the path that minimizes CO_2 and other environmental and social impacts, as much as is feasible.

Figure 9. 1 B EVs by 2047 and EV Fleet Overtakes ICEs: Fleet Sizes and EV Penetration Projections[41]

Global passenger car fleet, millions

Battery-electric vehicle sales penetration worldwide

ICE fleet

The number of cars with internal combustion engines (ICEs) to be surpassed by battery-electric vehicles (BEVs) before 2050 as the BEV fleet hits one billion

BEV fleet
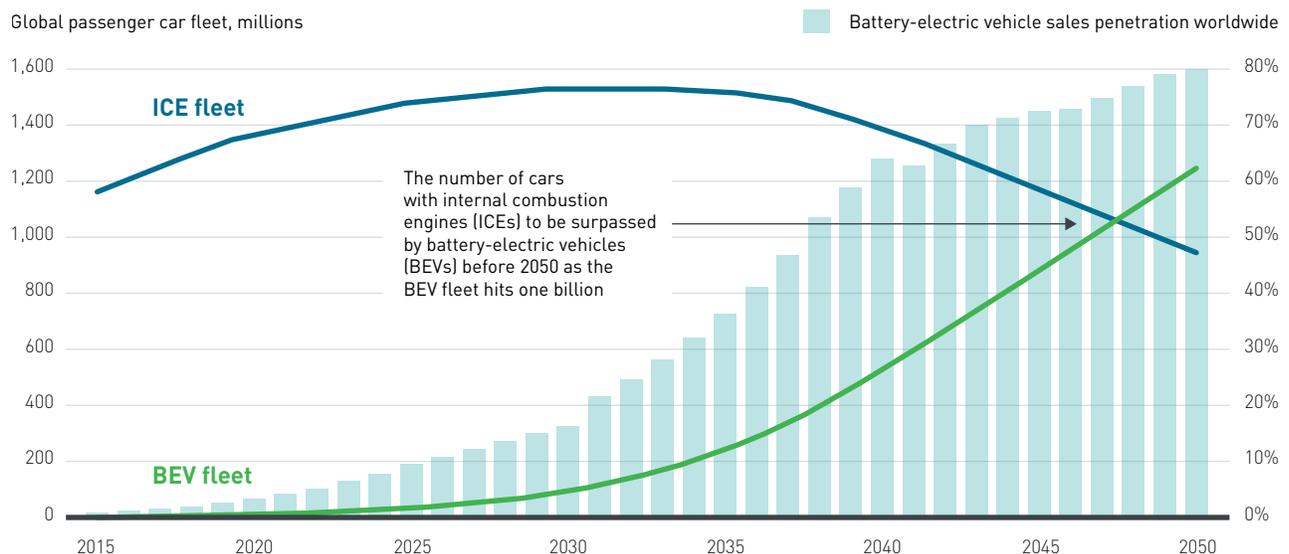
A life cycle analysis of full-value-chain CO_2 emissions can compare the impacts of internal combustion engine (ICE) vehicles and EVs. It would need to include at least:

• **Tailpipe emissions** (ICE vehicles)

• **Fuel-cycle emissions** (ICE vehicles: oil production, transport, refining; EVs: energy source, electricity generation for recharging batteries)

• **Emissions from manufacturing** battery (EVs) and non-battery components (ICE and EVs)[42]

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37 (IPCC, 2014).

38 (Roland, 2019).

39 (Dugdale, 2018).

40 (Desjardins, 2018).

41 Based on Morgan Stanley analysis (Morgan Stanley, 2017).

42 Carbon Brief analysis (Hausfather, 2019) drawing on initial analysis from (Hall & Lutsey, 2018).

How green and ethical are EVs today, considering the entire life cycle? The primary case for EVs compared to conventional ICE cars is zero tailpipe emissions, but an EV's fuel cycle (i.e., recharging the battery) can result in a substantial CO_2 footprint based on how electricity is generated. In largely coal-powered Germany, a European best-selling EV like the Nissan Leaf generates about half the emissions from its fuel cycle compared to tailpipe and fuel-cycle emissions from an average European ICE car. It comes in only 12% better when compared to the Toyota Prius Eco. In contrast, in countries like Norway and France, electricity is largely generated using hydropower and nuclear sources, and emissions associated with the fuel cycle are therefore near zero.

While EV manufacturers don't have control over global electricity grids, there is a strong policy and economic momentum underway toward grid decarbonization. The carbon intensity of electricity is expected to drop by more than 30% by 2030 in most markets that still rely heavily on fossil fuels.[43] Germany, for example, has pledged to phase out coal by 2038 in order to meet its climate targets.[44] We can assume that when it comes to the fuel-cycle portion of emissions produced by recharging EV batteries, EVs will keep getting greener and will eventually approximate the zero fuel-cycle emissions in Norway.

But this is only half of the EV story.

Figure 10. Life Cycle GHG Emissions (CO_2e Grams per Kilometer)[45]

Legend:
- Manufacturing of vehicle itself
- Fuel cycle (recharging the battery)
- Tailpipe emissions
- Manufacturing of battery
- Error for range of values for emissions from battery manufacturer

Conventional vehicles: Average European car, Toyota Prius Eco

Nissan Leaf: Germany, United States, Netherlands, EU average, UK, France, Norway

Tesla Model 3 (75 kWh Asian battery): Germany, United States, Netherlands, EU average, UK, France, Norway

43 (IEA, 2018).

44 (France 24, 2019)

45 Note: Life cycle GHG emissions for conventional vehicles and EVs (by country) in grams CO₂e per kilometer, assuming 150,000 kilometers driven over the vehicle lifetime. Adapted from Figure 1 in (Hall & Lutsey, 2018). Details of the calculations are in the methods section at the end of the article. The error bars show a range of values for emissions from battery manufacture. Chart by Carbon Brief using Highcharts. Exact values available at (Hausfather, 2019).

While the emissions associated with manufacturing non-battery components of a car are estimated to be roughly comparable for conventional ICE cars and EVs, EVs come with a substantial extra emissions load: the lithium-ion battery. In the case of the Nissan Leaf, its 30 kWh battery doubles the emissions from manufacturing the vehicle. Things get worse if we project forward as most EV manufacturers upsize their batteries. Tesla's mass-market EV, Model 3, already comes with 60 and 75 kWh battery options. Furthermore, most EV batteries today are manufactured in Asia (China, Japan, and South Korea) where 30%–60% of energy generation is from coal.[46] Manufacturing a 75 kWh battery pack generates 2.5 times more emissions than a 30 kWh pack (see Figure 10), bringing the extra emissions load from battery manufacturing to 13.2 tonnes for each new EV.[47]

If we build one billion EV batteries under present conditions, we would generate 13.2 gigatonnes in extra emissions load—in a world where we need to be reducing our emissions and taking gigatonnes of carbon out of earth's atmosphere.

What can EV battery manufacturers do to slash the CO_2 they would add to our battered atmosphere? Around 50% of battery emissions comes from the energy used in the manufacturing process.[48] Tesla is already powering their US gigafactory with solar. Europe's first gigafactory, Northvolt, which aims to produce the "world's greenest battery," chose to locate in Sweden to access hydropower.[49] However, most of the world's battery-manufacturing capacity today is in coal-powered Asia, and most publicly announced new battery plants in Europe are being opened in places like Germany and Poland—not countries with renewable-dominated grids (see Figure 11).

Figure 11. Planned Battery Capacity in Several European Countries[50]

Energy mix ■ Renewable ■ Nuclear ■ Non-renewable

16.7K Germany

9.2K Hungary

8.1K Sweden

5K Poland

1.1K France

1K Czech Republic

100 Finland
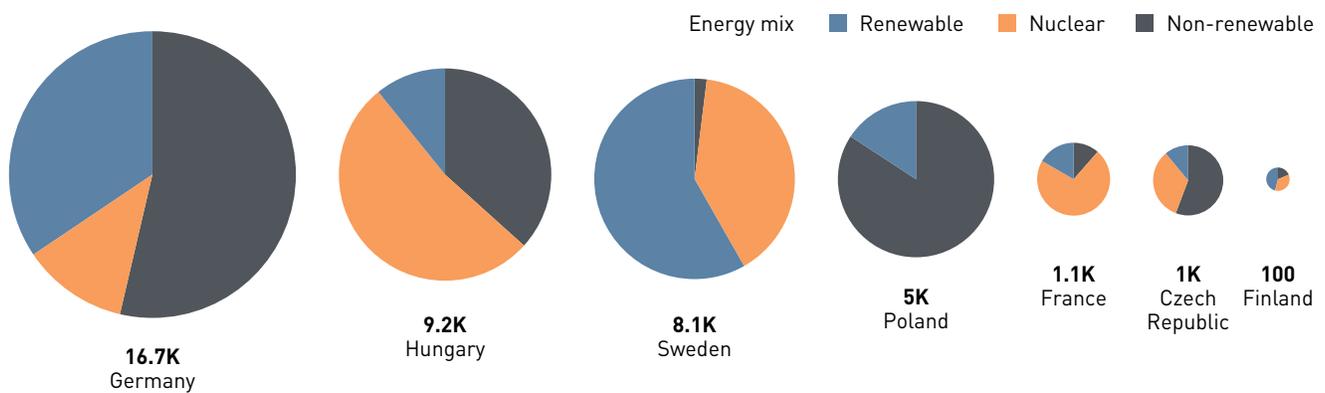
In an optimistic scenario where the global electricity mix shifts to 100% renewables, every EV on the road would have the fuel-cycle emissions of a Norwegian EV (i.e., zero) and as much as 50% lower emissions associated with battery manufacturing.[51] These "green" batteries would still generate 6.6 tonnes of emissions for every new EV replacing an ICE vehicle, or a total bill of 6.6 extra gigatonnes for replacing a billion-car fleet.

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46 In 2016, coal made up 62% of China's energy generation (CSIS, 2018); in 2017, coal fueled 40% of South Korea's electrical generation (EIA, 2018); and in 2014, coal fueled 31% of Japan's energy generation (METI, 2016).

47 Source: Carbon Brief analysis (Hausfather, 2019), drawing on initial analysis from (Hall & Lutsey, 2018).

48 (Romare & Dahllof, 2017).

49 (Hampel, 2019).

50 Sources: Bloomberg New Energy Finance, European Network of Transmission System Operators for Electricity. Actual energy generation in 2017. Capacity includes plants planned and under construction. See also (Rolander, Starn, & Behrmann, 2018).

51 (Hausfather, 2019).

Why? The lion's share of these emissions, as much as 70%–80%, comes from the production of raw materials that go into the lithium-ion battery (see Figure 12).[52] A 75 kWh EV battery with NMC-811 cathode chemistry—the likely average battery size and dominant chemistry by the time the EV manufacturing picks up real volumes in three to five years—requires 56.2 kilograms of nickel, 8.3 kilograms of lithium, 7.1 kilograms of cobalt, and 6.6 kilograms of manganese (see Table 1).[53] In addition, an EV would use 85 kilograms of copper (about 35 kilograms for battery connectors and another 50 kilograms for the electric harness). With over one billion EVs expected to be built over the next 30 years, the environmental and social impacts of producing millions of tonnes of base metals needed for these batteries are coming under increased scrutiny and pressure.

The availability, sustainability, and ethics of producing base metals for EV batteries are now widely seen as the Achilles' heel of the EV industry.[54] In this report, we focus on these four base metals—Ni, Mn, Co, and Cu—used in manufacturing battery cathodes (975–1,500 kilograms of CO_2 or 15%–23% of total "green" battery emissions) and electric connectors, which may potentially have an alternative, lower-carbon source with several advantages as well as a unique set of challenges.[55]

Figure 12. EV Battery Life Cycle Emissions Breakdown, by Component and Manufacturing Stage[56]

Component	kg CO_2-eq/kWh battery		
	Raw mineral mining and refining	Battery-grade material production (including mining and refining)	Manufacturing (component and cell + battery assembly)
Anode	2–11	7–25	
Cathode	7–18	13–20 (90)	
Electrolyte	4.00	4–13	
Separator	<0.5	Approx. 1	
Cell case	<0.1	Approx. 1	
Battery case	4–13	10–25	
Cooling	0–3	2–6	
BMS	<1	4–30	
Total	**18–50**	**48–121 (216)**	**20–110**
Most likely value (based on the assessment of transparency and scientific method done in the report)		**60–70**	**70–110**

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52 Carbon Brief analysis of IVL data puts likely emissions from offsite raw material and battery material production at 60–70 kilograms of CO_2e per battery kWh, implying 4,500–5,250 kilograms of the total 6,600 kilograms emissions for a 75 kWh battery produced under zero carbon energy.

53 An NMC-811 battery is so named because it is comprised of roughly eight parts nickel, one part manganese, and one part cobalt. Lithium is not included in this analysis as it cannot be obtained from nodules. For more information about lithium, see, e.g., (Katwala, 2018).

55 See a discussion of metal availability concerns by Forbes (Treadgold, 2018) and DRC's unethical practices and child labor by the World Economic Forum (WEF) (Broom, 2019).

56 Source: Carbon Brief analysis based on IVL data (Romare & Dahllof, 2017).

Table 1. Base Metal Contents of Li-Ion Battery Cathodes[57]

Cathode Chemistry	Kilograms per kWh				Kilograms per 75 kWh Battery				Total/75 kWh
	Lithium	Cobalt	Nickel	Manganese	Lithium	Cobalt	Nickel	Manganese	
LCO	0.113	0.959			8.48	71.93			**80.40**
NCA	0.112	0.143	0.759		8.40	10.73	56.93		**76.05**
NMC-111	0.139	0.394	0.392	0.367	10.43	29.55	29.40	27.53	**96.90**
NMC-622	0.126	0.214	0.641	0.200	9.45	16.05	48.08	15.00	**88.58**
NMC-811	0.111	0.094	0.750	0.088	8.33	7.05	56.25	6.60	**78.23**

THE ACHILLES HEEL OF GREEN, ETHICAL CARS

As the global supply of high-grade ore shrinks and metal demand increases, we can expect a larger environmental footprint as well as higher metal prices. A World Bank study shows that, in a projected scenario of a 2°C temperature rise by 2050, base metal demands for EV batteries could increase to 11 times today's levels.[58] The growing population and focus on renewables and carbon neutrality as well as global inclusion will continue to force metal demand upward.[59]

Since we cannot control the demand side to curtail the need to extract new resources in the short run, we look to the supply side—i.e., metal-ore reserves and production methods—to provide a solution.

All base metals going into EV batteries today are produced from land ores. The two potentially lower-impact alternative sources are secondary metals (i.e., recycled metals) and ocean minerals from deep-sea polymetallic nodules. If the goal is to produce the world's greenest, most ethical EVs, where should EV manufacturers source their base metals?

Source #1: Land ores

The first source to consider is the status quo: metal mining from land ores. This involves intense efforts to break apart and crush hard rock; millions of gallons of freshwater pumped in for processing; and emissions and chemical pollution to the air, land, and water.

Metal mining has harmful impacts on our environment, economy, and society that are substantial and growing. Producing metals from land-ore bodies often requires deforestation of some of the world's most biodiverse ecosystems (e.g., nickel laterites in Indonesia, cobalt in the Democratic Republic of Congo (DRC)) as well as displacement of communities living on or off the land above the ore bodies (e.g., laterite mines in Indonesia, Madagascar, and New Caledonia). The mining industry produces extraordinary amounts of waste—in 2011, an estimated 350 billion tonnes of mine waste were produced, enough to cover Ireland with a two-meter-thick blanket of sludge.[60] Chemical waste from mining is then released into the environment; in 2016, the US mining industry released 44% of all industrial chemical waste—more than triple that of the second-ranked industry, chemical manufacturing.[61] Mining is an energy-intensive and highly emissive process that can lead to 2–30+ kilograms of CO_2 emissions for each kilogram of metal produced. Three of the four base metals (copper, nickel, and manganese) rank in the top-12 metals for highest global warming potential (GWP), with copper ranking the highest for human health and ecosystem damage.[62]

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57 See Table 1 of (AMY, 2018). LCO = lithium-cobalt-oxide; NCA = nickel-cobalt-aluminum; NMC = nickel-manganese-cobalt.

58 (World Bank, 2017).

59 (McKinsey & Company, 2017).

60 (Blight, 2011).

61 (EPA, 2018).

62 There is extensive LCA literature that has quantified the GWP of cradle-to-gate metal production both for individual production paths and global averages across a wide variety of metals, including (Nuss & Eckelman, 2014) (63 metals were analyzed at 2008 production levels and static demand), (Dai, Kelly, & Elgowainy, 2018), (Kuipers, et. al., 2018), (van der Voet, van Oers, Verboon, & Kuipers, 2018).

Other major environmental and human health risks plaguing the mining sector include acid rock drainage from excavated sulfides that can contaminate surrounding land areas and groundwater, and devastating spillage of (sometimes toxic) tailings from failed dams that can claim human lives and contaminate the environment for decades. Despite global focus on human health and safety, every year hundreds of miners die and millions of miners get sick in mines around the world. In the case of cobalt, 60% to 70% is mined in the DRC, of which a significant fraction comes from unregulated artisanal mines and child labor. As a result, Amnesty International recently challenged EV manufacturers to "clean up their batteries" because "without radical changes, the batteries which power green vehicles will continue to be tainted by human rights abuses."[63]

Future dynamics are anticipated to exacerbate these environmental and social impacts. Nickel and copper ore grades have been falling for the last several decades and are expected to continue to do so into the future, as metal demand growth warrants mining into deeper and lower-grade ore grade deposits. Lower grade ores require greater amounts of materials and chemicals for concentration and processing— which means more energy needed to process larger amounts of ore to get at the same amount of metal. While land mining has a sizable opportunity to improve its impacts through improving process efficiency, electrifying mining equipment, and bringing renewables into the production energy mix, studies show these may not counter the impacts of grade decline. New high-grade ore deposits may also be found, and technology innovations can make such processing more economical, avoiding some of these costs, but such developments are difficult to predict. Global discovery rates have declined over the last 30 years, as easy-to-discover exposed deposits have already been found.

Over the past five years, several academic groups have published life cycle assessments (LCA) of the environmental impacts of metal production from land orebodies. Importantly, several published academic studies have also modeled the impacts of both falling

ore grades as well as scenarios where the land-based mining sector aggressively implements measures to improve their environmental impacts. Such life cycle impact quantifications under future dynamics scenarios are leveraged by this report to better understand the tradeoffs between options for sourcing transitional demand in base metals.

Source #2: Secondary (recycled) metals

95-99% of the metals used in an EV battery are recyclable. The transition to recycled metals would be a game-changer for reducing the environmental and social impacts of metal production. Recycling is cheaper, less energy-intensive, has lower CO_2 emissions, and reduces the environmental and sustainability footprints across the board. This is because it bypasses the material- and energy-intensive mining and concentration steps required for ore extraction. It can reduce energy requirements between 60-98% (UNEP, 2013), and CO_2 equivalent emissions, toxicity, acidification, and other environmental indicators can be reduced by 70-95% (Kuipers, et. al., 2018). Recycling furthermore avoids the wastes, pollution to air, ground and water, hazards, and social impacts of environmentally harmful physical mine sites.

Recycling high volumes of metals is technologically feasible and widely used. Copper's end-use recycle rate was 69% in 2016 (10-year average), and the product-related recycle rate of nickel was about 80% in 2017.[64] These are steps toward supporting the end goal of a circular economy.[65]

Mathematically, even with a 100% recycle rate, there will always be a gap between the recycled supply and the demand in a growing market. This gap is difficult to close without an injection of new primary metals. For instance, batteries represent just 4% of current nickel demand. Most nickel goes into stainless steel, which has high recycling rates. But total demand for stainless steel itself is increasing, and stainless steel generally has very long effective utilization periods. This means the metal is locked up for decades, unavailable for recycling. With this lag, even under extremely aggressive scenarios of 90%–100% recycling, the

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63 (Amnesty International, 2019).

64 See (ICSG, 2018), (Nickel Institute, 2018), and (GDB, 2017).

65 (Dominish, Florin, & Teske, 2019).

share of secondary production would take decades to catch up with primary production.[66] There are furthermore inefficiencies in the recycling recovery process that widen the gap. While the 10-year average copper-recycling collection rate in 2018 was 69%, after considering processing inefficiencies, this rate dropped to 48%. The actual recycling input rate was only 34%, indicative of the demand-recycle gap.

With population growth and standards of living steadily increasing—green revolution notwithstanding— the demand for metals is increasing, with a gap beyond what can be met through recycling. EV-battery-driven metal demand is a net new demand on top of this. There is simply not enough existing secondary metal stock to supply the millions of tonnes of new metal demand projected for the coming decades.

Factors beyond behavior may hinder society from reaching that 90%–100% quickly. Technological and scaling aspects add friction to recycling growth, as does the flow of recycled materials into any new sector. Aggressive changes in systems, production processes, and operating procedures across the materials cycle are needed to achieve scale and adapt to new supply-and-demand sources. These are ongoing system dynamics challenges for any supply chain innovation.

New technologies may eventually help enable a circular economy around battery metals. A recent innovation proved the ability to effectively self-replace batteries' metal content. The process produces near 100% recovery rates for nickel, cobalt, and manganese from the batteries. It does so in an efficient and clean manner, with high purity, and with minimal use of water. It is economically attractive as well; the recoverable value of metals comprising a 100 kWh NMC-111 cathode battery pack is estimated at $3,400 per battery—89% of the value of these metals contained in the battery.[67]

Applying this self-replacing metal technology, the supply-demand gap of a growing market would still remain for decades until the exponential demand growth levels off. Transitional base metal stock must first be extracted and produced into batteries and used for their lifetimes before the batteries' metals can be recycled. As EV batteries may have a 10+-year life, this process is lengthy while demand continues growing.

Given its vastly lower emissions and environmental footprint, secondary production is clearly the responsible solution for supplying base metals for every new battery produced. It will take decades to produce the first billion EV batteries with primary metals and get to this point. In the meantime, the green transition requires a transitional injection of primary metals.

This leads us to a third possible source, which, although it still entails primary production from earth's resources, comes with a different impact profile than conventional land-based mines.

Source #3: Deep-sea polymetallic nodules

Novel techniques, efficiency innovations, or alternate raw-material sources can create step-function changes in industry outcomes. Seafloor nodules may present such an opportunity; a very large supply of EV battery metals lies in a relatively small area of the ocean floor.

Ocean minerals come in several forms: seafloor massive sulfides (SMSs—similar to land sulfides), cobalt crusts, and polymetallic nodules. In this report, we focus only on polymetallic nodules sitting unattached on the ocean floor in an area of the South Pacific Ocean known as the Clarion-Clipperton Zone (CCZ) (see Figure 13). The metal composition of this ocean resource is uniquely aligned with the base metal needs of the EV industry; polymetallic nodules contain nickel, cobalt, and manganese required for EV batteries, and copper required for battery-current collectors and electric harnesses. The ratio of nickel to cobalt closely matches the ratio of NMC 811 battery chemistry (see Table 2). The size of the resource is substantial, with CCZ nodules containing enough metal to electrify the global EV fleet four times over.[68]

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66 (van der Voet, van Oers, Verboon, & Kuipers, 2018).

67 An NMC-111 battery is comprised of roughly one part nickel, one part manganese, and one part cobalt. (AMY, 2018).

68 Estimate assumes one billion EV cars with 75 kWh batteries with NMC811 battery chemistry and 85 kilograms of copper per EV. See (Morgan, 2000).

Figure 13. Manganese Nodules on Abyssal Seabed in Four Oceanic Regions; Formation of Nodules[69]
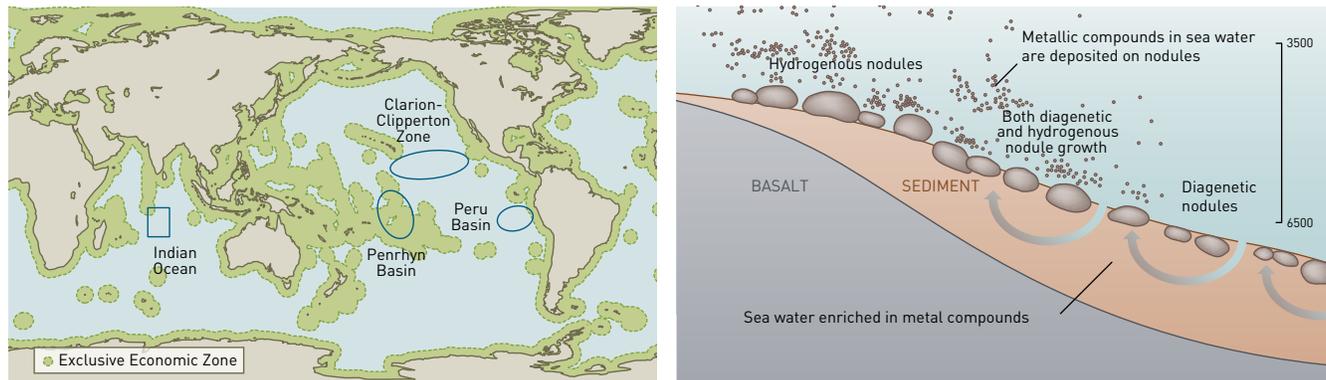
Table 2. Similarity of Metal Composition of CCZ Nodules vs EV Batteries

	Polymetallic CCZ Nodules (Kg Metal Contained in 4 Tonnes Dry Nodules)	NMC 811 Battery + Cu Connectors (Kg Metal Required for 1 EV)
Nickel	52 kg (1.3%)	56.2 kg
Cobalt	7.2 kg (0.18%)	7.05 kg
Manganese	1,168 kg (29.2%)	6.6 kg
Copper	43 kg (1.08%)	35 kg (battery) + 50 kg (electric harness)

Unlike land-based ore bodies that fall under the jurisdiction of sovereign nation-states, the CCZ polymetallic nodules are located in international waters and are deemed to be part of the "common heritage of mankind." According to international law, the development of this resource needs to be undertaken in a manner that benefits both developed and developing nations. The use of this resource is regulated by the International Seabed Authority (ISA), an intergovernmental body established in 1994 by the United Nations Convention on the Law of the Sea. The ISA has so far issued 16 exploration contracts, with the stated goal of having regulations in place by 2020 to allow prompt commencement of commercial production.[70]

The development of the polymetallic nodule resource has been greeted with opposition from several ocean-conservation-focused NGOs, including Greenpeace and DOSI.[71] The main objection is centered around impacts on deep-sea wildlife: removing nodules will mean removing a feature of the habitat that is critical for several life functions of nodule-dwelling marine animals. Some organisms attach to the hard surfaces of nodules, while others use the hard surfaces of nodules for laying eggs. Nodule-collection machines will disturb the seabed and suspend sediments, which could travel outside the collection zone and risk smothering marine populations in marine preservation zones.

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69   Source: (World Ocean Review, 2014).

70   See ISA website for overview of CCZ licensed areas for contractors: (ISA, 2019).

71   For example, see a July 2019 report from Green Peace calling—among other things—for an immediate moratorium on deep sea mining (Greenpeace, 2019).

These biodiversity concerns in the deep sea must be carefully weighed against the environmental and social impact profile of terrestrial mines—which already lead to habitat loss and degradation, contamination risks, and many other negative impacts. The ISA and contractors are in the process of generating a large body of work and environmental impact studies to assess and minimize these impacts. Proponents of nodule collection have argued that it imposes far fewer downsides compared to land-ore mining, as it provides a significantly lower carbon footprint, considerably greater safety, and less pollution; that it has minimal impact on ecosystem services (ES), inflicts no cultural displacement, and provides additional benefits like price stabilization. The debate has so far lacked a rigorous fact base or comprehensive study of the two sourcing options.

While there is a robust platform of prior academic research on environmental impacts of metal production from land ores, a life cycle assessment (LCA) of specifically producing battery-precursor materials from land ores and from ocean nodules has never been performed. The goal of this report is to create a like-for-like LCA analysis of the carbon emissions impact of the two options, as well as a broader life cycle sustainability assessment (LCSA) comparing the environmental, social, and economic impacts of producing the first one billion EV batteries, using battery precursors from land ores versus CCZ polymetallic nodules.

Neither source is impact free; each comes with a unique set of issues.

We hope our work helps frame the conversation and the difficult choices ahead of us to source battery metals responsibly, ethically, and with minimal extra CO_2 load on the planet.

II. SYSTEMS APPROACH AND EVALUATION FRAMEWORK

As described in the introduction, producing the millions of tonnes of base metals needed for a billion EVs has environmental and social consequences, and care must be taken to not merely shift the environmental burden from fossil fuels to metals. Faced with two primary metal source options, a comprehensive comparison of impacts from these two pathways is needed to form an educated policy decision. This paper attempts to fill that need by creating a systems-level comparison of impacts of producing the same set of base metals for one billion EV batteries from the two primary source types.

The study incorporates a quantification of global warming potential (GWP) and several critical impacts (e.g., land use, carbon sequestration, freshwater use, waste and tailings, human toxicity), qualitative supporting studies and literature reviews of biodiversity and social impacts, and a high-level economic assessment. Impact categories and measures are defined, evaluated for each option, and compared.

Among the aims of this paper are to **spotlight the importance** of the debate between land mining and ocean floor nodules within the context of the climate and wildlife crises; **create awareness** of how base metals are produced, both from land ores and from nodules in the near future; **provide a frame for discussion** around the impacts of metal production that is both productive and comprehensive; and **contribute to life cycle assessment (LCA) literature** with an impact study of producing base metals from deep-sea polymetallic nodules.

Figure 14. Two Primary Metal Sources to be Systematically Compared: Land Ores and Nodules

a) Nickel laterite mine in Indonesia

b) Deep-sea nodules collector concept
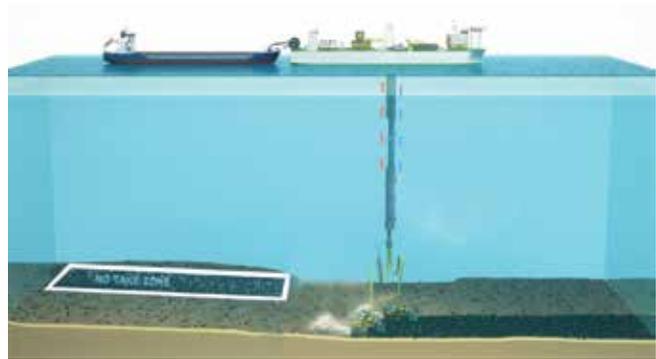
The paper is framed as a life cycle sustainability assessment (LCSA), which is a broadening of an LCA to include all three sustainability pillars—environmental, economic, and social—as well as future supply and demand dynamics.

- **LCA is a scientific approach widely used to quantify and aggregate the environmental footprint of a product.** Material and energy flow inventories are compiled from across a product's life cycle—including resource extraction, material production, product manufacture, usage, and disposal or recycling. Activities that directly contribute (e.g., extracted resources) and indirectly contribute (e.g., building the roads that carry equipment to the mine) can all be accounted for. Life cycle impact assessments (LCIA) then translate such inventories into selected indicators like climate change, acidification, and human toxicity. The International Organization for Standardization (ISO) standards 14040 and 14044 provide a framework for consistency across system boundaries, allocation methods, and modeling strategies for better comparability.[72] This paper applies LCA methodology to several indicators at varying levels of rigor as indicated.

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72   More information about LCA and LCIA is available in numerous literature references and guidebooks, e.g., the ILCD handbook on environmental impact assessment methodologies for use in LCA (European Commission, 2010), (UNEP, 2016), and (ISO, 2006).

- **LCSA is a framework built around LCA to allow inclusion of social and economic impacts as well as future supply and demand dynamics.** Inclusion of all three sustainability pillars allows LCA results to be better related to policy discussion, with environmental impacts viewable directly alongside the social and economic context. Inclusion of future dynamics is important since relevant factors like

demand, energy efficiency, grid decarbonization, and geological composition of untapped ore bodies will evolve by the time policies are enacted.[73]

The LCSA framework employed by the paper has been illustrated in Figure 15. Details of the paper's structure and analytic categories are further described below.

Figure 15. Study Framework for Evaluating Environmental, Social, and Economic Impacts

ENVIRONMENTAL
Climate Change | Biodiversity Nonliving Resources

SOCIAL
Fatalities and Illness
Vulnerable Populations
Financial and Social Costs
Cultural Disruption

ECONOMIC
Prices and Costs
Job Impacts
National Economies
Economic Risk

Ecosystem Services
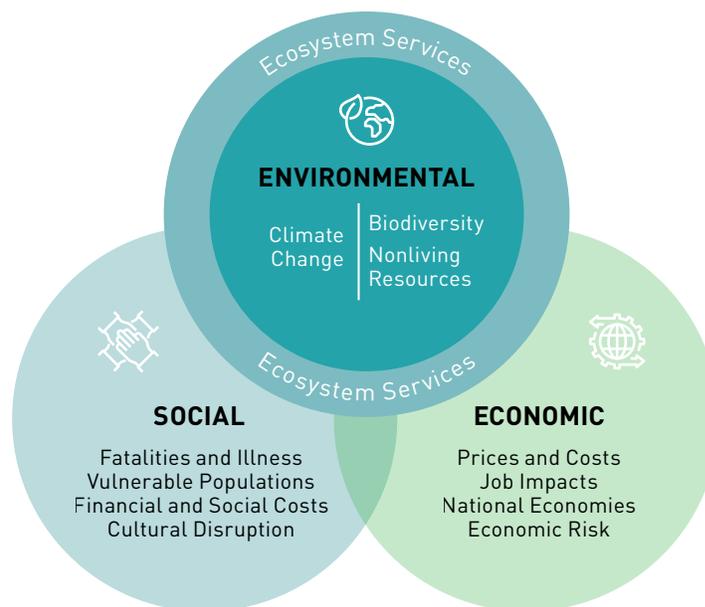
This paper begins by applying the ecosystem services (ES) framework to systematically compare how producing metals from the two different sources impacts the provision of ES. ES are a final "endpoint" damage category in LCA, as well as a separate standard used to understand an ecosystem's impact on humans.[74] These represent the benefits that humans gain from well-functioning ecosystems, such as forests, grasslands, and aquatic systems—with benefits ranging from provision of clean drinking water to waste decomposition. These are "services" that enable humans to be healthy and thrive. The 2005 Millennium Ecosystem Assessment concretized the ES framework and popularized its use for describing ecosystems' impacts on humans.[75] In some LCA impact frameworks, ES are viewed as an endpoint category or a final outcome driven by numerous intermediate outcome measurables. In fact, ES are directly impacted by many environmental impact categories discussed in this paper—including carbon dioxide emissions, biodiversity, nonliving resource usage, ecotoxicity, and various pollution indicators.

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73 See (UNEP, 2011), (Guinee J. B., 2011), (Guinee J. , 2016), and (van der Voet, van Oers, Verboon, & Kuipers, 2018).

74 See Chapter 1, "Integrating the ecological and economic dimensions in biodiversity and ecosystem service valuation," in (Pushpam, 2010).

75 See (Millennium Ecosystem Assessment, 2005), 'The Economics of Ecosystems and Biodiversity' (TEEB, n.d.), and TEEB report (Pushpam, 2010).

The brief ES side-by-side evaluation in this paper orients the reader toward the difference between land mining and nodule collection, outlining land ecosystems' and deep-sea ecosystems' current contributions to ES. This helps us form an intuition for the impact magnitudes of any disruptions resulting from metal production by each method.

The study then dives into five broad impact categories—three environmental categories, followed by social and economic impact evaluations—using varying levels of rigor and accompanied by some degree of quantification. The specific choices of indicators and methods of evaluation are explained in detail in the Methods section; these decisions were driven by a combination of prominence in LCA literature, relevance to metal mining and production, and level of fidelity required to reach meaningful comparative conclusions.

Following along the framework in the figure, within the environmental circle, **climate change** is addressed via a quantitative GWP assessment which integrates previous literature results for land-based mining while building a new model for ocean-nodule-based metal production; additionally, mechanisms of impact on carbon sequestration are modeled, projecting the stored carbon potentially at risk. Next, data on **nonliving resources** quantify the transformation of land, depletion of freshwater, air pollution, production of waste streams and tailings, and cumulative energy demand (CED). A **biodiversity** discussion then draws on published literature to illustrate the richness and magnitude of biodiversity in each habitat, as well as estimating their relative species richness, populations, and biomasses.

Social factors are then assessed, including human deaths and illnesses, vulnerable populations, and cultural disruption. Finally, **economic issues** are presented, including discussions of prices, cost curves, and market sizes, jobs created, national impacts from the potential market changes, and economic risk.

The static and dynamic scenarios considered in our analyses are overviewed in Figure 16.

Figure 16. LCSA Dynamic Demand and Supply Framework

	Supply Characteristics		Demand Characteristics
	Land Ores Supply Scenarios	**Nodules Supply Scenarios**	**EV Demand Scenarios**
Static Supply	As-Is Land Ores	Planned Nodule Project	Per-Kilogram Impacts (Static Demand)
	As-Is Land Ores	Planned Nodule Project	1B EVs by 2047 (Dynamic Demand)
Dynamic Land Ore Supply	Baseline Land Ores (Dynamic Supply)	Planned Nodule Project	1B EVs by 2047 (Dynamic Demand)
	Green Land Ores (Dynamic Supply)	Planned Nodule Project	1B EVs by 2047 (Dynamic Demand)

Dynamic Metal Demand: To keep results framed around a single focal point, in this paper we tie most impact explorations to the EV adoption demand scenario developed by Morgan Stanley, predicting that the global EV fleet will grow to one billion units by 2047.[76] We explore what would be the life cycle impacts of supplying the total demand of one billion EV batteries and connectors, using the selected metal source.

Dynamic Land Ore Supply: The future supply-side dynamics for land ores are centered around the influence that falling ore grades and/or increased usage of renewables can have on mining's environmental impacts. Following the procedure in (van der Voet, van Oers, Verboon, & Kuipers, 2018), the dynamic GWP LCA in this paper reflects the future states of further-depleted, high-grade ores by 2047. Indicators such as land usage and waste and tailings also take ore-grade dynamics into account: as ore grades fall, land use must increase, and any dependent factors, including wastes and tailings from land ore production, will also increase. For most analyses in this paper, an initial static "status quo" model is presented that assumes current sector performance for land ores (e.g., ore grade, energy efficiency). A baseline dynamic model then assumes that miners continue battling falling grades in copper and nickel. Some indicators like GWP also incorporate a "green" or best-case dynamic model that assumes that while ore grades continue to fall, mining also benefits from global equitability-focused policy shifts—with the share of renewables drastically increasing.

Planned Nodules Project: For the deep-sea models, a single impact profile has been developed. Referred to as the "Planned Nodules Project," this profile leverages currently planned nodule collection operational concepts, economic and resource assessments, and engineering plans, assuming that future producers of metals from polymetallic nodules adopt the minimum set of operational best practices currently envisioned by companies like Global Sea Mineral Resources and DeepGreen. These best practices are enabled by the unique nature of the nodules resource, location, and mineralogy—

including the no-tailings and no-waste approach to onshore processing and using clean electricity (e.g., hydropower) to power onshore processing.

Note that only one supply scenario has been modeled for nodules. Supply-side dynamics are less directly relevant for two reasons: (1) ore grades are fairly consistent across the CCZ nodule resource; and (2) the model already leverages the premise that onshore production plants can be much more readily located in places with access to near-zero carbon electricity (e.g., running-river hydropower). Note that potential improvements currently not captured by the Planned Nodules Project scenario include (1) environmental and economic benefits of co-locating nodule-processing plants next to silicomanganese producers that could enable hot slag transfer of the Mn product—a configuration that could lead to lower energy consumption, lower costs, and lower CO_2; and (2) indirect benefits from future reductions in fossil fuel usage across the value chain, as modeled in the land ores dynamic scenarios.

In the future, it is also possible that nodule project developers could adopt additional high-impact initiatives to reduce impacts. Such initiatives are not modeled in this paper; the industry is still in the exploration phase with many yet-to-be-defined opportunities, and further environmental and economic efficiencies are likely to be explored once the industry moves into commercial production. As an example, nodule project developers could explore pathways to get to net-zero CO_2 operations, by: (1) oversizing renewable power plants to power onshore processing, using excess power to produce zero-CO_2 electrofuels, and using these fuels to power offshore operations while selling excess power on the market; or (2) using excess renewable power to produce hydrogen and using the hydrogen gas to replace coal as a reductant during nodule processing. It would be premature to model the impacts of these potential initiatives in the short term, as most nodule players are focused on getting into production under pressure to favor proven low-risk, low-capital expenditure technologies.

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76 (Morgan Stanley, 2017)

Incorporated into this paper are a variety of analytical models, literature reviews, historical studies, publicly available industry data, published model results, and proprietary data and analyses. Specific methods were chosen based on the need to achieve the goals of the study and the nature and availability of data, literature, and standardized practices. Where quantification was not plausible, heavy emphasis was placed on evidence from literature and published data. We have done our best to select the most likely, realistic, and relevant scenarios, sources, and assumptions. Where different assumptions lead to material divergencies in results, we have so indicated.

Throughout, the question constantly underpinning our study is: If choosing between metal production from land ores versus deep-sea nodules, on balance, which alternative is less harmful?

III. METHODS

Figure 17. Overview of Life Cycle Assessment (LCA)[77]
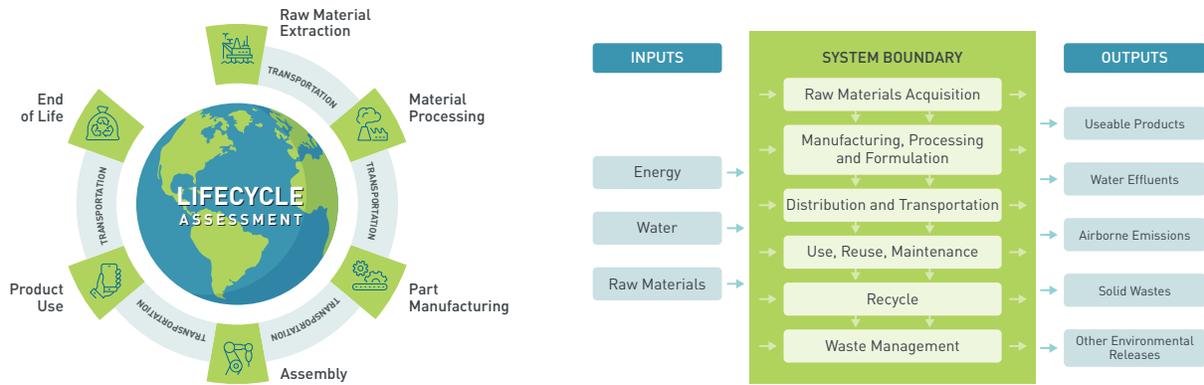
A LIFE CYCLE ASSESSMENT (LCA) estimates the aggregate impact of producing a complex technical output. It incorporates incremental contributions across the supply chain, including every material and energy input, transportation, assembly and manufacture of plants and equipment used, ship and road-building and maintenance, and resource extraction itself.
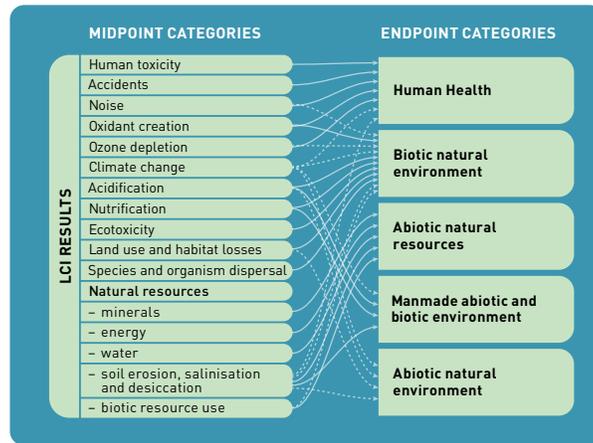
A LIFE CYCLE IMPACT ASSESSMENT (LCIA) is the step of the LCA that translates inventory into impact measurement. A wide variety of impact indicators maybe estimated via LCA. "Midpoint indicators" like climate change impact and cumulative energy demand serve as precursors of eventual "endpoint indicators" or "damage categories" like human and health impacts, ecosystem services, and biodiversity and species impacts.

THE LCA PRACTITIONER builds a basic model architecture using sizable databases of "background data" as building blocks. The practitioner then adds process-specific to the item being examined. This can be the most time-intensive part of the LCA study.
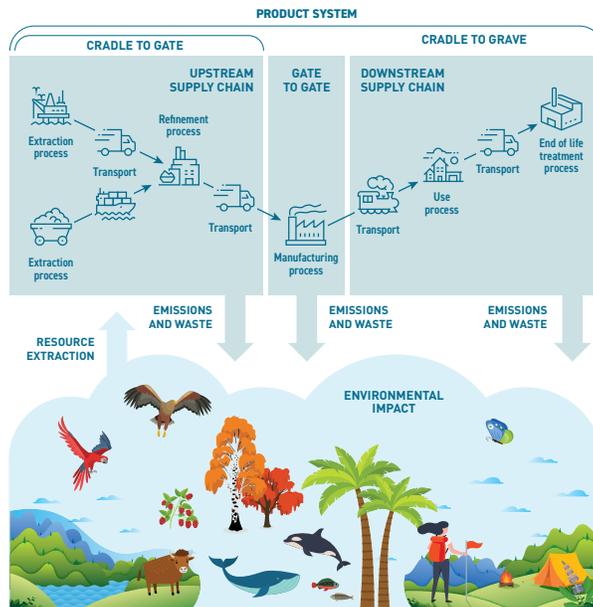
A "CRADLE-TO-GATE" LCA examines extraction through material production. This therefore excludes manufacture of the product, use, and disposal. This is a way to scope the impact with a focus on comparing different routes for producing a material, when the post-gate footprint is identical regardless of production method.

LIFE CYCLE ASSESSMENT STUDY

How can we measure the environmental footprint of drilling, blasting, and processing rock to extract the copper that eventually makes its way to an EV manufacturer? How would we compare this footprint to the end-to-end emissions of, say, producing a bag of coffee beans purchased at Whole Foods?

Life cycle assessment (LCA) has emerged as the preferred approach for such environmental impact comparisons, applied by practitioners globally.[78] In an LCA, the product's life cycle impact is represented as an environmental footprint associated with a set of flows of materials and energy. This is aggregated across the product's value chain—from extraction of resources through transportation, production, manufacture, usage, recycling, and disposal (see Figure 17). The life cycle impact assessment (LCIA) step compiles this information and translates it into impact indicators, enabling a comparative discussion of environmental impacts, no matter how different the product. ISO guidelines emphasize consistency across system boundaries, allocation methods, and modeling strategies for better comparability.[79]

This paper has generated LCIA assessments for all four metals needed for EV batteries, for both land and nodule sources, following ISO guidelines. For metal production from deep-sea nodules, a new cradle-to-gate LCA model was developed, following closely the methodology and assumptions adopted in existing literature on metal production from land ores.[80] For land ores, comparables from literature were selected and adapted to formulate a baseline for comparison. The four standard LCA steps were followed for generating the nodules model, as well as by each LCA used for the land-ores baseline. These four steps are as follows:

- **Goal and scope definition:** The goals of the study, methodologies, and indicators of choice are defined. Scoping is critical for project feasibility, given the substantial data requirements for a study.

- **Inventory analysis:** The individual life cycle inventory (LCI) data along the value chain is specified, collected from standard databases, literature, and/or experiment, and combined into a single model.

- **Impact assessment:** The selected LCIA indicators are computed from that LCI, following a number of LCIA standard protocols available, as determined by the LCA practitioner.

- **Interpretation:** The results are presented and implications are analyzed.

The LCAs performed for this paper were also supplemented by additional metrics and qualitative discussion, aligned to the paper's five impact categories as defined in the previous section.

In the rest of this subsection, we walk through key elements of the goal and scope of the study including system boundaries, selected indicators for study, and allocation methods; describe the prior art and data sources relevant to the land ores and nodules LCAs; and provide additional background on the supply and demand LCSA scenarios used. Impact assessment results and interpretation are presented in the Results and Discussion section. Detailed scoping assumptions and the inventory are available in the technical appendix.

To restate, the goal of this paper is to comprehensively compare environmental, social, and economic impacts of producing battery cathode precursors and copper from two different sources: 1) land ores, and 2) polymetallic nodules found on the ocean floor in the CCZ. We seek to produce realistic estimates of the relative environmental footprints that might be generated by creating metals for one billion EV batteries by 2047, using the two sources.

We scoped this LCA study as cradle-to-gate. A "**cradle-to-grave**" study would consider the entire life of a product and its input materials and energies. All life cycle stages would be modeled: resource

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78 By 1992, at least three LCIA methodologies had been developed: Environmental Priority Strategies (EPS), Swiss Ecoscarcity, and the Institute of Environmental Sciences (CML) 1992 guidelines; now there are at least 11. To normalize these, the ISO 14042 standard, precursor to ISO 14044, was formed in 1999.

79 Numerous literate references and guidebooks on LCA are available, e.g., (UNEP, 2016), ILCD Handbook on environmental impact assessment methodologies for use in LCA (European Commission, 2010).

80 Comparability was ensured through analysis of referenced papers, contact with literature authors, replication, study of standard production processes, and adherence to ISO guidelines.

extraction, production, manufacture, usage, recycling, disposal. This strategy is useful for comparing the total impacts of two types of products (e.g., conventional ICE car versus EV). However, a "**cradle-to-gate**" study, which considers production only up to the point of a refined material like nickel sulfate (product manufacture, usage, recycling, and end-of-life impacts are excluded), is useful for computing an impact difference within a subset of the value chain when the full impact need not be modeled. Cradle-to-gate is the relevant choice for this study, as we are comparing two different process types for producing the same final metal material—enabling an apples-to-apples comparison. Where an individual phase was focused on or only direct impacts were incorporated, such instances have been explicitly noted.

It was important to ensure system boundaries aligned for each analysis. The four final metal products compared are the direct inputs into EV cathode battery production—nickel sulfate, cobalt sulfate, and manganese sulfate, and copper cathode—in those specific product formats. Published LCA data,

literature, engineering models, and industry knowledge were used in combination to ensure the same format of metal was always being compared. For instance, where metal end products in existing literature did not align with these specified end products, LCAs for incremental process steps were modeled and the resulting impacts were added, or assumptions were otherwise noted.

Processing plant infrastructure and (for nodules) port construction were included in the models. For land ores, transportation and road construction were included in most cases, to the extent that prior art included them; these details are listed in the technical appendix.

The choice of specific production paths modeled for land ores were taken from literature comparables assessed to represent the majority of historical global production and/or paths likely to be used for future EV battery production, as well as weighted accordingly. Information about the metal production paths from land ores relevant for EVs is presented in the Metal Production Processes section.

IMPACT EVALUATION CATEGORIES AND STRATEGIES

Any LCIA study can vary in its choice, number, and degree of fidelity of impacts measured. Impact categories are selected from a number of standards, among those CML, ReCiPe, and LIME.[81] Common among standards is the notion of two subsets of LCIA impact indicators: "**midpoint indicators,**" or predictive measures like human toxicity, casualties, noise, acidification, ecotoxicity, land-use impacts, and mineral depletion; and "**endpoint indicators,**" or longer-term damage outcomes like human health, biodiversity loss, physical changes to land/soil/water, species risk, and ecosystem services impacts. Within ISO guidelines, a mixture of types and standards may be selected, focusing on the most relevant for answering the driving question, and at the level of fidelity appropriate to the question and the data.

This study employs a range of impact indicators, primarily midpoint indicators, to provide the basis for evaluating a category. The indicators were chosen at levels of complexity deemed useful in capturing essential differences between production methods.

Consideration was given to frequency of use in published LCA studies of metals, relevance to the mining and concentration phase, order-of-magnitude impact difference, and potential for insight. Indicators like CO_2 emissions, land and water use, waste, and carbon-sequestration impacts were modeled quantitatively. Other indicators like biodiversity impacts were assessed qualitatively, with the goal of clearly communicating impact differences, with some supporting quantifications.

81 The 'CML' LCIA standard derives its name from Leiden University's Institute for Environmental Sciences; the institute's name in Dutch is 'Centrum voor Milieuwetenschappen' (CML).

Table 3. Impact Categories and Evaluation Methods

IMPACT CATEGORY	EVALUATION METHOD
Climate Change	Full life cycle modeling (GWP) and quantification of specific impacts (carbon sequestration)
Nonliving Resources	Quantification of specific impacts
Biodiversity	Primarily qualitative assessment
Social Impacts	Primarily qualitative assessment
Economic Impacts	Quantification of specific impacts

The evaluation strategy for each impact category is summarized in Table 3 and detailed below.

Climate change. This consists of two major sub-categories. The first, GWP, is one of the first measures typically computed in a metal LCA study. A rigorous cradle-to-gate life cycle analysis focused on this indicator was appropriate since climate change impact from emissions is central to the study's purpose, and the impact is otherwise difficult to estimate. GWP of metal production from deep-sea nodules has not yet been addressed in literature, so an in-depth analysis was further warranted. The second sub-category, carbon sequestration, refers to the long-term storage of carbon within the earth's system. The potential impacts in this impact category are material and merit an in-depth analysis. This study offers a discussion of impacted carbon stores, mechanisms for potential release, and estimates of the amount of sequestered carbon at risk from metal-production activities. *Quantified: GWP 100a, stored carbon at risk.*

Nonliving resources. A number of midpoint indicators are related to the use or impact on nonliving resources, which drives impacts to biodiversity and ecosystem services. A few impacts were focused within specific value-chain steps and were modeled directly (e.g., seafloor use), requiring analysis and quantification but not warranting full LCA analysis to produce a qualitative impact judgment. Other indicators received a full LCA treatment. *Quantified: Freshwater usage, waste and tailings, land competition, forest use, seafloor use, SOx, NOx, ecotoxicity (terrestrial, freshwater), eutrophication potential, CED.*

Biodiversity. One cross-cutting LCIA damage category present with both metal sources is the impact on wildlife populations—on land, in freshwater, and in marine environments. While these impacts can be described, no LCIA metric sufficiently quantifies them, as the effects tend to be localized and highly interdependent. Midpoint indicators including those we explore under nonliving resources are useful in predicting biodiversity loss. The details of biodiversity loss also require an understanding of the habitats affected. For this evaluation, the subject of biodiversity is first clearly framed, some quantification is provided, and a qualitative discussion and literature review follows with detailed characterizations of terrestrial and abyssal wildlife. *Quantified: Wildlife at risk, biomass at risk.*

Social impacts. LCSA guidelines for social impact assessments include analyses of health and safety, child labor, discrimination, and other issues related to human rights and working conditions.[82] Impacts could relate to workers, local communities, society, consumers, and value-chain actors. This study focuses on illness and fatalities, vulnerable population impact, and the impact and relocation of indigenous people. *Quantified: Human toxicity, workforce at risk.*

Economic impacts. Life cycle costing may take into account private costs and benefits, external relevant costs, and/or societal costs (e.g., quantifying the cost of mining deaths).[83] This study approximates the life cycle private costs of metal production by first analyzing an industry standard for metal cost analysis known as the cost curve, as well as assessing the relative market sizes potentially affected by nodule

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82 (UNEP, 2011).

83 (UNEP, 2011).

operations. It then surveys the impacts on jobs, national economies, and economic risks. Societal costs (cost of human fatalities) are discussed under social impacts. **Quantified:** *Jobs (non-artisanal), nickel sulfate production cost (year 2025).*

The high-level methodological assumptions behind the models that generated indicator results for both land

ores and nodules are presented in Table 4 and Table 5. Where feasible, indirect impacts across cradle-to-gate stages were assessed and land ore dynamics through 2047 were included. In almost all cases, the impact was allocated on a per-metal-quantity basis and scaled up to one billion EVs. Methods were matched between production methods whenever possible, particularly for the LCIA midpoint indicators.

Table 4. Indicator Methodologies—Land Ores

INDICATOR	DIRECT OR INDIRECT	ALLOCATED	STAGES	DYNAMICS INCLUDED	METHOD	SOURCE
GWP	D + I	Yes	Cradle-to-gate	Yes	GWP 100a	Literature + Ecoinvent
Stored carbon at risk	D + I	Yes	Cradle-to-gate	Yes	Modeled per area	Research for parameters
Freshwater usage	D + I	Yes	Cradle-to-gate	No	Comparables	Literature Review
Waste and tailings	Direct	Yes	Cradle-to-gate	Yes	Comparables/ Model	Literature Review
Land competition	D + I	Yes	Cradle-to-gate	Yes	CML indicator	Literature + Ecoinvent
Forest use	D + I	Yes	Cradle-to-gate	Yes	CML indicator	Literature + Ecoinvent
Seafloor use	Direct	Yes	Tailings Disposal	Yes	Comparables	Literature Review
SOx	D + I	Yes	Cradle-to-gate	No	SimaPro Inventory	Ecoinvent
NOx	D + I	Yes	Cradle-to-gate	No	SimaPro Inventory	Ecoinvent
Terrestrial ecotoxicity	D + I	Yes	Cradle-to-gate	No	CML indicator	Literature + Ecoinvent
Freshwater ecotoxicity	D + I	Yes	Cradle-to-gate	No	CML indicator	Literature + Ecoinvent
Eutrophication potential	D + I	Yes	Cradle-to-gate	No	CML indicator	Literature + Ecoinvent
Cumulative Energy Demand	D + I	Yes	Cradle-to-gate	Yes	CED indicator	Literature + Ecoinvent
Wildlife at risk	D + I	Yes	Cradle-to-gate	Yes	Literature Review	Literature Review
Biomass at risk	D + I	Yes	Cradle-to-gate	Yes	Literature Review	Literature Review
Human toxicity	D + I	Yes	Cradle-to-gate	No	CML indicator	Literature + Ecoinvent
Workforce at risk	Direct	Yes	Extraction	Yes	Comparables	Literature Review
Jobs (non-artisanal)	Direct	Yes	Extraction	Yes	Comparables	Literature Review
NiSO4 cost, 2025	D + I	Yes	Cradle-to-gate	No	Market analysis	Cru assessment

Table 5. Indicator Methodologies—Nodules

INDICATOR	DIRECT OR INDIRECT	ALLOCATED	STAGES	DYNAMICS INCLUDED	METHOD	SOURCE
GWP	D + I	Yes	Cradle-to-gate	No	GWP 100a	DG Op Concept
Stored carbon at risk	D + I	Yes	Cradle-to-gate	No	Calculated	Research for parameters
Freshwater usage	Direct	Yes	Process/Refine	No	Modeled	DG Op Concept
Waste and tailings	Direct	Yes	Cradle-to-gate	No	Literature Review	DG Op Concept
Land competition	D + I	Yes	Cradle-to-gate	No	CML indicator	DG Op Concept
Forest use	D + I	Yes	Cradle-to-gate	No	CML indicator	DG Op Concept
Seafloor use	Direct	Yes	Extraction	No	Calculated	DG Op Concept
SOx	D + I	Yes	Cradle-to-gate	No	SimaPro + model	DG Op Concept + Lit Rev
NOx	D + I	Yes	Cradle-to-gate	No	SimaPro + model	DG Op Concept + Lit Rev
Terrestrial ecotoxicity	D + I	Yes	Cradle-to-gate	No	CML indicator	DG Op Concept
Freshwater ecotoxicity	D + I	Yes	Cradle-to-gate	No	CML indicator	DG Op Concept
Eutrophication potential	D + I	Yes	Cradle-to-gate	No	CML indicator	DG Op Concept
Cumulative Energy Demand	D + I	Yes	Cradle-to-gate	No	CED indicator	Literature + Ecoinvent
Wildlife at risk	D + I	Yes	Cradle-to-gate	Yes	Literature Review	Literature Review
Biomass at risk	D + I	Yes	Cradle-to-gate	Yes	Literature Review	Literature Review
Human toxicity	D + I	Yes	Cradle-to-gate	No	CML indicator	DG Op Concept
Workforce at risk	Direct	Yes	Extraction	Yes	Comparables	Literature Review
Jobs (non-artisanal)	Direct	Yes	Extraction	No	Modeled	DG Op Concept
NiSO4 cost, 2025	D + I	Yes	Cradle-to-gate	No	Market analysis	DG Op Concept

ALLOCATION AMONG BYPRODUCTS

In LCA, anytime a processing step results in two or more outputs, the step's footprint must be allocated among outputs. The choice of allocation method is critical for comparability of LCA study results. If byproducts are involved, as is the case with nodules, the results may wildly differ depending on the method used.

Suppose a tonne of ore was processed into five kilograms of copper, five kilograms of cobalt, and 990 kilograms of waste; to which output should we attribute emissions, energy demand, etc.? Should copper and cobalt receive equal allocations, even though the cobalt is much more valuable?

Under mass allocation, the footprints would be allocated in direct proportion to the product mass outputs; on a per-kilogram basis, copper and cobalt would be equally responsible for impacts. Under

economic allocation, footprints would be allocated in proportion to the economic values of the outputs; one kilogram of cobalt (much more expensive than copper) would be allocated the bulk of the impact, while one kilogram of copper would have a much smaller impact, so that the economic driver of the process would receive proportionally more burden. Economic allocation is the more general practice, particularly for metal LCAs. Whether mass or economic allocation is used, wastes or unsold and disposed of byproducts with no economic value or industrial utility do not have a footprint attributed to them. The 990 kilograms of waste would be attributed zero impact. Note that all such allocations are applied only after separating and excluding any subprocesses, inputs, or outputs that can be directly allocated to one product or the other, per ISO recommended practices.

Figure 18. Mass and Economic Metal Content of CCZ Polymetallic Nodules[84]
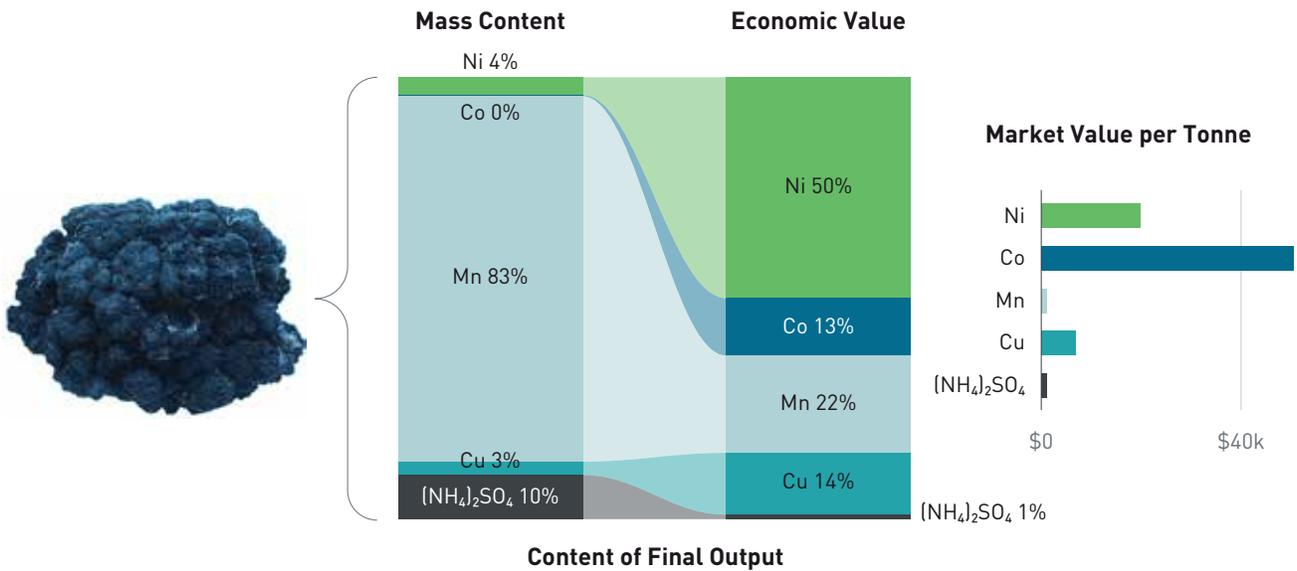
84 Market values and mass allocations based on preliminary economic analysis compiled for NORI Area D by AMC Consultants in April 2019, with independent inputs from Hatch on processing and several marine and subsea engineering contractors on collection. See (AMC Consultants (B), 2019).

To illustrate how allocation choice can impact LCA results for metal production, Figure 18 shows the difference between mass content and economic content for a CCZ polymetallic nodule. The manganese product has the highest production volume, but nickel accounts for 50% of the economic value of a nodule.

Note the practical implications of economic allocation—that without any changes in the operational profile of a processing plant, the emissions allocated to a kilogram of copper or cobalt will vary depending on commodity prices. Arguments for using mass-based allocation include the volatility of commodity prices (although common practice is to use multiyear moving averages to help counter this), and the intuition that physical proportions should matter. Arguments for economic allocation include the fact that economic drivers cause the activity to happen in the first place, with the product's price being the (imperfect) measure of the utility created.

Following scholarly recommendations and the predominant use of the economic basis in metal production LCA literature, this paper uses economic allocation.[85] For some indicators, including the more in-depth GWP study, a mass-based sensitivity analysis is also provided.

Below we provide a few details about the allocation design for the nodule-processing model. The allocation details for the land-ore studies are available in the comparables literature, and summarized in the technical appendix of this paper. Figure 19 shows a block diagram of nodule-processing operations along with its allocation methodology. Boxes highlighted in red are economically allocated among the byproducts. The main battery precursor products are seen on the far right.

Following ISO 14040/44, three basic sequential steps were taken. First, the multifunctional process was subdivided, identifying inputs and outputs per subprocess. The main process branches were grouped as follows: (1) from nodule collection through pyrometallurgy, with the exception of coal-based reduction; (2) coal-based reduction, which allows for separation of manganese from other metals; and (3) individual refining steps, separately for matte and for manganese. Second, where possible, direct physical causalities for allocation were identified—a clear mapping was made of inputs to outputs.[86] Third and finally, for subprocesses where using physical properties for allocation purposes was not possible, impacts were allocated based on economic value of end products.[87]

The unique composition of the nodule resource, along with the plant location flexibility, together enable a zero-tailings, zero-waste processing design. As a result, the model did not need to include additional environmental impacts from waste disposal or tailings pond construction and maintenance as have been modeled for land ores. The converter slag byproduct noted is not a waste, as it has value as an industrial input and is earmarked to be sold for a variety of end uses (e.g., abrasives and road ballast), but since any economic value is expected to be offset by the cost of transport to customer facilities, in this model it receives zero allocation. This same byproduct might be a waste if it were not economical to transport to a plant that could use it and it were instead simply disposed of; note that operational design in this way can directly impact the overall environmental footprint. The reused converter slag slightly reduces the overall life cycle impact by offsetting raw materials needed for abrasives and road ballast; this environmental benefit is quantified in the LCA as an offsetting credit.

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85 See the Handbook on Life Cycle Assessment: (Guinee, Gorree, & Heijungs, 2002).

86   An example of this is taking a mixed ore of manganese and copper oxides, with a manganese: copper ratio of 2:1, and reducing it with coal. Carbon atoms react with the oxides, grabbing an oxygen and emitting carbon monoxide or carbon dioxide. Since twice as many carbon atoms would go to manganese as copper (as there are twice as many manganese molecules), the carbon input would be allocated in a 2:1 ratio. This is why manganese, the majority of metal mass in a nodule, still has a high overall allocation result under the economic allocation scheme.

87 Economic values for the four base metals are given per mass of metal contained in final product form and based on projections in a preliminary economic assessment on the NORI Area D project in the CCZ; see (AMC Consultants (B), 2019).

Figure 19. Nodule Operations Impact Allocation Design Block Diagram[88]
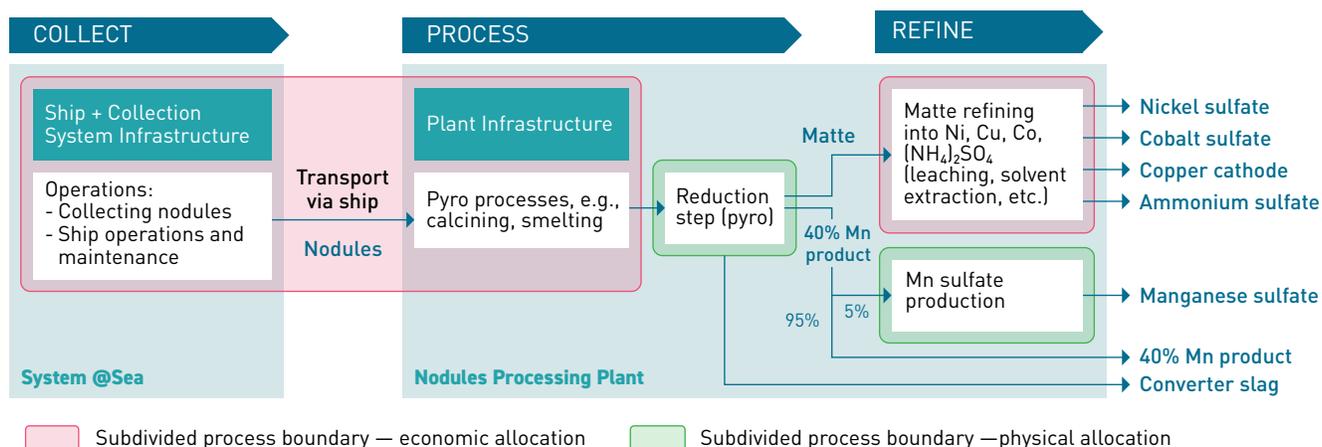
Two different manganese end products will typically be produced from the 40% grade manganese silicate intermediate product: silicomanganese alloy, a standard manganese product with a deep market structure, and manganese sulfate which is needed for EV battery cathodes. Based on supply-and-demand-side analyses of markets and economics for these products, it is expected that 95% of the manganese contained in nodules will end up in a silicomanganese alloy and 5% will be refined into manganese sulfates. The market value and mass of manganese metal contained in the 40% grade manganese silicate product was used as the basis for economic allocation of either manganese end product; the processing paths for both are identical up to this point.

Of these two manganese product end points, this paper focuses on refinement into the battery-grade sulfate, as it is the product form relevant to the one billion EV demand scenario. Although silicomanganese production is not modeled in this LCA, the allocated impacts from producing 40% manganese product are fully represented in the manganese sulfate LCA results. Modeling either product captures key processing and impact differences posed by nodules, as both include the process steps from collection through the point of 40% grade product attainment. Note that since the 40% product has already been partially reduced, the typical intensive impacts of reduction during silicomanganese alloy-making are expected to be somewhat lessened compared to land ore processing.

Piecewise and final aggregate allocations for both economic and mass-based methods for polymetallic nodule-based production can be seen in Table 6.[89]

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88 Note that the figure illustrates reduction occurring after the rest of pyrometallurgical processing. This is for graphical simplification and illustration of allocation groupings only. Reduction is one of the first steps in pyrometallurgical processing.

89 Allocations include calculation of mass and economic outputs based on a preliminary economic assessment; see (AMC Consultants (B), 2019).

Table 6. Economic and Mass-Based Allocations for Nodule Modeling

COLLECTION + PYROMETALLURGICAL PROCESSING	ECONOMIC ALLOCATION	MASS-BASED ALLOCATION
Manganese silicate product	22.3%	82.8%
Matte (copper, nickel, cobalt in output proportions)	77.7%	17.2%

REDUCTION STEP	PHYSICAL ALLOCATION	
Manganese silicate product	95%	95%
Matte (copper, nickel, cobalt in output proportions)	5%	5%

MATTE REFINING	ECONOMIC ALLOCATION	MASS-BASED ALLOCATION
Copper cathode	18.4%	17.0%
Nickel sulfate	64.5%	21.2%
Cobalt sulfate	16.3%	2.1%
Ammonium sulfate	0.8%	59.7%

OVERALL EFFECTIVE ALLOCATION OF ONE NODULE FOR CO₂E[90]	ECONOMIC ALLOCATION	MASS-BASED ALLOCATION
Copper cathode	2.9%	1.5%
Nickel sulfate	10.1%	1.8%
Cobalt sulfate	2.6%	0.2%
Manganese silicate product	84.3%	91.4%
Ammonium sulfate	0.13%	5.1%
Converter slag	0%	0%

DATA, PRIOR ART, AND ASSUMPTIONS

In an LCA, every individual element of material, energy, or process must be designated for one of two types of LCI data. **Background data** are precollected, publicly available standardized information sources. Thousands of common material and energy items are found in databases such as Ecoinvent, and are typically used when coarser estimates are acceptable. **Foreground data** are individually collected LCI data for items requiring higher fidelity or not found in background data sets. They may be collected through literature reviews, case studies, experiments, or surveying individual processing plants, as well as estimated from first principles using thermodynamic analysis and engineering efficiency factors.

To model a truck with a new type of diesel combustion engine, you might collect foreground LCI data for this truck's novel combustion elements, then pull background LCI data for the metal frame of the truck, the electricity expended to manufacture the truck, and diesel usage per tonne-kilometer. To model a bag of coffee beans sold at Whole Foods, you would collect foreground LCI data for novel steps of the coffee-bean preparation process, but you could rely on background LCI data for the truck transport.

For metal production from land ores, LCIA benchmarks were created for this paper, building on the work in numerous published studies that have performed land-based cradle-to-gate LCAs for the four metals in question.[91] Study results were aggregated into a representative set of impacts. When more than one source published results on the same metal, studies with the closest match on production pathways, or

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90   This shows the effective aggregate allocation outcome, incorporating all allocation steps including the physically allocated reduction process, as calculated for the CO₂e emissions LCA for nodules.

highest fidelity/quality data, were selected and weighted appropriately to represent modeling of metal production from land ores. Models were adjusted as described to match final product specifications.

As mentioned, a key aspect of the land-ore benchmark design was the choice of production paths to include. Most refined metals have numerous production pathways that may depend on ore characteristics, geography and surface depth of deposits, and required purification and refining methods (see Impact Drivers section for discussion on mineralogy). This study focuses on production paths that are most likely to be used in producing EV batteries in significant quantities in the future. Typically between one and three aggregate production pathway classes represented more than 90% of global production volume for a given metal. A small set of most representative production paths deemed likely to supply EV production were selected based on global volume and suitability for EV battery value chain.[92] For example, Class I nickel is the typical input for EV battery production. Historically, most Class I nickel has been produced from nickel sulfide deposits processed pyrometallurgically and then refined with hydrometallurgy. But the share of Class I nickel produced from nickel laterites processed hydrometallurgically is now growing. Both of these Class I nickel production paths have therefore been included. Where possible, a simple weighting scheme based on production volume projections has been used. For production pathways for nickel, cobalt, and manganese that ended as a metal powder product, a simple model for producing sulfates from these metal powders was added to the high fidelity LCA.

Foreground data for the nodules model was collected based on the operating concept of DeepGreen Metals, one of the nodule-exploration contract holders in the CCZ, including a preliminary economic assessment (PEA) independently compiled by AMC in May 2019 and detailed engineering models. The PEA itself is based on independent inputs from several specialized engineering houses—DRT, Cellula, and Herbert Engineering for the offshore production system and Hatch for design of the metallurgical plant and refining facility. DeepGreen's production-system design is sized to collect, process, and refine 4.88 million dry tonnes of nodules per year and produce five main product streams: nickel sulfate, cobalt sulfate, a 40% grade manganese silicate product, copper cathode, and fertilizer-grade ammonium sulfate. In addition, two other minor products are produced—manganese sulfate from refining a small portion of the manganese product, the converter slag used in abrasives, road ballast, etc. While this paper focuses on the impacts of four final products that go into EV production (nickel sulfate, cobalt sulfate, manganese sulfate, and copper cathode), the other products were taken into account when allocating impacts, as described previously. Where exact matches were not available, comparables were chosen and validated with sensitivity analyses.

The Ecoinvent v2.2 database was used for all background data, with few noted exceptions. This choice was made for best comparability with published land-ore literature sources, as most sources used this database version. Matching database sources allows the nodule and land-ore studies to leverage the same reference LCI for thousands of energy, material, metal, and other products. In exception cases, where individual items were unavailable in v2.2, v3.5 was used. Sensitivities around these version differences were performed, and negligible differences in outcomes were seen.

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91 (Nuss & Eckelman, 2014) presents a comprehensive study of over 60 metals. (van der Voet, van Oers, Verboon, & Kuipers, 2018) created a scenario-based study of seven metals that comprise 93% of global metal production, projecting to future global supply and demand scenarios including a potential decline of land-based ore grades, including nickel, copper, and manganese. (Kuipers, et. al., 2018) also studied in detail the environmental impacts of multiple copper production paths, augmenting the Ecoinvent database information. (Dai, Kelly, & Elgowainy, 2018) presents a detailed life cycle inventory (LCI) of the majority of land-based cobalt production which occurs in China, filling a significant gap in Ecoinvent's sparser dataset on global cobalt production. (Zhang, et al. 2020)'s robust LCA of electrolytic manganese metal (EMM), a frequent precursor to battery-grade sulfate, covers several Chinese regions and a large proportion of overall EMM production, while Ecoinvent includes industrial-grade manganese sulfate; as both lack final refining steps, they proxy as conservative estimates for battery-grade sulfate's impact.

92 The technical appendix of this paper provides further detail on the specific GWP impact contributions documented in the literature, the production paths, and weights chosen.

LAND-ORE SUPPLY SCENARIOS

Scenario analysis was used to study different potential futures of resources, policy priorities, behaviors, and geopolitics. Doing so allows us to form an intuition about impacts of metal production based on a range of potential futures. Land-ore supply scenarios explore the impacts of current base cases as well as a green mining scenario, while factoring in expected ore-grade declines and potential changes in electricity mixes over time.[93] Following the latter example, we first derive per-kilogram impacts for each kilogram of metal end product, then scale these to cover the metal needs of building one billion EV batteries by 2047, and finally, apply the dynamic impacts over time.

The dynamic land-ore scenarios incorporated two types of dynamics:

1. **Ore-grade declines, which drive energy requirements and emissions.** Falling grades for land-sourced metals like copper and nickel mean that larger and larger volumes of rock need to be excavated and concentrated to produce the same output. Larger volumes of excavated ores in turn substantially increase the environmental footprint. While at the micro level, numerous factors like economics, coproduction of metals, and geographic constraints determine which specific ore bodies on land are mined, at the macro level, ore grades for copper and nickel have been declining for several decades. Supply scenarios for land ores incorporate the impact of ore-grade declines on emissions at different steps of the value chain, projected over time.

2. **Human policies, which impact fossil fuel use and technological advances.** Adopting the choices made in land-ore studies, two dynamic cases are defined based on UNEP GEO-4 scenarios spanning economy, policy, security, and environment priorities, in conjunction with World Energy Outlook's electricity-mix scenarios.[94] The key material outcome of these policies is the amount of fossil fuel in the electricity mix used to power land-mining operations. Two policy scenarios are studied: Markets First, an economics-focused baseline case, and the environmentally focused Equitability First scenario. The electricity-

mix trajectory in Equitability First scenario drives significant improvements for land ores that can counteract some of the negative impacts driven by ore-grade declines.

Combining these two dynamic effects, the following land-ore supply scenarios are presented in this paper:

1. **The Baseline Land Ores Scenario, based on Markets First (UNEP) and Current Policies scenarios.**[95] In this scenario, economic growth continues to be the strongest driver for global growth and well-being, generally following the current trajectory. This scenario follows a business-as-usual approach, with global economic growth as the main policy driver. Global electricity mix shifts only slowly toward renewables from 22% in 2015 to 25% by 2050, with coal nearly constant around 41%–42% and natural gas around 22%-24%. The negative impacts of ore-grade declines in nickel and copper tend to dominate.

2. **The Green Land Ores Scenario, based on Equitability First (UNEP) and "450" scenarios.**[96] This scenario envisions an aggressive transition away from fossil fuels and toward renewables. A balance between human, environmental, and economic health is struck through vigorous government/civil/private sector collaborations. The focus is on goals set by the World Summit on Sustainable Development, including climate change, long-term impacts, and transparency and legitimacy. Significantly greater levels of decarbonization in electric grids are modeled, with renewables' share increasing from 22% in 2015 to 64% by 2050 and coal decreasing from 41% in 2015 to 0% in 2050 (see Figure 44). This scenario delivers material reduction in LCIA impacts compared to the baseline case but is still partially negated by the impact of ore-grade declines.

In addition to these supply dynamics, the copper LCA model incorporates slight projected processing efficiency increases over time. Copper production processes have historically been close to the optimal theoretical minimum energy requirements.[97] This dynamic was mathematically quantified for copper in the source literature and is included in this study.[98]

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93 As described in existing LCA literature, including (Northey, Mohr, Mudd, Weng, & Giurco, 2014) and (van der Voet, van Oers, Verboon, & Kuipers, 2018).

94 Land-ore studies: (van der Voet, van Oers, Verboon, & Kuipers, 2018) and (Kuipers, et. al., 2018). UNEP GEO-4: (UNEP, 2007). World Energy Outlook: (IEA, 2012).

95 (IEA, 2012).

96 (IEA, 2012).

97 See (Kuipers, et. al., 2018) and (Alvarado, Maldonado, Barrios, & Jaques, 2002).

98 (Kuipers, et. al., 2018).

IV. METAL PRODUCTION PROCESSES

As mining has been increasingly moving to more remote locations, often in the developing world, general public exposure to and awareness of mining processes have become more limited. Metal production from ocean-floor nodules, on the other hand, is a disruptive, new, and not yet widely understood alternative expected to come online in the 2020s.

Due to the unique nature and location of polymetallic nodules, different processes are needed to produce the same base metals. In order to compare the impacts of metal production from two different sources, it is important to understand the differences between land ores and ocean nodules as well as the specific production processes involved.

Below we present an introduction to the nature of each of these resources, the mining and processing procedures involved, and key drivers of differences in associated impacts.

GENERALIZED PROCESS

Any metal production path involves complex chemistries, energy-intensive processes, and interdependencies between metal production paths. We begin with a simple conceptual framework that is common to production from both land ores and seafloor nodules.

At the highest level of abstraction, metal production consists of three basic steps (see Figure 20):[99]

1. **Mining:** Extract mineral ores and, if needed, crush and concentrate them into a higher-grade ore (also referred to as "beneficiation" or "comminution").[99]

2. **Processing:** Use water-, heat-, or chemical-based processes to separate out the metal compounds.

3. **Refining:** Refine the metals from intermediate forms into pure metals or alloys.

Figure 20. Generalized Production of Metals, Cradle-to-Gate
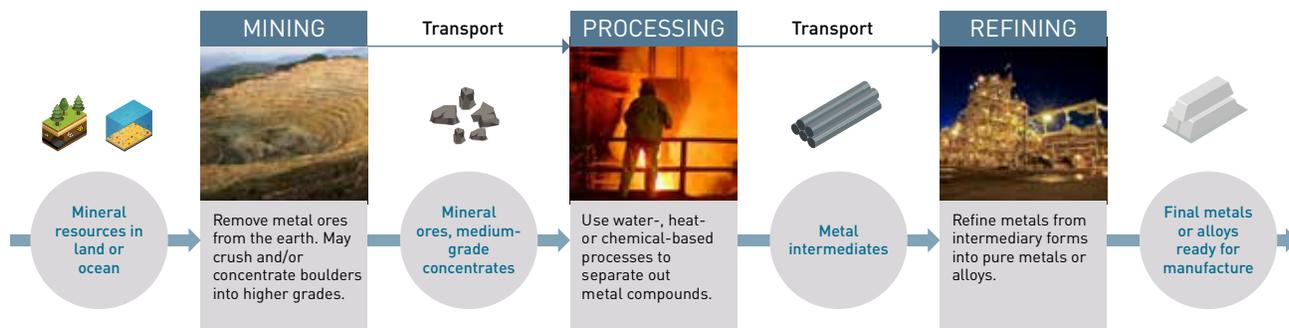
In the mining step, ore is extracted from either land-ore bodies or deep-sea nodules. This step has a complex life cycle. Its impact footprint varies significantly between land and nodules, but can also vary across different land-ore bodies depending on the ore-body grade, geology, and location.

The processing step usually occurs at a metallurgical plant. Ore inputs undergo processing to separate out the metal compounds. The specific processes used depend on the nature of the ore. Two of the most common approaches (or "flowsheets") are pyrometallurgical (heat intensive) and hydrometallurgical (water intensive). Both flowsheets may use a range of chemical inputs. Depending on the specific material, a hybrid or multistep process may also be used, as is the case for processing and refining nodules.

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99 Specific process stages vary per metal. The generalized process has a uniform framework that applies to most metals, with some modifications. Process stages are based on aggregated trends in the Ecoinvent database (University of Arizona, 2019) and (Nuss & Eckelman, 2014).

Pyrometallurgical and hydrometallurgical processes are quite different:

- **In pyrometallurgical processes,** inputs are heated to high temperatures, then smelted. The resulting molten phases separate into layers like oil and water, making it possible to separate different metals. Given high heat requirements, pyrometallurgical processes are typically energy intensive and require substantial amounts of coal, natural gas, electricity, and/or other sources of energy. To purify the compounds, pyrometallurgical flowsheets typically involve "reducing" a metal oxide or removing oxygen atoms. This is accomplished by binding oxygen with carbon atoms contained in coal and releasing CO_2 in the process. Slag is the main waste stream, which can sometimes be a useful byproduct.

- **In hydrometallurgical processes,** metal extraction is accomplished by leaching inputs with aqueous solutions—usually acids or bases with reducing or oxidizing agents. Among the methods used to do this are pressure leaching, dump leaching, heap leaching, or in situ leaching performed at the mining site. Each method has different material and energy requirements. These processes produce metals in aqueous solution that can be separated from the non-leachable solids for further purification and refining. Hydrometallurgical processes typically require large quantities of water, can be electricity intensive, and produce waste residues and effluents.

In the refining step, the intermediate product from the processing step is typically refined to produce the final desired metal or alloy. Refining methods include electrowinning, electrorefining, solvent extraction, and stepwise crystallization. Electrowinning is an industrial electrolytic process in which an electric current applied to a metal-rich solution pulls charged ions onto a cathode. Electrorefining uses a similar process to remove impurities from a less pure metal, depositing the pure metal onto a cathode. These processes are often used to produce copper cathode. Crystallization typically involves a reaction with sulfuric acid—for example, metallic cobalt or cobalt oxide reacts with sulfuric acid to produce a cobalt sulfate salt. Refining can also be more complex, as is often the case with nickel. Various methods can be used to refine nickel intermediates, including several acid-leach and purification flows, as well as carbonyl refining, which produces coatings by vapor plating.

While these steps are generally descriptive of metal production regardless of the source of the ore, materially important differences remain in the specifics of different processes when it comes to producing the four base metals from land ores compared to seafloor polymetallic nodules. The mining step takes place in two very different environments (land versus deep sea) and requires two very different mining operations. The unique nature of the nodule resource leads to differences in processing and refining even if very similar processes are used. We describe these differences next, beginning with land ores.

PRODUCTION FROM LAND ORES

The mining step of metal production on land is often complex, lengthy, and costly, both economically and environmentally (Figure 21).

Mining starts with prospecting and exploring for a suitable ore-body size, quality, and economics. It is a high-risk endeavor that costs millions of dollars and may take eight to ten years to complete.

Depending on the location of the discovered ore body, developing a new mine is a lengthy, costly, and high-impact effort. If the ore body is located in a populated area, the local community is resettled. If the ore body is located in a remote area, as new ore bodies increasingly

tend to be, years can be spent building infrastructure—including roads and railways to access the site, grid extensions to power it, and accommodations and other facilities for miners. In the case of open-pit mines, forests and vegetation are cut down, and a large area of overburden or top layer of soil covering the ore body is removed and dumped onto adjacent land. To create a spiraling terraced access to the body for heavy dump trucks and other mining equipment, a much larger volume of country rock surrounding the ore body is drilled, blasted, and dumped at the mine site, often leading to "stripping ratios" of two to ten tonnes of country rock for every tonne of ore body. In the case

of underground mines, years are spent drilling access shafts and development tunnels, installing underground infrastructure, and bringing power and ventilation into the mine. Billions of dollars and five to ten years are often invested in developing a mine before a single tonne of ore is mined.

The operational phase of a mine can last five to fifty years and beyond, with annual operating costs often in the hundreds of millions to billions of dollars. To dislodge boulders of ore and country rock, holes are drilled into the ore body, filled with chemical explosives, and blasted. The boulders are often fed into onsite crushers. Crushed ore may be beneficiated into more concentrated mineral forms, e.g., by using froth flotation to gather valuable metals at the surface of a froth layer. Crushed ore or concentrates are then transported to processing plants.

Figure 21. Metal Production from Land Ores: Mining Life Cycle[100]

MINING LAND ORES

Remove metal ores from the earth. May crush and/or concentrate boulders into higher grades.

Land Ore Mining Life Cycle

1 Prospecting and Exploration

2 Development

3 Mining and Extraction

4 Closure and Reclamation

1
- $1M to $10s of Millions
- ~2–8 years
- Locate economically viable ore deposits with high certainty

2
- Up to $ Billions
- ~10+ years from discovery
- Plan and execute on building mines and supporting facilities and roads

3
- Up to $ Billions/year, 5–50+ years
- Ongoing mining operation

4
Restore the lands to the extent possible. Remove bridges and roads, cover ground, revegetate, dry tailings ponds.

The bulk of the original mined tonnage goes into "tailings"—essentially waste rock containing toxic chemicals. Tailings are deposited outside the mine in specially constructed dams. Tailings represent one of the major long-term impacts from land mining, in part due to extreme ecosystem harm and fatalities caused by tailings dam collapses.

Mine closure and reclamation is a costly, lengthy, and difficult process. It can require flattening piles of discarded rock, covering sulfide-containing rocks to prevent rainwater from making sulfuric acid, allowing tailings ponds to evaporate then covering them for dust protection, applying topsoil throughout to support revegetation, fencing open pits, and closing shafts. An unrehabilitated closed or abandoned mine can drain acidic, toxic-metal contaminated water into streams, soil, and groundwater, produce windborne toxic dusts, and cause injuries.

The cost of rehabilitation is often underestimated. It is not uncommon for operators to go bankrupt before the rehabilitation is finalized, with rehabilitation costs frequently passed on to the state. Depending on its size, a single mine can cost taxpayers nearly $100 million to reclaim.[101] One estimate of metal and mineral production in Canada's three northern territories suggests a cumulative production value of $18 billion since 1977, but the country now faces around one billion dollars in closing costs.[102] Increasingly, some closed mines are maintained on a temporary closure status, waiting to be reopened once technology evolves and/or producing the remaining lower-grade ores becomes profitable. Other mines are simply abandoned. There are currently more than 500,000 abandoned hard-rock mines in the United States alone, with over fifty billion tonnes of untreated and unreclaimed wastes covering US lands.[103] A 2015 report from the Center for Western

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100 See, e.g., the Superfund Research Program (University of Arizona, 2019).

101 (McCarthaigh, 2019).

102 (Caldwell, 2013).

103 (Bureau of Land Mines, n.d.); (IIED, 2002).

Priorities suggests that the cost to reclaim 100,000 abandoned mines on public lands in the western US will reach $21 billion.[104]

Next, we detail the typical life cycle production paths used for producing battery-grade nickel, cobalt, manganese, and copper.

Nickel

The environmental impact of producing nickel can vary significantly depending on the production pathway. This is because nickel is produced from several ore types, using several production paths, with different outputs and metal byproducts. Depending on mineralogy, nickel-containing ores may be mined from either open pits or underground mines; either concentrated through mineral-processing techniques or left unconcentrated; and processed either pyrometallurgically or hydrometallurgically.

Most nickel is produced from two types of ore: sulfides and laterites:[105]

- **Sulfides** represent about 40% of global nickel reserves and about 30% of production, a significant reduction from only fifteen years ago when the production rate was about 60%.[106] Sulfides are magmatic, formed from plutonic or igneous processes and hydrothermal processes in the earth, and they tend to be located in particular continental geological settings. The largest sulfide deposit is located on a large igneous province in Norilsk, Russia. Other substantial sulfide deposits are found in China, Canada, Australia, and Southern Africa. The coproducts of nickel production are often copper and cobalt, with varying quantities of precious metals like palladium, platinum, and gold. Ore grades of produced sulfides are typically below 1% and falling, with an average grade of around 0.73% in 2010 and

a 0.26% projected long-term asymptotic reserve level.[107] Ore grades from the top ten sulfide producers globally show median project grades of sulfides at 0.50% in 2011 (see Figure 22). Sulfides can generally be upgraded to concentrates grading 10%–20% through physical separation by grinding and froth flotation.

- **Laterites** represent 60% of global nickel reserves and about 70% of production. Laterites are formed through extensive weathering of ultramafic rocks in wet, warm climates, and therefore are found in tropical regions between latitudes 24° north and 24° south of the equator. Substantial deposits are found in New Caledonia, Australia, the Philippines, and Indonesia. Cobalt may be a byproduct. The higher biodiversity typically found in tropical locations of laterite mines implies greater risk to biodiversity by mining laterites. For instance, Indonesia, the world's largest producer of nickel, ranks third in biodiversity overall and has the highest coral diversity in the world. The area in Indonesia where laterites are found has one of the highest rates of endemic species on earth. Laterites show a narrow grade range, with the majority of deposits above 1% grade, higher than sulfides on average. Two types of laterite deposits are found: lower-grade limonites (grading around 1.3% or less) and higher-grade saprolites (often grading over 1.8%). Limonites are processed hydrometallurgically and saprolites are processed pyrometallurgically. Average laterite ore grades are expected to fall from an average grade of around 1.8% in 2010 to a 1.12% projected long-term asymptotic reserve level.[108] While laterites are higher grade than sulfides, they cannot be readily upgraded to concentrates prior to smelting like sulfide ores can be because nickel in laterites occurs as silicates or oxides, which require significant energy to process.

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104 (Weiss, 2015).

105 For further details on nickel ores, classes, and markets, see (McKinsey & Company, 2017), (International Nickel Study Group, 2018); for sulfides, laterites, and grades, see (Mudd G. M., 2009), (Schulz, et al., 2010), (USGS, 2011), and (Mudd & Jowitt, 2014).

106 See (Dalvi, Bacon, & Osborne, 2004) for a historical laterite expansion assessment.

107 (van der Voet, van Oers, Verboon, & Kuipers, 2018).

108 (van der Voet, van Oers, Verboon, & Kuipers, 2018); (Mudd & Jowitt, 2014).

Figure 22. Cumulative Distributions of Ore Grades for Nickel Laterite and Sulfide Production in 2010[109]

a) Nickel Sulfides Ore Grade Distribution

~89.9% <2% Ni

Median grade 0.50% Ni

Sulfides

Percent (cumulative) / Ore Grade (%Ni)

b) Nickel Laterites Ore Grade Distribution

~90.0% <2% Ni

Median grade 1.1% Ni

Laterites

Percent (cumulative) / Ore Grade (%Ni)
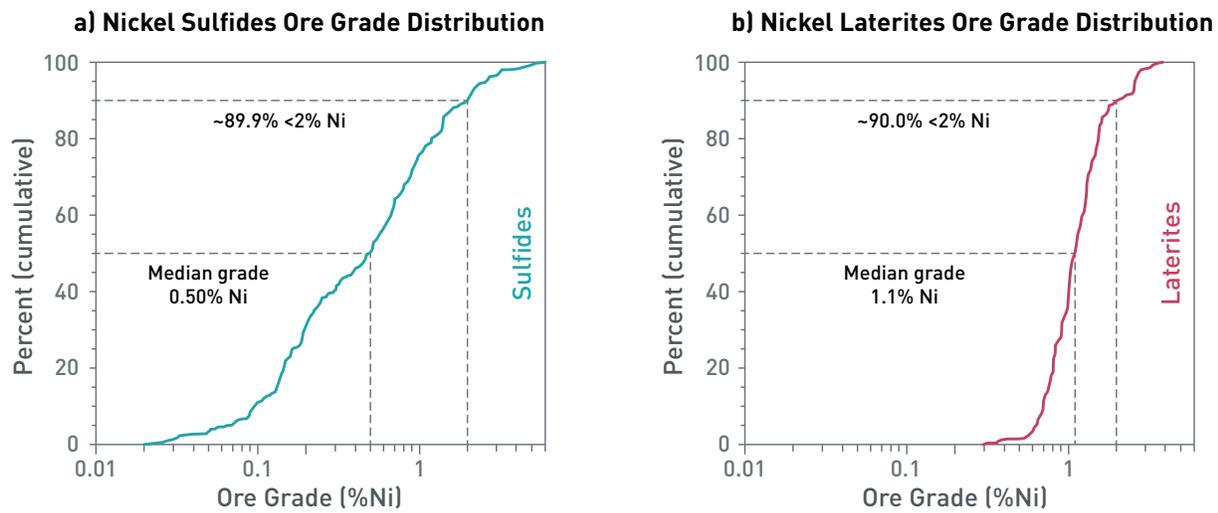
Nickel metal is generally produced as one of two output classes:

- **Class I nickel** has greater than 99.8% nickel contents and is a high-purity form of nickel metal. Until recently, Class I nickel comprised the majority of global nickel production. It is the type of nickel typically needed to produce EV batteries. Most Class I nickel is produced from sulfides.

- **Class II nickel** has less than 99.8% nickel contents. Historically, Class II nickel was a small but growing portion of nickel production. Around 2016, it overtook Class I nickel and now accounts for most global nickel production. Class II nickel products include ferronickel, nickel pig iron, and nickel oxides—mostly used as additives for steelmaking. Most Class II nickel is produced from laterites.

Stainless steel, the overwhelming driver of nickel production (68% of the market), can be made from either class, but ferronickel and nickel pig iron made from Class II are preferred due to their iron content and lower cost, whereas Class I typically attracts a premium price.

EV batteries represent a small but exponentially growing portion of the market (4% of nickel production in 2018) and require extremely high-purity nickel sulfate, which is most easily produced from Class I nickel by reacting it with sulfuric acid. High-purity nickel sulfate can also be derived from nickel intermediates produced by high-pressure acid leaching (HPAL) of nickel laterites.

In terms of processing methods, sulfides are typically produced using conventional mining, pre-concentration, pyrometallurgical smelting, and hydrometallurgical refining, although new technology has emerged to process them directly from ores using hydrometallurgy. Sulfides are typically processed into Class I nickel.

Meanwhile, laterites can be processed into nickel products in one of two ways:

1. Pyrometallurgically, typically to produce low-quality (Class II) ferronickel or nickel pig iron for use in stainless steel manufacturing; and

2. Hydrometallurgically, primarily using HPAL to produce high-quality (Class I) metallic nickel, suitable

109   Source: (Mudd & Jowitt, 2014).

for chemical uses and EV battery manufacture. Hydrometallurgical processes may also be used to produce nickel oxide or mixed sulfide products for further refining in matte refineries.

As mentioned, the majority of nickel production historically came from sulfides. Ore bodies were of high grade and included significant byproduct credits for economic viability. The ore could be concentrated and shipped, and the technology was well established. In contrast, laterites require extensive infrastructure investments and have limited or no byproduct credit potential. As resource availability evolved, the percentage of laterite production increased. No substantive sulfide discoveries in recent years have emerged to meet nickel demand; meanwhile, emerging laterite technologies have matured. Laterites now comprise a majority of global nickel production, as well as the majority of nickel reserves. However, they still comprise a minor portion of Class I nickel production, and hence a minor portion of battery-grade nickel production.

Two typical processing paths for producing Class I nickel from sulfides and from laterites are described below and depicted in Figure 23, highlighted in yellow in the figure. The paths relevant to EV battery production are dominated in volume by pyrometallurgically treated sulfides and hydrometallurgically treated laterites.

Sulfides via pyrometallurgy: The largest nickel mine in the world, in Norilsk, Russia, is representative of nickel processing from sulfides using pyrometallurgical processing. The mine is underground, with hard rock and deep shafts extending down more than a kilometer. In the basic process, rock is drilled and blasted, then mechanically crushed, ground, and floated to concentrate the material into approximately 20% nickel. This is smelted into matte. The matte is then refined into Class I nickel. Copper, cobalt, and precious metal byproducts are also produced.

Laterites via hydrometallurgy: Hydrometallurgical laterite processing, a minority pathway to Class I nickel production, is also representatively illustrated in Figure 23. The processes are heterogeneous, as several different outputs could result, with different paths eventually becoming inputs to an EV battery. In this example, laterite ore containing 1.5% nickel and 0.1% cobalt is extracted from an open-pit mine and transported to a plant where the ore undergoes HPAL to create a pregnant solution (i.e., solution containing valuable metals). The pregnant solution is neutralized with limestone (with associated CO_2 emissions, which can be substantial) to precipitate iron, aluminum, and other contents of the laterite. This residual solid is separated from the pregnant solution and discarded in storage facilities. The solution is piped to the refinery section of the plant, where solvent extraction and various processes are employed to produce nickel powder, nickel briquettes, nickel cathode, or nickel oxide. Some operations do not have refineries and instead produce nickel/cobalt-mixed sulfide or mixed hydroxide that is then refined elsewhere into Class I nickel or nickel sulfate.

Figure 23. Several Production Paths for Nickel from Land Ores (Two Typical Class I Paths Highlighted)
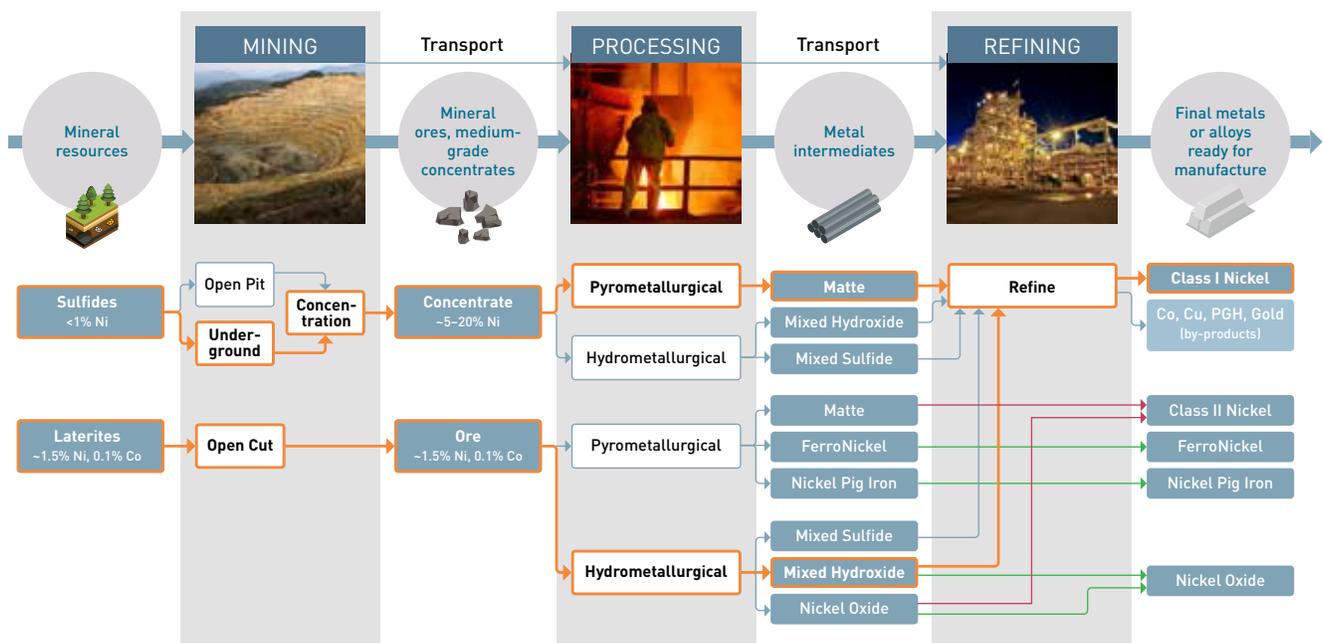
For both paths, an additional step is required to convert nickel metal into battery-grade nickel sulfate: the metal is dissolved in acid, water is boiled off, and a crystallized sulfate results.

Note that, for Class I nickel production, hydrometallurgically processed laterites may be environmentally preferable to underground-mined pyrometallurgically processed sulfides. The advantage with sulfides is that the ore can be concentrated during mineral processing into a concentrate high in sulfur, which contains a lot of energy. Burning the sulfide material releases the energy, reducing the total energy input needed to extract the metal. However, two forces can counter this sulfide advantage. First, the sulfides often come from underground mines, which generally require more electricity to haul, ventilate, and dewater.[110] Second, the comminution and concentration process is also energy intensive and generates tailings for storage; sulfides with their lower ore grades tend to require this concentration step. Oxygen employed to burn the sulfur-rich concentrates in the smelter also consumes significant energy, and the resulting sulfur dioxide must be captured and converted to sulfuric acid for market.

Cobalt

Cobalt typically occurs in nickel or copper ores, and it thus is produced as a byproduct of nickel and copper production.[111]

More than 55% of mined cobalt comes from the Kinshasa region of the Democratic Republic of Congo (DRC). Most of the ore is sent to China, Finland, or other countries for processing and refining. China is the world's largest cobalt producer, responsible for around 60% of refined production in 2017 and 2018, while Finland is home to the world's largest cobalt

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110   (Norgate & Haque, 2010).

111   Note the implications for the price elasticity of cobalt. Being a byproduct of other metal production, its supply grows and shrinks with nickel and copper demand, rather than with its own independent drivers of demand. Mismatches of cobalt supply and demand are not uncommon, leading to greater price volatility for cobalt. This phenomenon is referenced in the Economic Impacts section of the paper.

refinery, controlled by Norilsk.[112] Cobalt is typically produced from three types of ore deposits:[113]

- **Stratiform copper deposits,** which are found in the DRC and Zambia. These are sediment-hosted, fine-grade sulfides disseminated in black shale, sandstone, and limestone, and are the world's primary cobalt sources.

- **Nickel sulfide deposits,** which are found in Sudbury, Canada; Norilsk, Russia, and other areas.

- **Nickel laterite deposits,** which are found in tropical regions such as Indonesia and the Philippines.

The average grade of cobalt is typically low in comparison to its coproducts. A 2011 USGS survey of 120 nickel-cobalt deposits explored worldwide showed the average grade was 1.3% for nickel and 0.08% for cobalt.[114] The reserve-weighted average ore grade of three mines representing the majority of DRC cobalt output was recently surveyed at 2.44% for copper and 0.47% for cobalt.[115] The Cobalt Institute estimates average cobalt grades for several deposit types between 0.05% and 0.4%.[116]

A notable exception to these cobalt ore grades is high-grade, informal, unregulated artisanal mines in the DRC, accounting for 17% of DRC's cobalt production in 2015.[117] Cobalt-rich ores are handpicked, often by children, and have been the subject of humanitarian concern for dangerous working conditions. The mining process releases toxic dust that contains cobalt and many other metals, including uranium. Children living in the mining district have been found to have ten times more cobalt in their urine than children living elsewhere. The long-term consequences of this increased cobalt exposure are still being studied, but preliminary results show DNA damage and high risk of birth defects.[118] Unmitigated safety hazards, illness, prostitution, rape, and environmental damage have been reported as commonplace in the DRC's cobalt mining district. In 2012, around forty thousand children between ages seven and seventeen worked in DRC's

southern Katanga region, roughly one-third of the total number of workers.[119] Note that the impacts of artisanal cobalt mines are largely excluded from the scope of this study, in part due to limited data availability.[120]

Coproduction with nickel yields just over half of cobalt output. Two types of nickel production processes that can yield cobalt as a byproduct were described above and are shown in Figure 23: sulfide pyrometallurgical process and laterite hydrometallurgical process. The nickel-processing flow is followed until the point of separating out the cobalt intermediate, which is then purified and refined into a final cobalt product.

Cobalt as a copper byproduct. An illustration of a typical production path, starting with copper-cobalt mines in the DRC and processed in a plant in China, is shown in Figure 24. Sulfide and oxide forms of cobalt are often found together in the same mineral deposit. Oxide and sulfide ores are mined, then concentrated using milling and floating. Sulfide concentrates are pretreated by a roasting or pressure-oxidation step. Sulfur dioxide gas produced in this step is recycled for other processing steps rather than emitted. After this pretreatment, sulfide and oxide forms of cobalt are treated together using hydrometallurgical processing. The concentrates are acid leached, creating a copper-cobalt solution. Solvent extraction produces a cobalt-rich solution and a copper-rich solution. Copper is electrowinned into copper cathode. Cobalt is precipitated to remove impurities, and a number of possible production paths then branch out, depending on the final product. The cobalt intermediate can be refined into battery-grade cobalt sulfates, oxides, or pure cobalt metal. In China, intermediate outputs such as cobalt sulfate (the input to EV battery production) are more frequently produced, whereas in other plants globally, processing is typically taken all the way to pure cobalt metal. In this case, producing battery-grade cobalt sulfate requires the added step of sulfate production from pure cobalt metal via crystallization, similar to going from nickel metal to nickel sulfate.

112 See (USGS, 2018), (Boland & Kropschot, 2011), (Cobalt Institute, 2019), (Markets Insider, 2019), and (Dai, Kelly, & Elgowainy, 2018).

113 See (Boland & Kropschot, 2011) and (MineralsUK, 2007).

114 (USGS, 2011).

115 (Dai, Kelly, & Elgowainy, 2018)

116 (Cobalt Institute, 2019).

117 (USGS, 2017).

118 (Nkulu, et al., 2018).

119 (Walther, 2012).

120 (Dai, Kelly, & Elgowainy, 2018).

Figure 24. Cobalt Production as Byproduct of Copper Oxides (Hydro)[121]
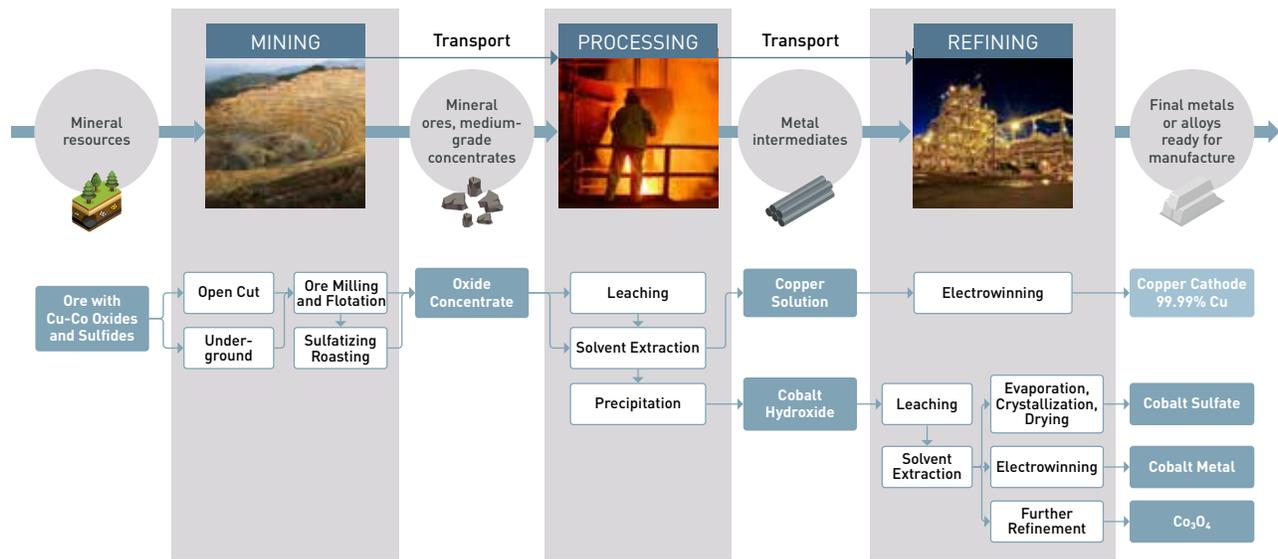
Manganese

Manganese is a highly abundant metal used primarily in steelmaking. The fourth most consumed metal globally after iron, copper, and aluminum, it is most typically produced from a number of types of oxides and carbonates, although some silicate ores are frequently found mixed with the oxides.

The Kalahari manganese district of South Africa contains 70% of the world's total manganese resources.[122] Of high-grade manganese resources, South Africa captures around 90%.[123] Manganese deposits are also found in large quantities in Australia, Brazil, Gabon, and Ukraine. Ores containing at least 35% manganese are typically considered commercially exploitable. Manganese ores are typically mined in open pits, and they can be processed into many different products, including pure manganese, alloys (ferromanganese, silicomanganese, high-carbon alloys), intermediate oxides, concentrates, slags, and sulfates.

Ferromanganese and silicomanganese are typical steelmaking inputs and together account for 80% of all manganese production. Out of the two, silicomanganese dominates at about 70% of manganese alloys produced. Both products are produced pyrometallurgically—smelting the ores in a blast furnace or electric-arc furnace, and reducing the manganese oxides. Figure 25 illustrates this process.

Pure manganese can also be produced using hydrometallurgical and electrolytic processes, which typically use carbonate ores or slags as feedstocks. Manganese ores are roasted, dissolved in sulfuric acid, then chemically precipitated into a purified solution. The solution is then fed into the cathode portion of an electrolytic cell: electric currents cause manganese to deposit into a cathode sheet, then to be hammered and flaked into a pure manganese.[124]

Battery-grade manganese sulfate is commonly produced from two routes. The easier but costlier path is a refinement of such electrolytic manganese metal (EMM), and a technically harder route entails chemical refinement of ore. Both routes are depicted in Figure 25. Production of battery-grade sulfate is dominated by China.

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121 Process flow is adapted from (Dai, Kelly, & Elgowainy, 2018), Figure 1.

122 (Cannon, 2014).

123 (Postle, Nwaogu, Clark, & Heinevetter, 2015).

124 (Downing, 2013).

Figure 25. Manganese Sulfate and Alloy Production
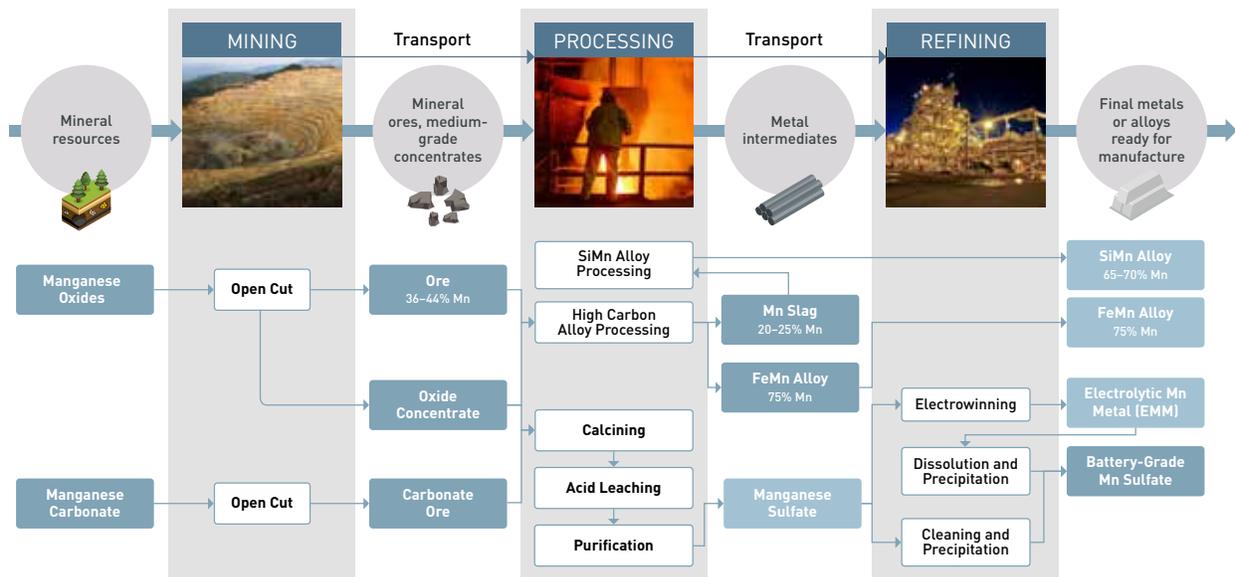
Copper

Copper is found worldwide in a number of geological environments. Chile is by far the world's largest producer of copper, hosting six of the ten largest copper mines globally. Next on the list are China, Peru, the United States, the DRC, and Australia.[125] Copper ores are often mixed with zinc, molybdenum, nickel, gold, platinum-group elements (PGE), and silver, among other byproducts. Most forms of copper ore are mined from open pits, which means lower emissions and less energy costs than underground mining, but greater land disruption. Copper cathode is the predominant output format of copper.

While finer categories of copper mineral deposits exist, most copper is produced from one of two ore groups—oxides and sulfides:

- **Oxides** account for a minor share of global copper production. Ore grades are lower for oxides than for sulfides, although oxides are abundant near the surface and can be less costly to process than sulfides. Oxides are typically treated hydrometallurgically, usually by sulfuric acid heap leaching where the ore is crushed, arranged in piles, and showered with sulfuric acid. The resulting solution is collected and further processed by solvent extraction and electrowinning. Cementation using scrap iron (producing a slightly less pure output) may also be employed.

- **Sulfides** account for most of copper production. The copper iron sulfide mineral chalcopyrite alone accounts for half of global copper production and is sourced largely from porphyry copper deposits. Other sources include sediment-hosted deposits comingled with cobalt in the DRC and Zambia, as well as copper coproduced from nickel sulfides. Porphyry copper deposits are the source of most **chalcopyrite** ores and the dominant global resource for copper production. **Porphyry deposits** are typically formed in mountainous areas. They are found in the world's largest copper mine site, Escondida in Chile, with additional deposits in Arizona, Indonesia, Mongolia, and Peru. They are dominantly sulfides but contain some oxide ores in the upper stages of development, are of lower relative grade, and may have molybdenum or gold byproducts. Copper concentrates are typically produced using grinding and froth flotation followed by pyrometallurgical processing. Sulfides collocated with oxide ores are usually leached directly. Hydrometallurgical processing of copper concentrates is also emerging

125 (Mackenzie, n.d.).

as a production pathway.[126] Besides porphyry deposits, copper deposits found in sedimentary rocks account for one-fourth of the world's identified copper sources.[127]

Ore grades for copper have been declining steadily, with an average grade now around 0.5%.[128] Sulfides can be more expensive than oxides to process and are less abundant, but are nevertheless mined because of their higher ore grades and ability to be concentrated through mineral processing.

In general, the processing steps are broadly similar to processing nickel and cobalt:

Copper from oxides (hydrometallurgical). A general hydrometallurgical process flow was shown in Figure 24. A second version of hydrometallurgical processing involves heap leaching, commonly used for low-grade ores that would otherwise not be economical to process. After the boulders are crushed, they are piled into a heap. Dilute sulfuric acid is poured over the heap and dissolves the copper into a pregnant solution including copper sulfate. Solvent extraction is then used to separate a copper solution from impurities.

The solvent again undergoes electrowinning, thereby pulling out copper ions to create a pure copper cathode. Hydrometallurgical production represents a minority of global copper production, estimated at 20% in 2017.[129]

Copper from sulfides (pyrometallurgical). Sulfides, representing the majority of copper production, are often processed pyrometallurgically. After ore is crushed, it is converted into a liquid slurry by fine grinding and undergoes froth flotation to separate out the copper sulfides. The remainder of liquid containing waste rock is disposed of as mine tailings, which typically represent about 97% of the ground material. After the froth is thickened into a concentrate containing about 30% copper, it is sent to a smelter. In a sequence of high-temperature steps, the metal is smelted and impurities are sequentially burned off. The ore is smelted exothermically, generating reusable energy and acid, which helps reduce energy consumption. A 98% pure blister copper is produced, which is then reduced into a 99% pure copper anode and cooled into a slab. The 99% pure copper anode can be purified through electrorefining, creating a 99.99% pure copper cathode (see Figure 26).

Figure 26. Copper Production from Sulfides (Pyro)

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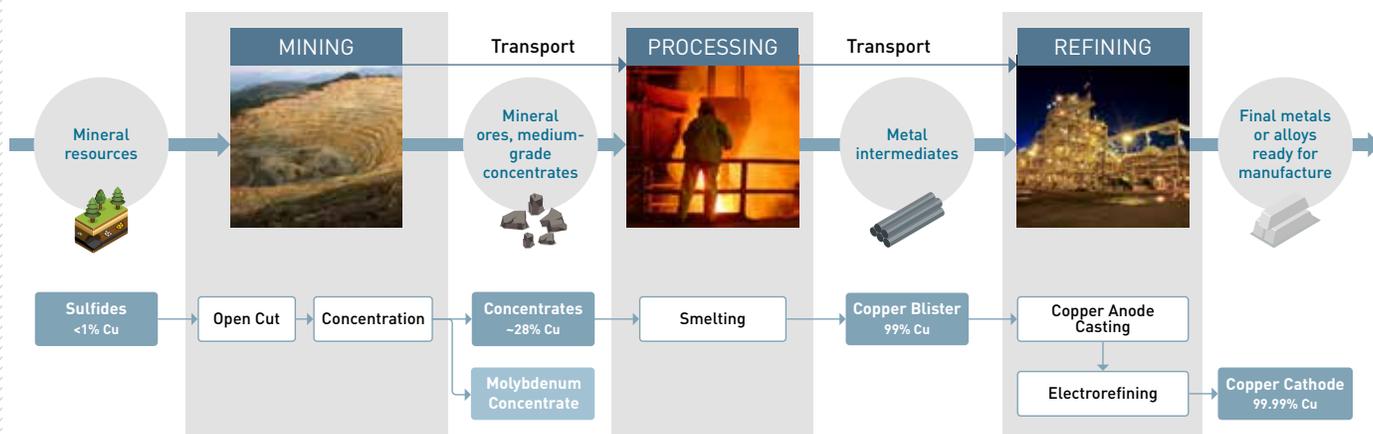
126   See (MineralsUK, 2007) and (USGS, 2019).

127   See (Geology.com, 2009) and (USGS, 2009).

128   See, e.g., (Crowson, 2012) and (MineralsUK, 2007).

129   (ICSG, 2018).

PRODUCTION FROM SEAFLOOR NODULES

Polymetallic nodules are concretions on the seafloor—hard, compact lumps of matter formed through precipitation and interactions of water contained in seafloor sediments (pore waters) and more oxidized seawaters. The low oxidation state of the pore waters, caused by low-abundance reduced organic matter, results in manganese being reduced as water soluble $Mn2+$. Seawater is highly oxidized, which results in manganese being oxidized into 3+ and 4+ oxidation states. This causes precipitation of insoluble manganese hydroxide minerals with a remarkable propensity to scavenge copper, cobalt, and nickel from the sediment pore waters and from seawater, resulting in high grades from polymetallic nodules.[130]

This process occurs over millions of years and is consistent over wide areas, with very large, high-grade deposits having been defined. Because of the consistency of the process, polymetallic nodules have remarkably consistent abundance and metal contents over large areas.[131]

Nodules sit unattached in the top layer of sediment on the seafloor. As a result, removal of nodules does not require blasting, drilling, or excavating—nodules simply need to be collected from the seafloor.

The CCZ is one of the four deep-ocean seabed areas known to contain large quantities of nodules. The CCZ is an abyssal plain spanning 4.56 million square kilometers in the Pacific Ocean roughly 500 miles south of Hawaii.

Polymetallic nodules found in the CCZ contain the four base metals critical for EV battery production in a single ore body—comparable to compacting three land ore bodies (copper-cobalt, nickel-cobalt, and manganese) into one.

The nodules resource is highly abundant. At three CCZ sites studied, nodules cover 31% to 39% of the seabed surface.[132] In total, the CCZ alone contains nearly ten times the manganese available from economically viable terrestrial supplies, three-and-a-half times the nickel, one-third of the copper, and six times the cobalt. The total mass of nodules is estimated at about 21 billion tonnes.[133] One area targeted for mining, known as the NORI Zone, has about 900 million wet tonnes of nodules consisting of manganese (29.2% grade), nickel (1.30% grade), copper (1.08% grade), and cobalt (0.18% grade), with a significant coverage of nodules.[134] Assuming half of the CCZ is set aside at the regional level by the International Seabed Authority and at the local level by exploration contract holders as marine protection and no-take zones, the remaining resource would be sufficient to electrify the global light vehicle fleet.

The "mining" portion of the generalized metal production process is simpler for deep-ocean nodules than mining on land (see Figure 27). Nodule collection disturbs large areas of deep seabed but avoids the environmentally costly steps of mining and concentration typical of metal production on land.

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130   (Hein, Koschinsky, & Kuhn, 2020).

131   (AMC Consultants (B), 2019).

132   (De Smet, et al., 2017).

133   (Secretariat of the Pacific Community, 2013). 21 billion tonnes of nodules in the CCZ is sometimes deemed a conservative estimate, as varying methods have produced estimates up to 34 billion tonnes. Note that these estimates are constrained to the CCZ only and exclude additional nodule fields whose nodule masses may be several times that of the CCZ. See (Schulz, DeYoung, Seal II, & Bradley, 2017).

134   (AMC Consultants (A), 2019).

Figure 27. Metal Production from Deep-Ocean Nodules: Offshore Collection Process Life Cycle[135]

COLLECTING NODULES

Collect nodules from the seabed floor and transport to the surface using a vertical lift system

Deep-Ocean Nodule Mining Life Cycle

1 — Prospecting and Exploration
2 — Development
3 — Mining and Extraction
4 — Closure and Reclamation

1
- $20 Million
- <1–2 years; mostly complete
- Non-invasive, simple. Can do in parallel with development

2
- ~$1B system to manufacture
- ~4–6 years from discovery, including ~3 years for environmental impact assessment and ~2 years to construct and deploy

3
- <$1B yearly, 20–30+ years
- Ongoing collection operations at sea

4
Investigate ways to offset displacement of sea life and attachment surfaces

The prospecting and exploration phase for nodules is less risky and faster than on land. In large part, this is because four large regions of substantial nodule deposits have already been identified, and the consistency of the resource is significantly greater than land-based resources. Unlike prospecting for deposits on land where the subsurface ore body must be "imagined" or "inferred" based on an understanding of local geology and drilling core samples, nodule fields can be observed directly on the seafloor using sensors mounted on an autonomous underwater vehicle (AUV) (see Figure 28).

The development phase consists of engineering and building an offshore collection system with surface production vessels, a vertical lift system, and seabed collection machines. In contrast to land mining, which requires construction of roads for transporting equipment, rock, and ore, as well as trenches, pits, and tunnels for mining, nodule collection requires no fixed infrastructure. No communities need to be resettled to access nodule resources.

Figure 28. Seafloor Images from Prospecting of Nodules[136]

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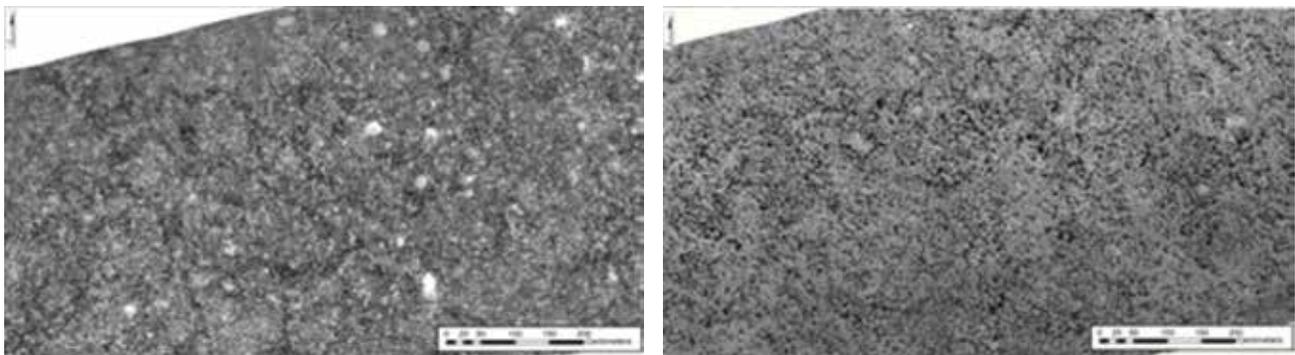
135   Source: detailed engineering estimates from (AMC Consultants (B), 2019).

136   Source: DeepGreen's offshore campaign August 2018 using Hugin AUV five meters above seafloor with an eight-meter swath width.

Figure 29. Nodule Collection System Including Production Vessel and Riser
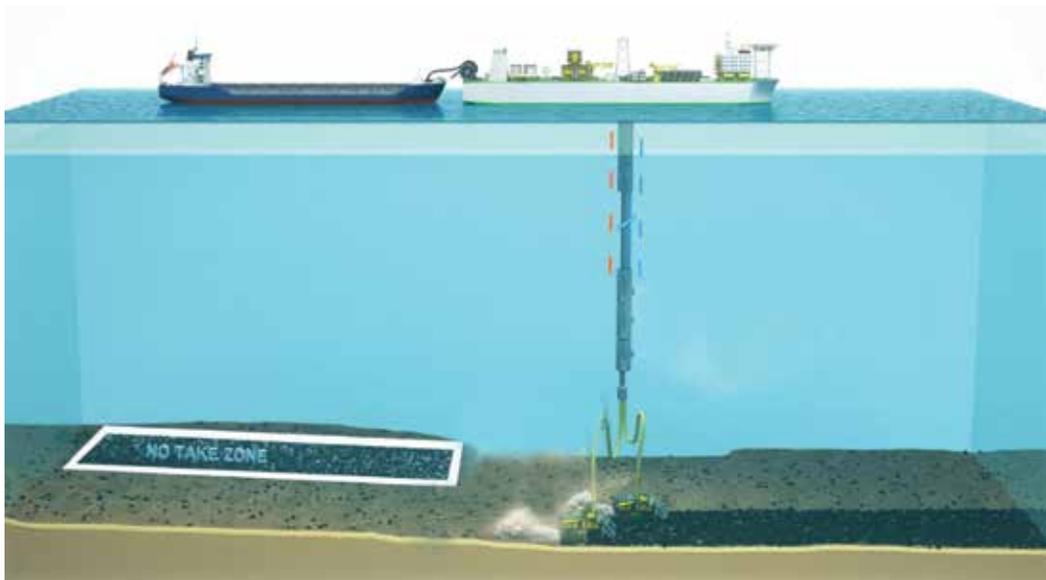
A single nodule collection operation can last more than thirty years, with annual operating costs in the hundreds of millions of dollars—comparable to or slightly lower than typical land-mining operations. Little waste is created when collecting nodules; pollution to air and water is mostly limited to the typical waste from operating a ship under International Maritime Organization (IMO) standards. On the other hand, nodule collection disturbs a large area of the deep seafloor ecosystem through three main mechanisms:

1. **Removal of hard nodule surfaces.** Nodules' surfaces serve as attachment points for certain organisms and are used for laying eggs and other critical life functions. Their removal kills the attached organisms and reduces the surface area available for future attachments.

2. **Suspension of sediment (plumes) at the seabed by nodule-collection machines.** Plumes can settle over an area of several square kilometers and, depending on the thickness of the blanketing layer, risk smothering and killing marine life in those areas.

3. **Reinjection of deep seawater used for vertical transport in the mid-water column.** When deep seawater used in vertical lift transport is reinjected in the mid-water column, it can potentially disrupt the water column with turbidity and an altered temperature.

Each of these major impacts is further detailed in the Results and Discussion section.

Once collected, nodules are transferred from a surface production vessel to a transshipping fleet and transported to an onshore plant for processing and refining. Since transport to the processing plant is directly by ship, processing plants can be located in any of a large number of deep-water ports, so site selection may be optimized for access to existing infrastructure, abundant renewable power (e.g., hydropower[137]), and proximity to customers—all of which enable further reductions in the environmental footprint.

The "reclamation" stage for nodule collection is somewhat different than land-ore mining. When collection operations cease, the ship and collector system simply return to port. There is no mine to

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137   Note that certain types of large-storage hydropower plants can produce substantial CO_2-equivalent emissions from the submerged vegetation and solid biomass, particularly in tropical areas, while running-water and low-storage hydropower plants have a very small footprint.

close, tailings to dam and maintain, earth to cover for revegetation, or toxic emissions and dusts to deal with. The main issues that need to be considered at seabed mine sites are restoration of hard nodule surfaces and decompaction of seabed sediment. Nature's own mechanism for abyssal ecosystem regeneration takes millions of years to precipitate new nodules for attachment and egg-laying. The disturbed deep-sea ecosystem must be given time without human contact to resume its natural ecosystem development. While there are currently no proven mechanisms to regrow disturbed deep-sea ecosystems within a short timeframe, several possibilities are being investigated (e.g., substituting polymetallic nodules with artificial substrates). Preventative measures are also being considered, such as collecting only 85% of seafloor nodules to aid faster ecosystem recovery. More details about the challenges of nodule reclamation are provided in the Results and Discussion sections.

Next, we detail the typical polymetallic nodule processing and refining steps (see Figure 30). While the mineralogy of polymetallic seafloor nodules is quite different from land ores, their processing borrows from the same general techniques. The flowsheet developed by Hatch, one of the world's leading process engineering firms, is described below.

- The first half of the process is **pyrometallurgical**, closely comparable to the pyrometallurgical processing of nickel laterites. An intermediate output of this pyrometallurgical step is a manganese silicate with 40% manganese content. Most of it is to be shipped to an alloy plant for processing into silicomanganese, while a small portion required for the NMC 811 battery cathode chemistry is processed into manganese sulfate. The other primary output of the pyrometallurgical step is an intermediate matte containing nickel, cobalt, and copper.

- The nickel-cobalt-copper matte is then processed **hydrometallurgically**. The matte is first leached, then each metal is separated from the rest. These separated metals are then refined into their final forms. Copper undergoes electrowinning to produce a 99.9% copper cathode, while nickel and cobalt are each extracted, refined, and crystallized into sulfates. Additionally, a substantial quantity of fertilizer-grade ammonium sulfate is produced.

Figure 30. Processing Polymetallic Deep-Sea Nodules

60
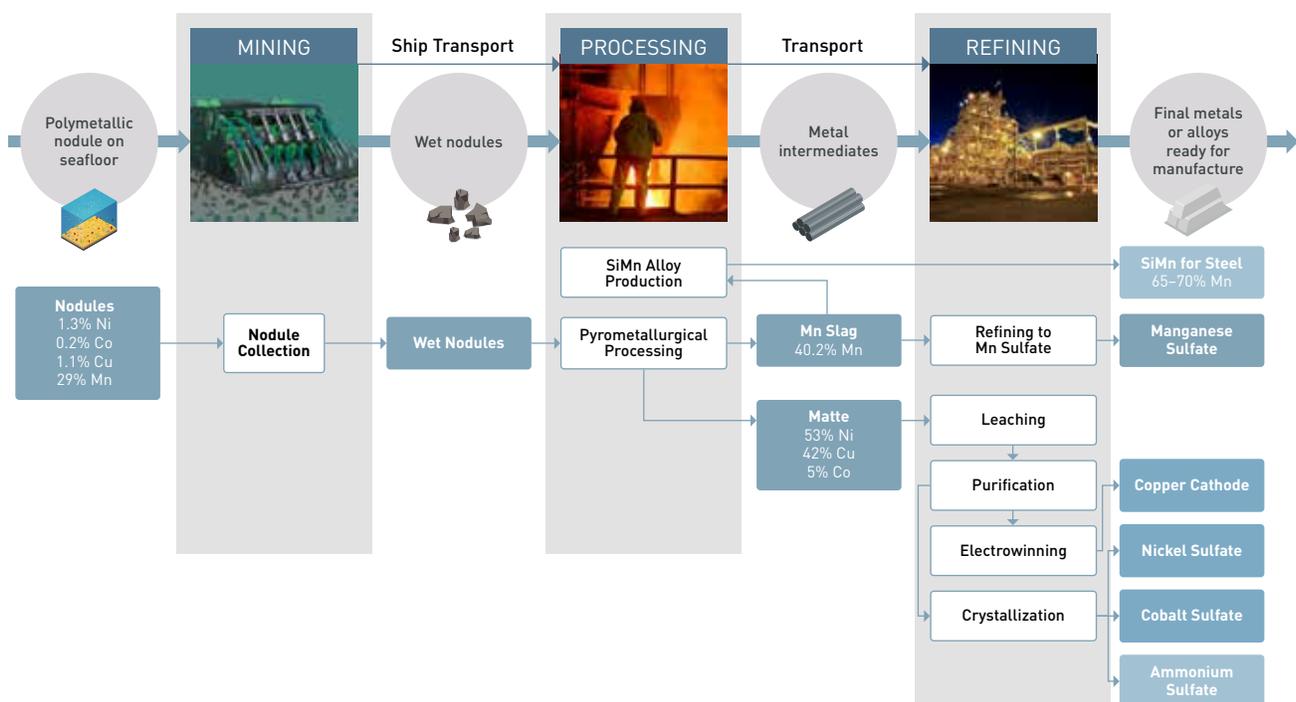
The high-level material flows of DeepGreen's planned system as an example of nodules processing is shown in Figure 31. The processing and refining steps will have gaseous emissions and consume a fair amount of water, as with land-ore processing, but, as the flowsheet shows, these steps generate zero solid waste.

Figure 31. Sample Material Flows for 4.9 Mt/Year Nodule Processing and Refining Plant

PROCESSING

Nodules 4.9Mt

Electricity 2,300 GWh
Natural gas 263M NM³
Diesel 940,000 L
Coal 746 kt
Liquid sulfur 27 Mt
Silica flux 300 kt

40% grade SiMn product 3.5Mt

Converter slag 510 kt

Ni-Co-Cu Matte 115 kt

REFINING

Electricity 0.360 GWh
Natural gas 46M NM³
Diesel 320,000 L
Sulfuric acid 180 kt
Sodium hydroxide 1.5 kt
Anhydrous NH₃ 47 kt
SO₂ 370 t
Oxygen 100 kt

Ni sulfate 61 kt

Co sulfate 6 kt

Copper cathode 49 kt

Ammonium sulfate 170 kt

SUMMARY OF KEY PROCESS DIFFERENCES

Key metal production process differences for land ores and nodules are summarized in Table 5 below.

Table 7. Key Process Differences

		LAND ORES	NODULES
MINING	Exploration	• Prospecting is high risk, with no major discoveries of tier I mining assets made over the last decade. • Prospecting involves remote sensing of geological structures and on-site drilling into hard rock to collect drill cores to test for composition.	• Prospecting is less risky, with several nodule deposits identified (e.g., the Clarion Clipperton Zone, the Peru Basin, the Central Indian Ocean Basin) and characterized as high grade and high abundance. Most of the ~20 ISA nodule exploration contract areas would each be classified as a tier I deposit. • Prospecting involves observing the seafloor using sensors mounted on vessel hulls and/or autonomous underwater vehicles, and collection of nodule and biological samples.
	Development	• If the mine site is in a remote location, new infrastructure is built and maintained (roads, bridges, power, water, miner accommodation). • Underground mines require drilling of access shafts and tunnel networks. • Open-pit mines require clearing forests or other vegetation and removing topsoil to access the ore body. To build a terraced access to the ore body, a much larger area needs to be excavated, with stripping ratios of 1-10 tons of waste rock for every ton of ore body not uncommon. If the site is populated, communities are resettled. • Development of a mine can take more than five years.	• Development involves building an offshore production system (surface vessel, vertical lift system, seabed collection machines). • Manufacture of each offshore production system can take up to two years. This does not include initial system design phases and pilot mining systems development, which may take three or four years. Full-scale system design can take an additional year, though subsequent systems would be iteratively designed on tighter timelines as learning and improvement takes place, as with any large-scale system development undertaking.
	Ore Extraction or Collection	• The most common method used to excavate a metal-bearing ore body is to drill holes into hard rock, fill them with chemical explosives, and blast. Resulting fragments of blasted rock are then fed into a crusher and, in the case of sulfide ores, can be chemically concentrated on site. • Mining disrupts tracts of land at the mining site and for connecting roads. • Mining for base metals increasingly takes place in some of the most biodiverse places on the planet. • Transport is primarily by truck to remote locations. • Particulates and harmful dust are released into the atmosphere, with noted health risks to miners and surrounding communities. • Substantial amounts of freshwater are drawn from lakes, streams, and groundwater sources. • Contamination of groundwater can result in human and wildlife illness and death. • Marine-water impact consists of runoff pollution, especially from near-coastal mines, possibly harming marine animals. Deep-sea tailings placement can also impose a major marine impact. • Communities are impacted because mining sites may be near local inhabitants; direct physical harm or cultural disruption may occur. Communities can also benefit because mining can bring development and industry to remote areas. • Waste streams are commonly produced in large quantities from mining and concentration, often putting communities, wildlife, and habitats at risk locally and regionally.	• Nodules sit unattached in the top 5 centimeters of sediment. They are picked up by seabed collection machines, which may direct jets of deep-sea water along the surface of the seabed to lift and channel nodules into the machine along a curved nozzle head using the Coanda effect (the pressure-differential effect that lifts airplanes off the ground). Nodules are separated from entrained sediment inside the collection machine and channeled into a vertical lift system; most separated sediment is discharged at the back of the collector. Nodules are transported to the surface production vessel using a vertical-lift system inside an enclosed riser pipe. Deep-sea water from nodule transport containing residual fines is reinjected at a depth below 1,000 meters. • Nodule collection removes the hard substrate of nodules. Some wildlife requires these substrates for attachment ('nodule obligates'), and other relies on these hard substrates for critical life functions (e.g., egg laying). The populations of these species will be disrupted in collection areas. • Collection machine movement along with sediment discharge generate plumes (i.e., suspended seabed sediment). As plumes resettle on the seabed, they can smother, kill, and disrupt wildlife in the impacted area, depending on the blanketing thickness. • Transport is primarily by ship. • Air impact is limited to typical ship emissions during operation. • There is little direct freshwater impact. • Marine-water impact includes reinjection of slightly-warmed, decompressed deep seawater with turbidity, possibly harming ocean wildlife, as well as typical ship emissions, which include discharges into the water. • No local communities are impacted as nodule collection takes place far from human populations. Nodule collection can provide jobs and economic benefit, with potential to aid developing nations who act as sponsoring states for ISA contractors.

		LAND ORES	NODULES
MINING	Closure and Reclamation	• Mine closure is costly to implement. It is often postponed indefinitely or not completed. • Unrestored land further pollutes habitats, causes human illness, and prevents future habitats from redeveloping. • Improper disposal of tailings causes human and animal illness and death from dam collapses, toxic dusts, and groundwater pollution. • Environmental protection measures and enforcement vary greatly, depending on the strength of the national and local governments, particularly in developing countries.	• Nodule collection can stop immediately, with limited associated cost. However, reclamation of the seafloor presents substantial scientific and logistical challenges. • No disasters or human illness or death are caused by leaving nodule-collection sites unrestored. • While leaving 15% of the nodule cover in collection sites will likely aid the natural habitat restoration process, the process will likely take a very long time. • Environmental protection measures are developed in consultation with a broad range of stakeholders and enforced by the International Seabed Authority.
PROCESSING		• Processing plants are usually located within trucking distance from the mine site (especially for bulk ores that cannot be easily concentrated at the mine site), mostly in developing countries, and are powered by local electricity grids that often rely on coal. • Ores often contain toxic levels of heavy elements that need to be removed and stored during processing. Large volumes of processed tailings and residues from this phase require specially engineered facilities (tailings dams) and ongoing monitoring and maintenance indefinitely into the future. • Physical footprint consists of land occupied by a processing plant, tailings dams, and residue storage facilities, as well as road building and maintenance. Some processing is constrained to the mine site while some is more distant. • Impacts result from pyrometallurgical and/or hydrometallurgical processing and depend on the ore. Significant pollution and waste are generated from standard techniques.	• Processing plants can be located anywhere in the world with access to a deep-water port. Site selection can be optimized for access to renewables like hydropower. • Nodules do not contain toxic levels of heavy elements and can be processed with no tailings, residues, or solid waste. • Physical footprint consists of land occupied by a processing plant, as well as road building and maintenance. • Impacts result from pyrometallurgical processing, optimized for low waste and emissions along with hydrometallurgical refining due to the unique mineralogy and location flexibility.
REFINING		• Additional plants may need to be built for refining, with associated extra costs for transport and land use, and powered by local electricity grids. • Tailings and residues may be produced by this phase. • Refinery locations attempt to be optimized for transport to market.	• Hydrometallurgical refining is co-located with processing. Additional plants may be built for refining into other final products, with associated extra costs, powered by local grids. • Intermediates can be processed with no tailings or residues. • Transport to market minimizes the use of trucks due to location near a port for international market access.

V. IMPACT DRIVERS

What are the characteristics, severities, and drivers of impacts that result from each step of the metal production process? Below, we:

• Outline major impacts by phase

• Discuss characteristics of ore deposits and key drivers of impact differences

• Compare impact inventories at a structural level (to be explored in more depth in Results and Discussion)

OVERVIEW BY PHASE

Mining Phase

At its core, base metal mining (or any mining) is an environment-transforming activity. The very purpose of the activity is to remove metal-containing ores from their current environments for further transformation into the materials needed for products like EV batteries.

On land, mines release carbon dioxide, sulfur dioxide, particulates, and other air pollutants; leave behind tonnes of waste tailings, slag, and acid drainage; can release metal contaminants and toxic chemicals into the air, water, and land; in many cases threaten animals, plants, and/or wildlife reserves; may affect many ES, including carbon sequestration; consume large amounts of fossil fuels and freshwater; destroy land that is not reclaimed; materially infringe upon the lives of nearby communities; and cause cancer, other health issues, and even death among the miners and surrounding communities. Around half of toxicity impacts can arise from the mining phase alone, depending on the mineralogy as well as the age of the mine. Damage may continue years after the mine has shut down, including deaths of fauna and flora, habitat erosion, and freshwater pollution.

Nodule collection causes almost none of the impacts of land-ore mining. However, it comes with its own environmental challenges. It affects marine life that needs hard surfaces like nodules for essential life functions (e.g., laying eggs, attaching for growth). Roughly 85% of nodules are removed within a mined area, leaving behind only 15% of these hard surfaces. Nodule-collection vehicles stir up sediment as they traverse the seabed, burying some of the residual

nodule cover. Collection vehicles pick up both nodules and sediment, which is subsequently separated and discharged behind the vehicle; the heavier particles of this suspended mud, known as sediment plume, take several days to resettle, while the smallest particles take much longer and can travel outside the vicinity of the collection vehicles. Depending on the level of particle concentration in the water and the thickness of the particle layer once it resettles, the sediment plume can impact the functioning of local organisms and may smother some marine life. Most proposed nodule-collection systems transport nodules in an enclosed riser using ocean water that is sucked up at the base of the riser. Once nodules are separated from the ocean water, the water must be injected back into the ocean at a different water layer, which can cause some ecosystem disturbance. Finally, nodule-collection operations can generate noise and light that disturb marine life. We discuss all of these topics in more detail in the Biodiversity section.

In LCIA terms, nodule collection does not have a significant impact on eutrophication, land use, terrestrial ecotoxicity, freshwater ecotoxicity, or human toxicity. While second-order effects may exist, nodule collection does not create direct, first-order effects of these kinds simply because it is not taking place on land. Most ES are also unaffected. Air emissions are primarily driven by fuel that powers the offshore collection system, a supply services fleet, and shipping operations to bring the nodules to shore for processing. These emissions are a fraction of land-ore mining emissions. Operations incur typical vessel discharges, including ballast water, gray and black water, and bilge water.[138] MARPOL international

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138   For more information on standard vessel emissions, discharges, and other impacts, see the World Shipping Council's overview of environmental issues at (World Shipping Council, 2019).

standards (1973/1978) require protective measures to be implemented, such as transport and proper disposal of all potentially hazardous goods, including diesel fuel, lubricants, hydraulic fluids, solvents, corrosion inhibitors, and waste products, and proper treatment of all domestic waste, sewage, and gray water prior to discharge.[139]

Processing and Refining Phases

Although metal production processes from land ores and ocean nodules can be similar in terms of technology, some of the impacts are materially different due to the unique nature of the polymetallic nodules as a feedstock.

Environmental impacts from pyrometallurgical processes include carbon emissions from heat-intensive reduction processes, electricity use by electric furnaces, fugitive sulfur dioxide and nitrogen dioxide and other emissions, gangue waste (commercially valueless material that is intermixed with the ore), and life cycle contributions from material inputs like limestone and ammonia. Impacts from hydrometallurgical processes include leach residue or tailings, effluent, high freshwater consumption, and life cycle contributions from greater material requirements, such as extensive use of titanium. Refining steps include processes like solvent extraction, electrowinning, crystallization, and reduction. Generally, for the four metals studied here, the impacts from these steps are lower than mining and processing steps for other metals.[140]

Transport between the mine, processing plant, and refining plant locations may also contribute substantially to the environmental footprint. This is especially true if trucks are used at large distances, typical with land-ore mining. Trucks' life cycle footprints per tonne-kilometer can be an order of magnitude greater than for ships, considering the trucks' reduced efficiency and the additional required road building to many remote mining sites.[141]

Some differences may arise even when treating similar ores; smart plant design can optimize the footprint from processing and refining steps. This may include reuse of byproducts of subprocesses as inputs into different subprocess steps, designing chemical processes specifically optimized for minimal emissions and waste, and converting what may otherwise be dumped as waste into products reusable by nearby industry (e.g., converter slags). Both land-ore plants and nodules plants present such opportunities, although nodule plants may have a greater advantage because they largely lack location constraints. Location flexibility also means nodule-processing facilities can be more readily located near markets for high-mass, low-value materials that would otherwise become wastes because high shipping costs from remote locations make them uneconomical.

CHARACTERISTICS OF ORE DEPOSITS AND OTHER IMPACT DRIVERS

Several properties of polymetallic nodules drive substantial differences in toxicity, waste, and emissions.

The overall effort and total environmental footprint of metal production is a function of extraction difficulty, complex chemistries, processing steps and time, material usage and waste, location characteristics, and energy and fuel requirements. The impact from producing the same kilogram of refined metal can vary by a factor of two or more based on these parameters.

Ore-deposit characteristics alone, in fact, can drive most of the impact differences. Ramifications ripple all the way through the metal-production value chain:

- **Ore grade.** The lower the grade, the greater the amount of rock that must be extracted, the more crushing and concentration must be performed, the greater the amount of waste rock and tailings that must be stored, and the greater amount of freshwater and material inputs needed for hydrometallurgical processing. All of this increases the environmental footprint.

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139   For more information on the International Convention for the Prevention of Pollution from Ships (MARPOL), see (IMO, 2011).

140   See per-stage analysis in (Nuss & Eckelman, 2014).

141   For instance, running a GWP 100a LCIA using Ecoinvent v3.5 shows a carbon dioxide emissions equivalent (CO_2e) of 91–163 grams per tonne-kilometer for a medium or large truck, versus 6–11 grams CO_2e per tonne-kilometer for a transoceanic tanker or freight ship. (See, e.g., (Valsasina, 2018) and (Spielmann, 2018).)

- **Metal mix.** The presence of several valuable metals in a single ore can mean greater overall value of extraction and fewer emissions allocated to any given metal, but can also increase processing complexity and requirements.

- **Mineralogy.** Mineralogy is the chemistry, molecular structure, and physical properties of a given mineral deposit. These properties determine the specific purification and refinement steps needed, which impact everything else. For instance, ores that release energy during processing (i.e., that undergo exothermic reactions) can require far less external energy input, also saving on emissions and cost.

- **Geographic location:** Mine location makes a significant difference. It determines transport costs for moving heavy rock to processing plants, effort involved in constructing the mine, cultural infringement factors, human health impacts, biodiversity impacts based on habitat characteristics, risk of death from tailing-dam collapse, access to hydropower and ports, and many other factors. On land, mine location can significantly constrain choices available downstream.

Of the above, the specific **mineralogy** is perhaps the biggest driver of the processes required to produce a metal. It determines whether chemical-based concentration is needed, whether hydrometallurgical or pyrometallurgical flowsheets are used, whether high-emissive steps like coal-based reduction of oxides are needed, and how much energy input is required to fuel the reactions. Understanding the nature of the ores being extracted for each metal and production path is critical.

One additional key driver, indirectly enabled by ore characteristics, is also worth mentioning: plant and process design. Equipment and processing plants can be designed for zero solid processing waste, low residues, optimal recovery, and no processing tailings. Several factors enable feasibility of this objective for nodules. First, polymetallic deep-ocean nodules are remarkably free of toxic quantities of heavy elements hazardous to the environment and human health. Second, the location flexibility of the processing plants enables selection of a site close to markets for byproducts as well as hydropower. While nodule-field locations themselves are fixed as with land-ore deposits, being located at sea enables far cheaper and less emissive transport to the processing plant—shipping by sea instead of by truck. This plant-location flexibility enables choices like optimization for hydropower, or near its destination market, thereby minimizing transport costs and emissions. This is not the case for mining on land. Third, the pyrometallurgical equipment is ideal to safely and cleanly consume otherwise problematic residues, with the benefit of increased recovery and production of useful byproducts.

Strategies like using alternative reagents, making process changes to produce valuable products instead of waste streams, and considering site location to enable use of hydropower and synergies with other industries are key to environmentally optimal process design.

SUMMARY OF IMPACT INVENTORY DIFFERENCES

The figures and table below show impacts across the three metal-production stages.

Figure 32. Key Impacts of Metal Production, by Phase — Land Ores

Mineral resources in land or ocean	MINING	Transport	PROCESSING	Transport	REFINING	Final metals, compounds, or alloys
	Remove metal ores from the earth. May crush and/or concentrate boulders into higher grades.	Mineral ores, medium-grade concentrates	Use water-, heat-, or chemical-based processes to separate out metal compounds.	Metal intermediates	Refine metals from intermediary forms into pure metals or alloys.	Ready for manufacture

KEY POTENTIAL IMPACTS

Mining:
- Deforestation and topsoil loss
- Habitat loss and degradation
- Carbon sequestration impact
- Biodiversity loss
- Wasterock and tailings
- Freshwater depletion
- Marine water pollution
- Acid drainage
- Freshwater contamination
- CO_2 emissions
- SO_x and NO_x emissions
- Human death and illness
- Vulnerable populations exploitation
- Community relocation
- Cultural disruption and loss of heritage
- Noise pollution

Processing:
- Fossil fuel–based electricity
- CO_2 emissions (direct)
- SO_x and NO_x emissions (direct)
- CO_2 emissions (materials)
- Tailings
- Residue, waste, slag generation
- Toxic chemicals release
- Acid drainage
- Freshwater depletion
- Freshwater contamination
- Deep-sea tailings placement (DSTP)

Refining:
- Fossil fuel–based electricity
- CO_2 emissions (direct)
- SO_x and NO_x emissions (direct)
- CO_2 emissions (materials)
- Tailings
- Residue, waste, slag generation
- Toxic chemicals release
- Acid drainage
- Freshwater depletion
- Freshwater contamination
- Deep-sea tailings placement (DSTP)

Figure 33. Key Impacts of Metal Production, by Phase — Nodules

Polymetallic nodules on seafloor	MINING	Transport	PROCESSING	Transport	REFINING	Final metals, compounds, or alloys
	Collect nodules from the seabed floor and transport to the surface using a vertical lift system	Wet nodules	Use heat- and chemical-based processes to separate out metal compounds.	Metal intermediates	Refine metals from intermediary forms into metal products that go directly into EV battery production.	Ready for manufacture

KEY POTENTIAL IMPACTS

Mining:
- CO_2 emissions
- SO_x and NO_x emissions
- Biodiversity loss
- Nodule removal
- Sediment resuspension and deposition
- Compaction of surface sediment
- Discharge of sediment and water
- Underwater noise
- Surface vessel's noise, light, and waste

Processing:
- CO_2 emissions (direct)
- CO_2 emissions (materials)
- SO_x emissions (direct)
- Freshwater depletion
- Disruption of carbon sequestration (land use)

Refining:
- CO_2 emissions (direct)
- CO_2 emissions (materials)

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Table 8. Impact Drivers of Metal Production, Land Ores, and Nodules by Impact Category

	MINING	PROCESSING	REFINING
CLIMATE CHANGE			
LAND ORES	• **About half of land ores' GWP impact comes from this phase.** Every aspect of the mining life cycle contributes, from truck transport and mine building to operation of generators, blasting, and excavation. Concentration of lower-grade ores can heavily contribute. Removal of vegetation has direct carbon sequestration impacts.	• **GWP impacts vary,** depending primarily on ore metallurgy and on whether pyro or hydro processes are used. Coal-intensive processes and certain material inputs increase the impact. **Some carbon sequestration impacts arise from physical plant area as well as life cycle contributions** from material inputs to processing.	• **This step typically represents a minority of overall impact** for the four metals studied in this paper.[142]
NODULES	• **Emissions are an order of magnitude lower than for land ores.** Emissions result from ship and collection operations, their construction, and ship transport to the plant.	• **Most of the GWP impact of nodule production comes from pyrometallurgical processing. Nodules' carbon sequestration footprint is also primarily driven by the physical plant area** as well as life cycle contributions from materials for pyrometallurgical processing.	• **The hydrometallurgical refining processes used are less emissive** than pyrometallurgical processes.
NONLIVING RESOURCES			
LAND ORES	• Land-ore mining is characterized by substantial water usage, water pollution, and air pollution. It is also the highest chemically polluting industry. It significantly alters the land and produces waste, making sites difficult to restore.	• **Primarily attributable to any excessive tailings and waste produced, and indirect impacts** from pollutants like sulfur dioxide affecting habitats.	• **Primarily limited to indirect impacts** from pollutants, packaging, and consumables. **Some chemicals are produced** during the refining process.
NODULES	• Producing metals from ocean nodules reduces many of the nonliving-resource impacts present with land-ore mining. Large areas of seabed sediments are disrupted during the nodule collection process.	• Nodule processing and refining plants can be optimized for zero tailings, residues, and solid waste for disposal, to minimize impact to land, water, and air resources.	• **Primarily limited to indirect impacts** from pollutants, packaging, and consumables. **Only small amounts of chemicals are produced** during the refining process. Refinery bleeds can be designed to be recycled into the kilns.
BIODIVERSITY			
LAND ORES	• **Land-mining sites, such as in the tropics, can be extremely biodiverse.** Some mining sites can be home to rare local species. Land mining causes habitat loss and degradation and can cause species extinction.	• **Primarily attributable to any excessive tailings and waste produced**, and indirect impacts from pollutants like sulfur dioxide affecting habitats.	• **Primarily limited to indirect impacts** from pollutants, packaging, and consumables. **Some chemicals are produced** during the refining process.
NODULES	• **Biomass and numbers of organisms and species living in the CCZ are lower than on land, sometimes by orders of magnitude.** Nodule collection causes habitat loss and degradation and can cause species extinction.	• Plants to process nodules are optimized for zero tailings, residues, and solid waste for disposal, to minimize habitat impact.	• **Primarily limited to indirect impacts** from pollutants, packaging, and consumables. **Only small amounts of chemicals are produced** during the refining process. Refinery bleeds can be designed to be recycled into the kilns.

142   See per-stage analysis by (Nuss & Eckelman, 2014).

	MINING	**PROCESSING**	**REFINING**
SOCIAL IMPACTS			
LAND ORES	• Land-ore mining has significant inherent dangers, including fatalities and illnesses, as well as financial costs. It furthermore affects vulnerable populations, including children exploited by artisanal mines and underprivileged people in developing countries. By the nature of displacement of physical land sources, it presents a risk of affecting indigenous cultures.	• Risks of illness and death arise from the pollution, tailings, and waste associated with land-ore processing.	• No substantial social impact risk.
NODULES	• Producing metals from ocean nodules eliminates most social-impact risks present with land-ore mining. The primary inherent dangers are those from operating a ship at sea. The only vulnerable populations affected may be those whose countries are impacted economically, as discussed earlier. Risk of cultural displacement is eliminated.	• No substantial social-impact risk because of the opportunity to design plants for zero tailings or waste.	• No substantial social impact risk.
ECONOMICS			
LAND ORES	• Cost and risk of prospecting, developing, operating, and restoring a mine may be slightly higher than comparable costs for nodule collection. While mining provides more jobs than ocean-nodule collection, some land-mining jobs are hazardous and exploitative.	• Processing cost is comparable to nodules.	• Overall, land-ore production is characterized by higher prices, greater underlying uncertainties from prospecting, sensitivity to global commodity prices due to their positions on the cost curve, and disruptions from not-uncommon disasters.
NODULES	• Nodule-extraction operations are economically viable. The collection process provides fewer jobs but these jobs tend to be safer and more technologically driven than the jobs associated with land-ore mining.	• Processing cost is comparable to land ores.	• Prices of produced metals are on the low end of the cost curve. This, along with the broadening of supply and well-surveyed resources, lessens price pressures and lowers risk. Some economies may be impacted by the new manganese supply.

VI. RESULTS AND DISCUSSION

We now walk through the impacts for each category framed by this study.

Each subsection begins with key takeaways of the evaluations of both sources of metals for that impact category. Following this, a detailed exposition or side-by-side analysis of that category is presented using the quantitative and qualitative evaluation methods described previously. Finally, sections generally conclude with a summary table assigning qualitative

relative impact indicators of low, medium, or high for subtopics of that category. These qualitative assessments drive the aggregate determinations regarding impact from each production method.

We begin with a brief exposition of the impacts that mining and nodule collection have on ES. This cross-cutting topic provides relevant context and intuition for the in-depth impact discussions that follow.

ECOSYSTEM SERVICES IMPACT OVERVIEW

Ecosystem Services Impacts at a Glance

AT A GLANCE
Ecosystem Services
• Land mining, with its intricate integration into physical habitats that interact with humans, impacts numerous ES. Mining imposes substantial negative impacts on all four service types: provisioning, regulating, supporting, and cultural.
• Deep-sea nodule collection will disrupt ecosystems in the abyssal plains. While the potential impact of this disruption on ES is still being researched, nodule collection is expected to impact very few services due to the remoteness from human communities and activities; currently known impacts are small or nonexistent with the exception of habitat impacts.

A common framing to study ecosystems is their ability to support people and nature, a concept termed ecosystem services (ES). ES are defined as the direct and indirect contributions of ecosystems to human well-being.[143] A study of ES impacts provides a human-centered, utilitarian perspective, by attributing value to ecosystems and their component species primarily for the benefits that these are providing to people. Sustainability dictates that mining and other activities should not impact or undermine ES.

ES are typically grouped into the following four categories:

• **Provisioning:** materials such as food, water, and other products that directly support human communities.

• **Regulating:** services that control the quality of soil, water, climate, disease, and so on.

• **Supporting:** nutrient cycles, oxygen production, habitats, pollination, and other services that maintain the quality of air, soil, and water.

• **Cultural:** recreational, aesthetic, and spiritual benefits to humans.

ES impacts of land-ore mining and deep-sea nodule collection, as defined in the report by The Economics of Ecosystems and Biodiversity (TEEB), are summarized in Table 9 and discussed in further detail below.[144]

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143   (Pushpam, 2010). See also (Millennium Ecosystem Assessment, 2005).
144   See (Pushpam, 2010), chapter 1.

Table 9. Land Mining and Nodule Collection Impacts on Ecosystem Services[145]

KEY

Color	Meaning	Color	Meaning
▮ (teal)	May **positively** impact an ES	▮ (red)	May have **serious** negative impact on an ES
▮ (orange)	May have **moderate** negative impact on an ES	▮ (gray)	**Low or no impact** on an ES

ECOSYSTEM SERVICE CATEGORY	LAND MINING	DEEP-OCEAN NODULES
PROVISIONING		
Food	🟥 Habitat cleared, erosion, toxins	⬜ Low or none
Water	🟥 Excessive withdrawal, pollution	⬜ Little water for processing
Raw materials (e.g., wood, fiber)	🟧 Loss of trees and vegetation	⬜ Low second-order effects
Genetic resources	🟧 Potential loss of endemic species	🟧 Possible, but uncertain
Medicinal Resources	🟧 Potential loss of endemic species	🟧 Possible but uncertain
Ornamental Resources	🟧 Damage to vegetation and species	⬜ Low or none
REGULATING		
Air-quality regulation	🟥 Blasting and toxic dusts	🟧 Some from vessels, refining
Climate regulation	🟧 Loss of soil and vegetation	⬜ Low or none
Moderation of extreme events	🟧 Loss of soil and vegetation	⬜ Low or none
Regulation of water flows	🟥 Water drawdown and pollution	🟧 Water for processing
Waste Treatment	🟧 Loss of soil and vegetation	⬜ Low or none
Erosion prevention	🟧 Loss of soil and vegetation	⬜ Low or none
Maintenance of soil fertility	🟥 Toxic dusts, polluted water, vegetation	⬜ Low or none
Pollination	🟧 Vegetation loss, toxic dusts, water impact	⬜ Low or none
Biological control	🟧 Harm to vegetation and aquatic life	🟧 Possible but uncertain
SUPPORTING		
Resident/migrating species	🟥 Habitat loss, noise, pollution	🟥 Habitat loss, noise, light
Maintenance of genetic diversity	🟥 Species extinction risk	🟥 Species extinction risk
CULTURAL		
Aesthetic information	🟥 Excavation, noise, species loss	⬜ None
Recreation and tourism	🟥 Exclusion areas, fish kills, noise	⬜ None
Inspirational culture, arts, design	🟩 Jewelry, tools, lore, books, films	🟩 Some books written
Spiritual experience	🟥 Harm to/exclusion from sacred sites	⬜ None
Cognitive development impact	🟩 Technological developments	🟩 Science, knowledge, tech

Note that mines are heterogeneous within a category, and therefore the table indicates spans of impacts. For example, freshwater withdrawal by mines in wet areas may not affect availability for human communities and wildlife, but withdrawal by mines in dry areas can severely decrease water availability for human consumption. The table presents average judgments. A red bar signifies that some mines can have very severe impacts on ES, while others may have low or no impact. Similarly, a yellow bar indicates that some, though not necessarily all, mines may have moderate impacts on ES. Gray bars indicate no impact. Green bars indicate instances where mining has impacted an ES positively.

On land, mines have substantial impacts on many ES. In contrast, deep-ocean abyssal plains such as the CCZ impact very few ES based on our current understanding. They are so remote from human communities and activities, both geographically and by depth, that effects of nodule collection are expected to be low or absent for most services. However, effects on the seafloor habitat and its biodiversity could be material, and they are discussed in depth in the Biodiversity section under Results and Discussion. See (Thurber, et al., 2014) for additional consideration of deep-sea ecosystem services.

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145 We summarized available information, with quantitative and qualitative data from available data and news reports regarding hundreds of Ni, Cu, Mn, and Co mines operated by various companies in different countries. For nodules, statements based on initial sampling are presented, as the areas proposed for mining are very large and relatively homogeneous.

Provisioning Services

- **Land.** Mines often deplete and contaminate surface and groundwater resources. Toxic dusts and polluted water harm crops and fisheries of local communities. Mines and miners may cut down forests, remove topsoil, and pollute rivers with industrial waste. Harm to biodiversity can impact availability of plants or animals for medical, genetic, or ornamental use. Mining may also deny access to local plants used by indigenous communities for medicinal purposes.

- **Deep seabed.** Nodule collection will not affect freshwater, populations of fish consumed by humans, or other material provisions. Reinjection of lift water into the ocean in mid-water could affect deep-water plankton or fish populations. Marine protected areas (MPAs) and other no-take zones, mandated for the purpose of protecting species and habitats, are designed to contain representative habitats and samples of all animals, protists, bacteria, and other species. Therefore, species of possible medicinal or genetic value should remain available. No ornamental species are present.

Regulating Services

- **Land.** Land mining can create toxic dusts that harm air quality. Removal of vegetation and trees causes soil erosion and release of stored carbon, reduces climate regulation and the ability to treat wastes, and can lead to moderate drought or floods. Collapse of tailings dams can destroy all ES in streams or rivers for hundreds of kilometers from the mine site. Harm to biodiversity can reduce pollination and biological controls within the ecosystem.

- **Deep seabed.** Collection of nodules does not require freshwater, and toxic emissions are limited to ship fuel emissions. Deep-sea sediments containing small amounts of carbon are temporarily disturbed but are expected to resettle on the seabed without releasing carbon into the atmosphere (see Carbon Sequestration section for detailed discussion).

Supporting Services

- **Land.** The varied locations where mining takes place contain or are adjacent to areas used as habitats or nurseries for resident and migratory species (flora, macro-, micro-, meio- and microbial fauna). These habitats are cleared to get access to the underlying ore body. Erosion, wastes, (toxic) tailings and other harm to soil, water and vegetation further degrades the quality of impacted habitats.

- **Deep seabed.** The seabed hosts resident macrofauna, microfauna, meiofauna, microbial, and epibenthic communities, including many species new to science. Nodule collection will strongly affect organisms living in mined areas. It may also affect demersal scavengers that migrate in search of food sources (see Biodiversity section for detailed discussion).

Cultural Services

- **Land.** Mines produce no aesthetic information, but they can harm the aesthetic qualities of the natural landscape with noise, dust, and physical disruption of habitat, vegetation, and surface waters. Operating mines are off-limits to recreation and tourism, but they can detract from those experiences by harming water resources, fisheries, or biodiversity. Some types of mines have inspired arts and design via the jewelry or tools made from mined metals (e.g., copper, silver, gold), or by providing settings or plots for books or movies (e.g., The Treasure of the Sierra Madre). They have impacted spiritual experiences by harming or preventing access to sites sacred to traditional peoples. They have historically encouraged technological innovations by mining engineers and others. The metals produced are essential to many aspects of civilization.

- **Deep seabed.** The CCZ seabed provides one cultural service, information for cognitive development, by providing new knowledge about the habitat and its organisms, many of which are new to science, and by stimulating technological development of new methods for studying the habitat and/or collecting nodules. Nodule collection should not impact other cultural services.

Table 10. Ecosystem Services Impacts of Metal Production

	PRODUCTION FROM LAND ORES		PRODUCTION FROM OCEAN NODULES	
Provisioning	Med-High	All services may be impacted, with food and water placed at greatest risk	Med-Low	Most services are not impacted. There is low potential for medical or genetic loss.
Regulating	Med-High	All regulating services see medium to high risk.	Med-Low	Due to the remoteness of ocean nodules, the vast majority of regulating services are not impacted.
Habitat	High	Habitat loss and degradation, noise, pollution, and tailing dam collapses endanger species.	High	Habitat loss and degradation, noise, light endanger species.
Cultural	Med	Aesthetics, recreational and spiritual opportunities may be damaged, although there can be inspiration for culture and design and positive technological development.	Low	No harmful impacts are seen, while additionally there can be benefits to science and knowledge acquisition, as well as technological development.
Overall	**Med-High**	**Medium to High Impact**	**Med-Low**	**Medium to Low Impact**

AGGREGATE RESULTS SUMMARY

Next, we present an aggregated collection of the impact category assessments to be discussed in the subsections that follow.

The "spider chart" shown in Figure 34 graphically plots the relative ratings assessed for impact categories for land ores (dark gray) versus nodules (blue). In general, the greater the area, the greater the negative impact footprint. Assessments were determined by quantifying the "low, medium, high" ratings provided at the end of each impact category's results discussion. Measures can range from 1 to 15. For quantifiable categorical results, such as climate change, a qualitative evaluation for the higher assessment was plotted, followed by mathematical proportional scaling for the lower value. Rationale for each of the rankings plotted here is explained in detail in the category results subsections.

Figure 34. Summary of Category Impact Ratings
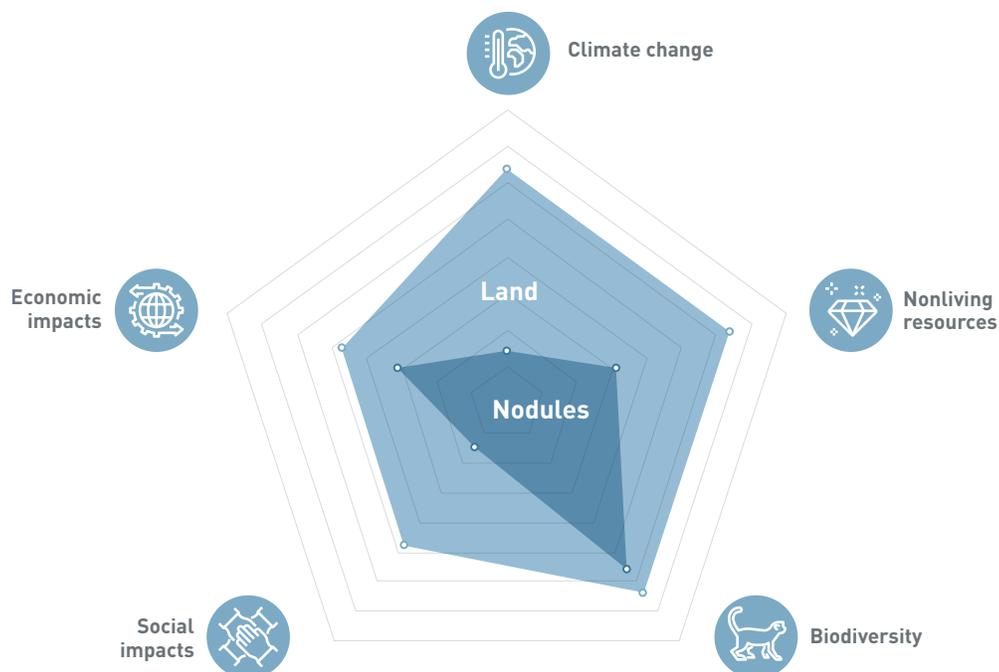
The plotted results reflect mostly medium to medium-to-high impact ratings for land ores, and mostly low-to-medium impact ratings for nodules. The main factors driving these ratings are:

- **Climate change** – Producing metals from nodules generates 70% lower GWP compared to producing metals from land ores' in the green mining scenario. Mass allocation shows an even stronger result. Furthermore, carbon sequestration impacts associated with land mining pose far greater risk than the potential disruption of carbon stored in deep-sea sediments and water.

- **Nonliving resources** – Resource use, waste, and toxicity are far lower with nodules, with 90%+ reductions across many quantified categories.

- **Biodiversity** – Much greater richness and greater diversity of species may be affected by land mining sites. This is caveated by the lesser knowledge of the deep-sea ecosystems and species.

- **Social impacts** – Nodules-based production of metals results in fewer human fatalities, illness, and abuses to vulnerable populations and cultures.

- **Economic impacts** – Producing metals from nodules is expected to be in the bottom quarter of the cost curves for all contained metals. Nodule-based production is expected to impose fewer economic risks. As an industry, nodule collection is expected to employ fewer people, albeit in higher quality jobs.

As outlined in the Methods section, several supplementary analyses were performed as we delved into the study, and within each major impact category results were quantified where possible, even for qualitative categories. The full set of quantified results is shown here in Table 11, including associations to impact categories. Side-by-side results of indicators by category are graphically depicted in Figure 35. Each indicator's results are derived and discussed in the category results subsections that follow.

Table 11. Quantified Results by Impact Category—Land and Nodules

ITEM	LAND ORES	NODULES	UNITS	LAND ORE REDUCTION	NODULES REDUCTION	IMPACT CATEGORY
GWP	1.5	0.4	Gt CO_2e		-70%	Climate Change
Stored carbon at risk	9.3	0.6	Gt CO_2e		-94%	Climate Change
Freshwater usage	45	5	km^3		-89%	Nonliving Resources
Waste and tailings	64	0	Gt		-100%	Nonliving Resources
Land competition	156,000	9,800	km^2		-94%	Nonliving Resources
Forest use	66,000	5,200	km^2		-92%	Nonliving Resources
Seafloor use	2,000	508,000	km^2	-99.6%		Nonliving Resources
SOx	173	17	Mt		-90%	Nonliving Resources
NOx	8	1.0	Mt		-87%	Nonliving Resources
Terrestrial ecotoxicity	33	0.5	Mt 1,4-DCB-eq		-98%	Nonliving Resources
Freshwater ecotoxicity	21	0.1	Gt 1,4-DCB-eq		-99%	Nonliving Resources
Eutrophication potential	80	0.6	Mt PO_4-eq		-99%	Nonliving Resources
Cumulative Energy Demand	24,500	25,300	Petajoules	-3%		Nonliving Resources
Wildlife at risk	47	3	Trillion megafauna		-93%	Biodiversity
Biomass at risk	568	42	Mt of biomass		-93%	Biodiversity
Human toxicity	37	0.3	Gt 1,4-DCB-eq		-99%	Social Impacts
Workforce at risk	1,800	47	# of fatalities		-97%	Social Impacts
Jobs (non-artisanal)	600,000	150,000	# of worker years		-75%	Economic Impacts
NiSO4 cost, 2025	14,500	7,700	USD per tonne Ni		-47%	Economic Impacts

Figure 35. Side-by-Side Quantified Indicator Results, Land Ores vs. Nodules

% reduction (nodules relative to land)   % reduction (land relative to nodules)

CLIMATE CHANGE

GWP, Gt CO_2e
Stored carbon at risk, Gt CO_2e

NONLIVING RESOURCES

Freshwater usage, km^3
Waste and tailings, Gt
Land competition, km^2
Forest use, km^2

Seafloor use, km^2

SO_x, Mt
NO_x, Mt
Terrestrial ecotoxicity, Mt 1,4-DCB-eq
Freshwater ecotoxicity, Mt 1,4-DCB-eq
Eutrophication, Mt PO_4-eq

Energy extracted, Petajoules

BIODIVERSITY

Wildlife at risk, Trillion megafauna
Biomass at risk, Mt of biomass

SOCIAL IMPACTS

Human toxicity, Gt 1,4-DCB-eq
Human lives at risk, number

ECONOMIC IMPACTS

Jobs (non-artisanal)
$NiSO_4$ cost, 2025

-100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0 -10 -20 -30 -40 -50 -60 -70 -80 -90 -100
%

CATEGORY 1: CLIMATE CHANGE

In this section we look at two impact sub-categories—Global Warming Potential (GWP) and Carbon Sequestration—each of which can exacerbate the ongoing climate crisis.

GWP Impact at a Glance

IMPACT SUB-CATEGORY
Global Warming Potential

- Mining ores from land requires significant energy, effort, infrastructure, and transport, resulting in substantial emissions and waste production. In the base-case scenario, cradle-to-gate life cycle emissions are estimated at 1.85 gigatonnes of CO_2e to produce the Ni, Co, Mn, and Cu inputs for one billion EV batteries by 2047. Under the optimistic "green" supply scenario, emissions are estimated at 1.47 gigatonnes of CO_2e.

- Due to its low-impact mining phase, lower transport costs, and easy access to hydropower (or other sources of renewable power), deep-sea nodule collection and processing generates less CO_2e life cycle impact, with only 0.44 gigatonnes of CO_2e produced by the planned nodules projects' baseline scenario. Nodule-based production reduces CO_2e cradle-to-gate emissions by more than 70% compared to land ores, including in the optimistic green land-mining scenario, with reductions nearing 90% under a mass-based sensitivity analysis.

This section presents the LCIA for GWP using standard LCIA methods. Marginal per-kilogram cradle-to-gate impacts of metal production from land ores and nodules are compared then aggregated for a side-by-side comparison of the global impact to support the expected exponential demand for EVs. The typical LCIA indicator for GWP is CO_2e emissions per kilogram of output. This has been computed using the industry-standard LCA tool SimaPro by summing relevant emissions along the value chain (e.g., carbon dioxide, sulfur dioxide, carbon monoxide), converted into CO_2e units. The GWP 100a standard is used.

We begin with as-is GWP assessments, then build to more realistic scenarios step by step. The following sequence is followed; also see the summary in Table 12.

- **As-is per-kilogram impacts.** GWP results are presented for each metal individually using today's material and energy conditions. Land-based results, aggregated from existing literature, are compared to nodule-based model results.

- **As-is one billion EVs static result.** The static per-kilogram impacts are multiplied by the masses of each metal present in an EV battery and the rest of the car (for copper wiring). We assume all metals are extracted using today's ore grades and electricity mixes.

- **Land ores' dynamic baseline scenario versus nodules project.** A more realistic computation of the impact of one billion EVs is attempted. Changes in ore grade, electricity mix, and energy density translate into different per-kilogram impacts for each year of production. These new per-kilogram impacts are applied to yearly EV sales projections, reaching a cumulative one billion EVs produced by 2047. Ore degradation dominates, and GWP for land-based metals worsens.

- **Land ores' dynamic green scenario versus nodules project.** In this modification of the baseline case, projected future elecricity mix improvements are ambitious. The improvements outweigh the negative impacts of grade declines, and GWP for land-based metal production decreases, though GWP impact for one billion EVs is still significantly higher for land-based than for nodule-based metal production.

Table 12. Supply-and-Demand Scenarios for GWP Analysis

STEP	CALCULATING	DEMAND SCENARIO	SUPPLY SCENARIO
As-is supply and demand	Per-kilogram GWP life cycle impacts	None	Today's ore grades, electricity mix, efficiency
As-is supply, one billion EVs static-demand scenario	GWP life cycle impacts to produce metals for one billion EV batteries today	One billion EV batteries today	Today's ore grades, electricity mix, efficiency
Dynamic-demand, dynamic-supply scenarios	GWP life cycle impacts to produce metals for one billion EV batteries by 2047	One billion EV batteries by 2047, using projected EV demand scenario[146]	Land ores: Baseline scenario Nodules: Planned project
Dynamic-demand, dynamic-supply scenarios	GWP life cycle impacts to produce metals for one billion EV batteries by 2047	One billion EV batteries by 2047, using projected EV demand scenario	Land ores: Green scenario Nodules: Planned projects

As-Is Per-Kilogram Impacts

Today, around six kilograms of CO_2e is emitted for every kilogram of copper produced, on average, just to make the metal. For cobalt and nickel, the number is even higher. Figure 36 shows how CO_2e for a single nodule-production system breaks down between mining, processing, and refining.

- For metals like copper, roughly half of emissions comes from the mining and concentration steps. For the LCA model built for nodules, less than 10% of emissions is contributed by offshore harvesting and transporting nodules to the onshore plant. Driving the lower emissions are a simplified extraction process, higher grades, specific mineralogy, and ocean location enabling low-footprint transport to the processing plant.[147]

- Electricity is one of the largest contributors to greenhouse gas emissions due to heavy use of fossil fuel sources in global grids. Nodules' hydropower access provides a significant near-term advantage. Nodule-processing plants can be flexibly placed near any deep-water port for easy access to customer plants and hydropower. Land-based mining

concentration plants must be located close to mines because low-grade metal ores, with their high mass and low value, cannot be economically shipped. Many mines are off grid and burn diesel and fuel oil for electricity generation, although this is shifting as more off-grid renewables are implemented.

- On balance, a portion of benefits of metal production from nodules is offset by the high volume of manganese, given its carbon-intensive pyrometallurgical reduction process. Manganese reduction alone contributes nearly three-quarters of the overall cradle-to-gate CO_2e of nodule production.[148] Note that nodules conceptually receive an impact 'credit' against manganese alloy production, since a substantial part of the emissive reduction required to produce an alloy has already been performed.

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146 EV dynamic-demand-scenario projections to 2047 are described in (Morgan Stanley, 2017).

147 See earlier discussion of key input drivers leading to higher emissions in metal production.

148 Nodule processing includes extraction through final products ready for battery manufacture. Source: Implemented LCA model for producing metals from polymetallic nodules.

Figure 36. CO$_2$e to Produce Metals from One kg of Nodule: Dominated by Polymetallurgical Step

Collection	Ship to plant	Pyro processing	Refining
0.01kg CO$_2$	0.01kg CO$_2$	0.25kg CO$_2$	0.043kg CO$_2$
3.1%	3.2%	80.1%	13.6%
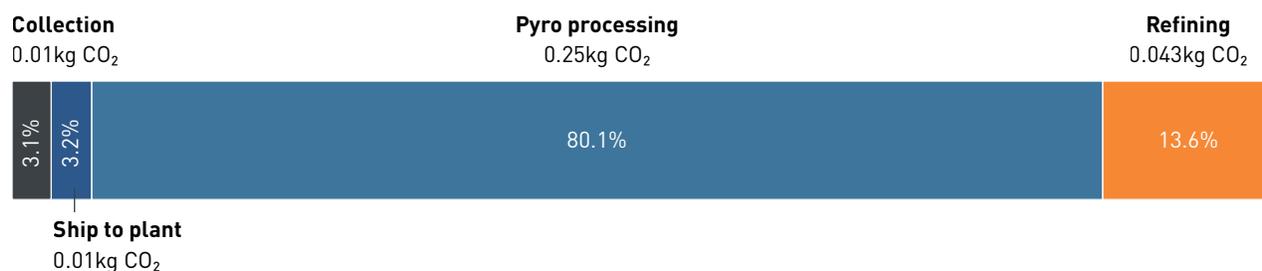
Table 13. Masses and Values of Nodule Product Streams

MASS ITEM	ANNUAL FLOW (TONNES)	AVERAGE VALUE ($ PER TONNE)	ANNUAL VALUE ($M)
Dry nodules at processing facility	4,880,000		
Nickel contained in sulfate	60,700	$19,926	$1,210
Cobalt contained in sulfate	6,000	$51,007	$306
Manganese contained in sulfate and silicate product	1,383,000	$390	$538
Copper cathode	48,700	$7,084	$345
Ammonium sulfate	171,000	$90	$15
Converter slag	509,000	$0	$0

Additional low-value byproducts generated as part of metal production from nodules do not receive substantial emissions allocations. In the case of ammonium sulfate, most commonly used as a high-nitrogen soil fertilizer, the relative per-kilogram market value is negligibly low compared to the value of metal products that get all of the allocation. As a result, nodule processing effectively becomes a source of near-zero emissions fertilizer-grade ammonium sulfate—while conventional sources of ammonium-sulfate production typically generate two tonnes of CO$_2$e emissions for every tonne of ammonium sulfate produced. In the mass-based allocation sensitivity analysis, ammonium sulfate receives a much larger allocation, driving down the per-kilogram emissions of metals products. In the case of converter slag, the per-kilogram market value is so small it could be negated by transport costs (depending on customer location). As a result, the converter slag is excluded from both economic value and mass-based allocation schemes while ammonium sulfate as a valued byproduct is included. Table 13 shows the mass content and economic values of all product streams produced by a nodule-processing facility.

Finally, Figure 37 summarizes the as-is case of per-kilogram GWP for cradle-to-grate production of Ni, Co, Mn, and Cu inputs into EV production using the two different sources under both economic and mass-based allocations. The analysis shows that all four metals generate significantly less CO$_2$e when produced from nodules, regardless of the allocation method. Of the four metals analyzed in this paper, nickel and copper represent the bulk of the metal mass in EVs.

Figure 37. Cradle-to-Gate Emissions Comparison, Land Ores vs. Nodules (kg CO_2e per kg metal)[149]

Economic allocation (Primary result)

	Nickel sulfate	Cobalt sulfate	Manganese sulfate	Copper cathode
Land ores	19.6	14.2	6.4	5.9
Nodules	3.9	10.1	5.0	1.4

Nickel sulfate: -80%
Cobalt sulfate: -29%
Manganese sulfate: -22%
Copper cathode: -76%

Mass-based allocation (Sensitivity analysis)

	Nickel sulfate	Cobalt sulfate	Manganese sulfate	Copper cathode
Land ores	13.6	9.8	6.4	5.9
Nodules	0.7	0.7	5.1	0.7

Nickel sulfate: -95%
Cobalt sulfate: -93%
Manganese sulfate: -20%
Copper cathode: -88%

(As-Is) One Billion EVs Result

We now apply the per-kilogram values to the first demand case to calculate how many tonnes of CO_2e will be emitted to produce the Ni, Co, Mn, and Cu (in final specifications) required to build batteries and copper wiring for a global fleet of one billion EVs.

In the static case, we consider today's ore grades and mineralogies, electricity mix, energy densities, and global demand. Applying the ratios of these metals to produce one EV, then multiplying by one billion (see Figure 38(a)), land ores' GWP cradle-to-gate life cycle impact for these four metals is estimated at quadruple that of nodules:

- Metals produced from land ores: **1,749 megatonnes**
- Metals produced from nodules: **445 megatonnes**

149   Sources: For land-based values, see note 11. For nodule-based values, see technical appendix for LCA model and analysis.

Figure 38. CO_2e per EV, As-Is Land Ores and Planned Nodules, Economic Allocations

(a) Economic Allocation (Primary Analysis)

CO_2 per kg	1 EV Battery Metal Contents	1 EV Battery CO_2e (Land)	1 EV Battery CO_2e (Nodules)
Ni SO$_4$	56.2 kg (36%)	1,103	221
Co SO$_4$	7 kg (5%)	100	71
Mn SO$_4$	6.6 kg (4%)	42	33
Copper	85 kg (55%)	503	119
	Total CO_2 for 1 EV Battery Metals + Connectors	**Land** 1,749 kg	**Nodules** 445 kg

(b) Mass-Based Allocation (Sensitivity Analysis)

CO_2 per kg	1 EV Battery Metal Contents	1 EV Battery CO_2e (Land)	1 EV Battery CO_2e (Nodules)
Ni SO$_4$	56.2 kg (36%)	764	40
Co SO$_4$	7 kg (5%)	69	5
Mn SO$_4$	6.6 kg (4%)	42	34
Copper	85 kg (55%)	503	60
	Total CO_2 for 1 EV Battery Metals + Connectors	**Land** 1,379 kg	**Nodules** 139 kg

Performing a sensitivity analysis with mass-based allocations, we see significant reductions in emissions for both production types (as a larger share of emissions gets allocated to high-mass byproducts while ignoring their economic value), but an even steeper benefit for nodules (see Figure 38(b)).[150] Results are now:

- Metals produced from land ores: **1,379 megatonnes**

- Metals produced from nodules: **139 megatonnes**

The breakdown of GWP impact by metal is shown in Figure 39, calculated by applying the relative proportions of each metal in an EV battery and electric harness to today's per-kilogram impacts for each metal product.[151]

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150 See this paper's technical appendix for literature and modeling assumptions for mass-based sensitivity analyses.

151 Battery composition is based on NMC811 chemistry and 75kWh battery size. Proportions are straightforwardly applied to per-kilogram carbon dioxide values to attain the results.

Figure 39. CO$_2$e Contributions to One Billion EVs by Metal, As-Is Land Ores and Nodules (Mt CO$_2$e)

Economic Allocation (Primary result)

Mass-Based Allocation (Sensitivity analysis)

- Nickel sulfate
- Cobalt sulfate
- Manganese sulfate
- Copper cathode
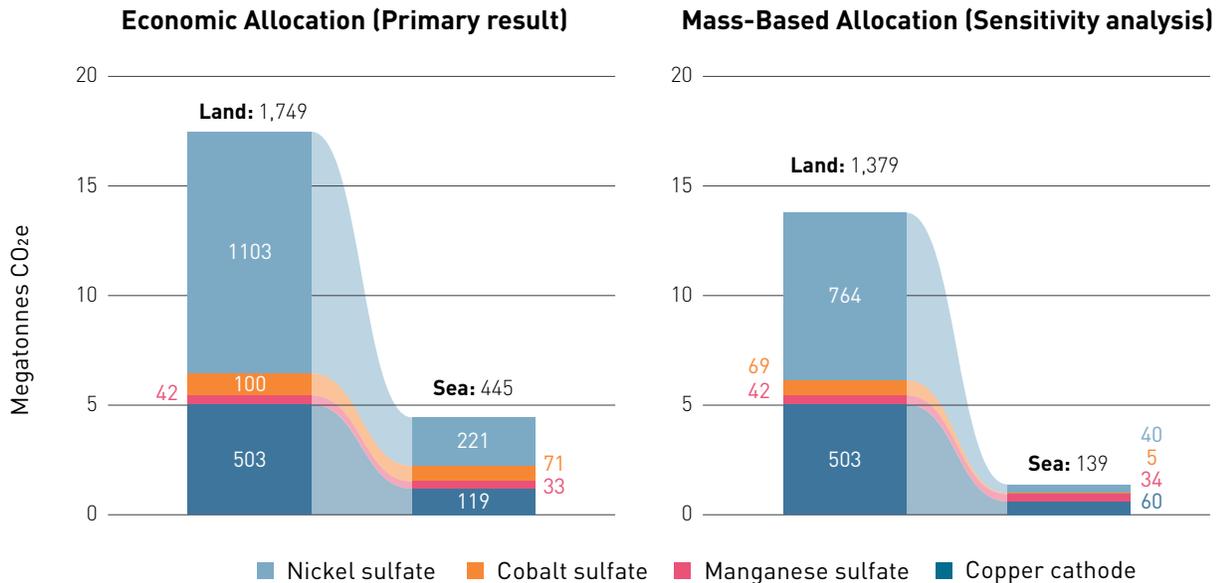
Figure 40 shows that nodule emissions are dominated by pyrometallurgical processing with a relatively small contribution from nodule collection, whereas mining phase contributes roughly half of life cycle emissions in the case of land ores.

The as-is scenario driving these calculations assumes that nothing changes as we drill and blast massive quantities of ore on land going forward. In reality,

as grades for nickel and copper continue to decline, mining countries will implement policies to lessen grid dependence on fossil fuels and miners will have no choice but innovate. Depending on which effects dominate, the GWP may improve or worsen once these dynamics are added. This is why, as a next step, we consider dynamic scenarios to model these changes and generate more realistic GWP estimates.

Figure 40. CO$_2$e Contributions to One Billion EVs by Phase, As-Is Land Ores and Nodules (Mt CO$_2$e)

- Mining and Concentration
- Processing
- Refining
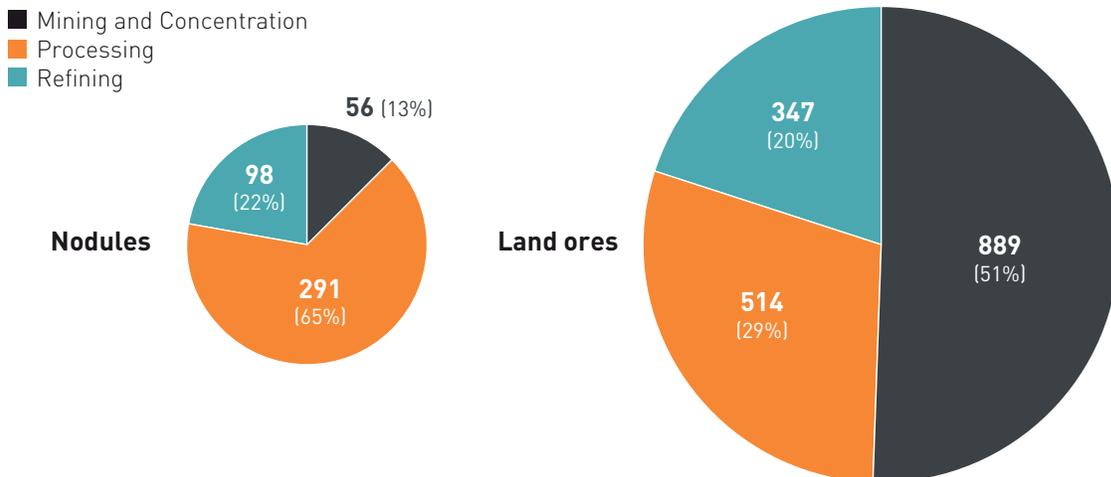
Dynamic Future Projections in a Baseline Land-Ores Scenario

Key drivers of change that can materially affect the GWP impact of metal production over the next thirty years include ore-grade degradation, improvements in technology driving efficient use of energy, and policy-driven decrease in dependence on high environmental footprint inputs (e.g., fossil-fuel-derived electricity).

Two scenarios of plausible future developments are adapted from UN GEO-4 supply and demand scenarios and International Energy Agency's World Energy Outlook (WEO) scenarios, projected up to 2050.[152] Here we explore the baseline land-ores scenario, which is based on the UNEP Markets First and WEO Current Policies scenarios.

In the baseline land-ores scenario, status quo policies are expected to continue, resulting in only modest changes in electricity mix. The scenario is modeled as follows:

• The effects on ore grade (nickel and copper), electricity mix, and energy density (copper) on per-kilogram LCIA results are modeled. For intuition on relative impact, one study showed ore-grade decline and electricity mix for two sample metals to adjust GWP by around 10%, with net GWP adjustments in

2050 considering all three factors for the Markets First scenario ranging from -11% to +23%, and electricity mix of the Equitability First scenario in 2050 adding a benefit ranging from -11% to -43%.[153]

• This approach converts static per-kilogram impacts into a time series of adjusted impacts in five-year increments.[154]

• Using the demand projections described in this paper's introduction, per-kilogram values are scaled up to yearly aggregate impacts and summed over all production years, so that cumulative metal products for one billion EVs are produced by 2047.

• Dynamic changes are applied to land-based results only. As previously discussed, ore-grade decline projections do not apply to nodules, since surveys show preexisting large quantities of high-grade polymetallic nodule deposits. Benefits from electricity mix changes are ignored for nodule-based metal production as the effects are second order.

The **electricity-mix scenario** for the baseline case is shown in Figure 41. Global electricity mix shifts only slowly toward renewables from 22% in 2015 to 25% by 2050, with coal nearly constant, around 41%–42%, and natural gas around 22%-24%.

Figure 41. Background Electricity Mix for Baseline Land-Ores Scenario[155]

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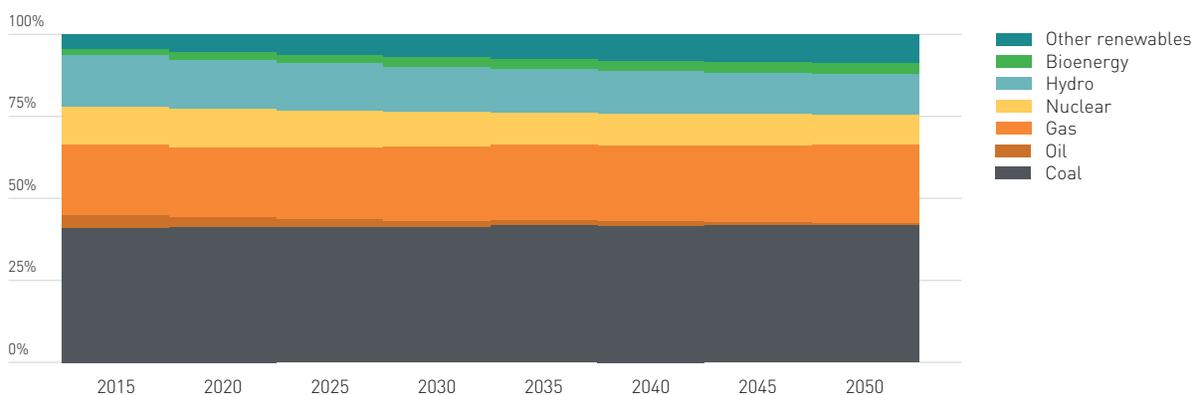
152 (van der Voet, van Oers, Verboon, & Kuipers, 2018); (IEA, 2012).

153 Details of this sensitivity analysis are shown in Appendix 8 of (van der Voet, van Oers, Verboon, & Kuipers, 2018).

154 (van der Voet, van Oers, Verboon, & Kuipers, 2018).

155 These and additional electricity mix scenarios projected to 2050 are found in (Kuipers, et. al., 2018).

The **copper energy-efficiency increase projections** are based on a survey of historical efficiency improvements for seven metals, including nickel and manganese.[156] Trends were easily measurable for copper, as its energy requirements have historically been close to the theoretical minimum.[157] This dynamic was mathematically quantified for a subset of copper processes and production paths based on an adaptation of the U.S. Department of Energy "bandwidth method" to define a practical minimum that considers global average energy requirements, best practice requirements, and the theoretical minimum. Studies assumed this minimum will be matched by 2050 for pyrometallurgical smelting and reduction processes and scaled the energy inputs for those LCI projections.[158] These results were used directly by this paper.

Depletion of high-grade ore supply matters to our analysis. Consider what is happening with nickel sulfide deposits, which currently provide the optimal nickel sulfate input for EV battery production.

- **Lower-grade land ores will likely be tapped, increasing GWP.** At a macro level, nickel ore grade has historically shown downward trends over time, and barring revolutionary technological disruption,

this is expected to continue. Lower-grade ore means more ore is required to achieve the same metal output. Larger volumes of ore are extracted, transported, and stored, and more time and energy are spent concentrating the ore.

- **Proportionally more processing losses will occur.** Processing losses increase with lower-grade ores. The energy and rock mass required for mining and beneficiation vary inversely with ore grade. As grades decline, waste and energy use increases, further driving up GWP.

- **More nickel laterite sources will be used for EV batteries.** Laterites will likely be tapped for battery production, requiring additional processing steps to produce the same nickel sulfate required for EV batteries.

Illustrating the anticipated continued decline, Figure 42 shows a fitted curve of historical and projected future average ore grades for copper and nickel metals, created from historical ore-grade data and using a mathematical projection of future global ore grades.[159]

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156 (Kuipers, et. al., 2018).

157 (Alvarado, Maldonado, Barrios, & Jaques, 2002).

158 (Kuipers, et. al., 2018).

159 (van der Voet, van Oers, Verboon, & Kuipers, 2018). See also (Norgate & Jahanshahi, Energy and greenhouse gas implications of deteriorating quality ore reserves, 2006) and (Northey, Mohr, Mudd, Weng, & Giurco, 2014). Following (van der Voet, van Oers, Verboon, & Kuipers, 2018), the study did not apply ore-decrease projections for manganese and cobalt, judged as less substantial.

Figure 42. Historical and Fitted Copper and Nickel Ore Grades (Sulfides and Laterites)[160]

(a) Copper Grades Since 1750

$R^2 = 0.9293$

Historical (Crowsen, 2012)   Projected

(b) Nickel Grades Since 1750

$y = 2E+45x^{-13,68}$
$R^2 = 0.1935$

Ore grade decline
Power (Ore grade decline)

(c) Copper and Nickel Grades since 1880 (Fitted)

Nickel
Copper

(d) Copper and Nickel Grade Projections

Nickel
Copper
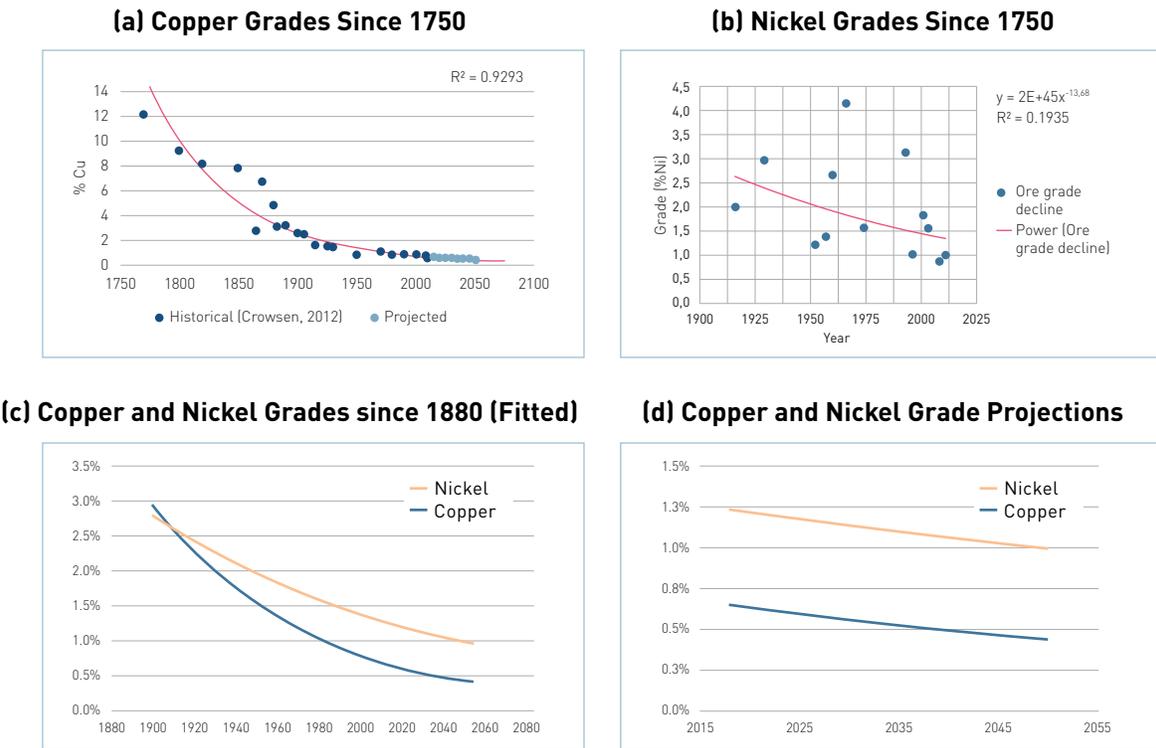
Note that new, undiscovered deposits may be of variable grade, and that increasing metal prices or new technologies can make mining lower-grade ores more profitable. On the other hand, these dynamics are less likely to play out within our thirty-year analysis horizon, given the long lead times and uncertainty associated with step-function resource or technological changes. We therefore focus on the more likely near-future, which requires mining lower-grade ores with lower recoveries and the added brute force of additional crushing, concentration, and transport in order to continue operating within contemporary production technologies.

These ore-grade declines will increase the GWP impact of land ores over time, which means we can expect the dynamic scenario to produce greater overall GWP impact than the static case, unless the expected "business as usual" projected benefits are large enough to counteract it.

In the baseline scenario for land ores, we find that the negative impact of falling ore grades prevails. Compared to the as-is scenario, in this first dynamic scenario GWP estimates for nickel and copper from land ores increase by 8% and 14% respectively, while the overall GWP to produce battery metals and connectors for one billion EVs increases by 6% or 0.1 Gt CO_2e.

The results show that GWP for producing metal for one billion EV batteries under a dynamic scenario is 76% lower when using nodules. Savings are even greater under mass-based allocation. CO_2e emissions required to produce metal for one billion batteries are:

- Metals produced from land ores (baseline dynamic case): **1,850 megatonnes**

- Metals produced from nodules (as-is case): **445 megatonnes**

160 Sources of figures: Top left, (Kuipers, et. al., 2018); top right, bottom left, bottom right, (van der Voet, van Oers, Verboon, & Kuipers, 2018). Nickel graphs combine laterites and sulfides.

Figure 43. GWP for Baseline Land-Ores Case versus Planned Nodules Project (Mt CO$_2$)

(a) GWP per year (Mt CO$_2$e) Projected

Legend:
- Land: Economic
- Land: Mass
- Nodules: Economic
- Nodules: Mass

X-axis: 2017 2022 2027 2032 2037 2042 2047
Y-axis: 0, 50, 100

(b) Total GWP for 1 Billion EVs by 2047 (Mt)

1850
1464
445 (-76%)
139 (-91%)

Y-axis: 0, 500, 1000, 1500

Total for 1B EVs
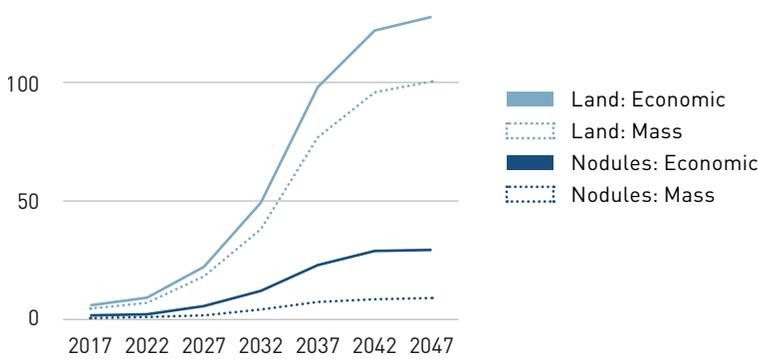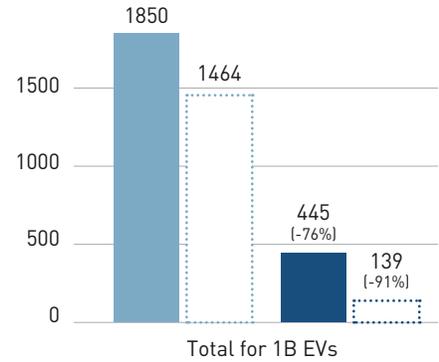
The estimated GWP advantage for nodules may be underestimated because only ore-grade declines for copper and nickel are included, and because electricity improvements were not modeled for nodule-based production. Even though nodule plants are assumed to be designed with a renewable power source, marginal life cycle improvements would still be gained from value-chain components experiencing the benefit of changes in the electricity mix. The estimated GWP advantage may also be overestimated if new ore deposits with substantially higher grades are discovered and exploited. As any such LCA relies on estimates and practitioner's judgment, a reasonable margin of error should be kept in mind in either direction. Qualitatively, the differences between land-based and nodule-based production are large, and they are robust to sensitivity analyses performed on foreground data and on land-based-model aggregation assumptions.

Dynamic Future Projections of Optimistic "Green" Land-Ores Scenario

We now apply our second scenario, based on the UNEP Equitability First and WEO 450 scenarios. Our "green" land-ores scenario envisions an aggressive transition away from fossil fuels and toward renewables, as well as global standard-of-living improvements that further fuel-technology investment and demand growth.

The **electricity-mix scenario for the green scenario** is shown in Figure 44. Significantly greater levels of decarbonization in electric grids are modeled, with renewables' share increasing from 22% in 2015 to 64% by 2050, and coal decreasing from 41% in 2015 to 0% in 2050.

The copper energy-efficiency projections and nickel and copper ore-grade assumptions remain the same as the baseline case.

Figure 44. Background Electricity Mix for Green Land-Ores Scenario[161]
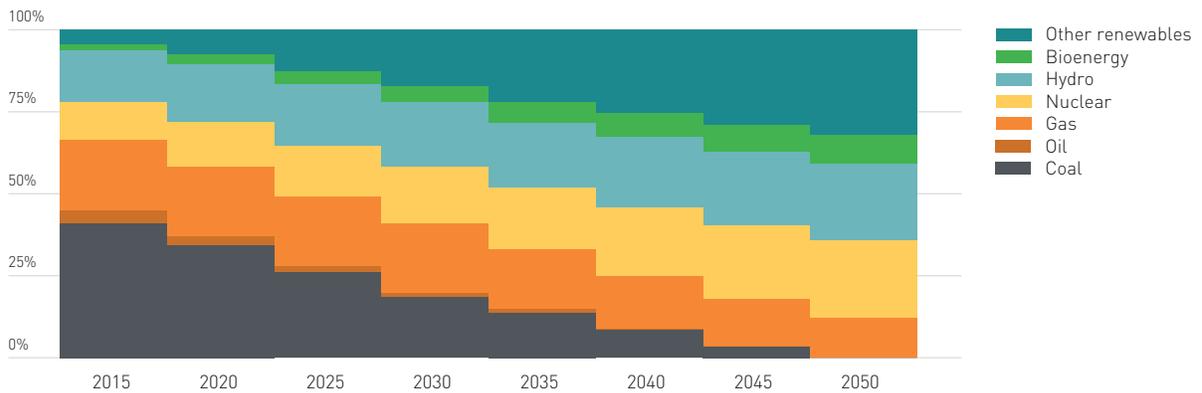
These improvements are once again applied only to the land-based LCIA. As cobalt modeling was not available for this analysis it is assumed to derive the same overall benefit as manganese, whose results are applied directly as neither was modeled as having an ore-grade decline.[162]

This scenario materially and positively impacts the GWP projections since the electricity mix improves significantly. Unlike in the baseline scenario, electricity-mix benefits are several times larger than the negative impact of ore-grade declines, leading to a net beneficial result. Figure 45 illustrates this GWP improvement by comparing the per-kilogram static GWP values to the per-kilogram GWP values for the green scenario in 2050. Individual metals' GWP values decrease between -19% and -35% by 2047, with nickel seeing the greatest absolute decrease. As nickel and copper each see around -19% decreases and comprise the majority of the EV metal requirements, we can expect a significant improvement for one billion EVs.

Figure 45. Per-kg CO$_2$e for Land Ores (kg), Comparing As-Is (2017) to Green Scenario (2047)

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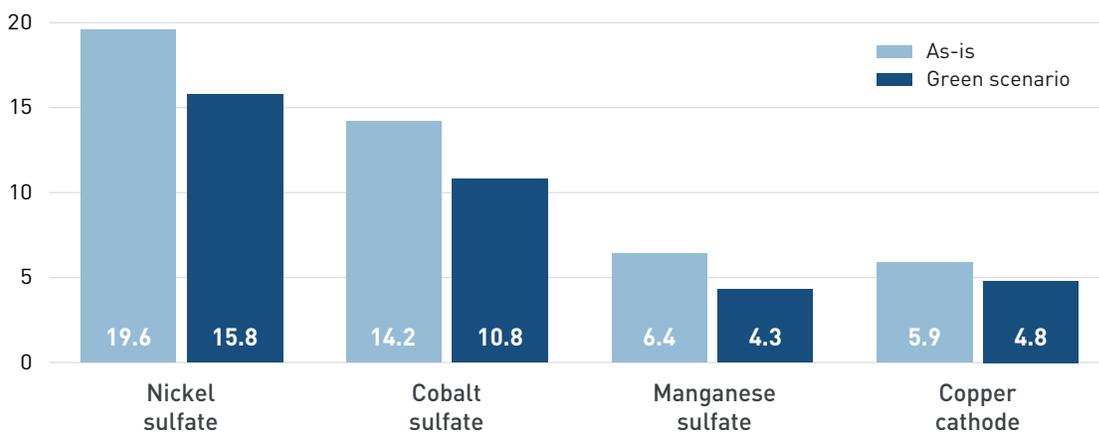
161   These and additional electricity-mix scenarios projected to 2050 are found in (Kuipers, et. al., 2018).

162   (van der Voet, van Oers, Verboon, & Kuipers, 2018).

Figure 46. GWP (Mt CO_2) for Green Land-Ores Case versus Planned Nodules Project

(a) GWP per year (Mt CO_2e) Projected

(b) Total GWP for 1 Billion EVs by 2047 (Mt)

Legend:
- Land: Economic
- Land: Mass
- Nodules: Economic
- Nodules: Mass
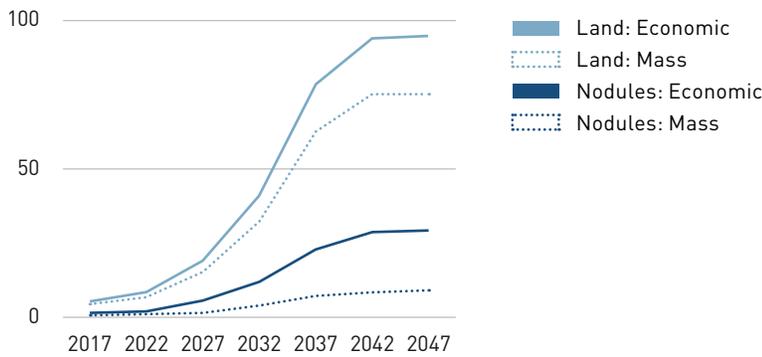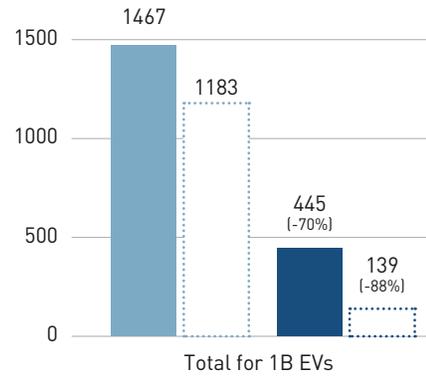
CO_2e emissions required to produce metals for one billion batteries, for the optimistic dynamic case, are now:

- Metal production from land ores (green dynamic scenario): **1,467 megatonnes**
- Metal production from nodules (as-is case): **445 megatonnes**

For land ores, the green scenario marks a 16% improvement over the static case with no dynamics and a 21% improvement over the baseline land-ores case in which ore-grade declines net worsen GWP impact. The green scenario represents a clear and significant improvement over the baseline scenario for metal production from land ores.

Despite a set of aggressive green policies that should produce an optimistic view for land ores, the GWP to produce one billion EV batteries is still at least 70% lower using nodules.

See Figure 47 for a metal-by-metal comparison of land ore and nodule GWP impacts, for both the baseline and green land-ores scenarios, to supply metals for one billion EV batteries by 2047.

Figure 47. CO$_2$e Attributable to Production of Battery Metals and Copper, 1 B EVs, 2017–2047 (Gt)

Legend:
- Copper cathode
- Cobalt sulfate
- Manganese sulfate
- Nickel sulfate

Baseline Land: 1.85 (Nickel sulfate 1.16, Copper cathode 0.55)
Green Land: 1.47 (Nickel sulfate 0.93, Copper cathode 0.43) — -70%
Baseline Nodules: 0.44 (Nickel sulfate 0.22, Copper cathode 0.12) — -76%
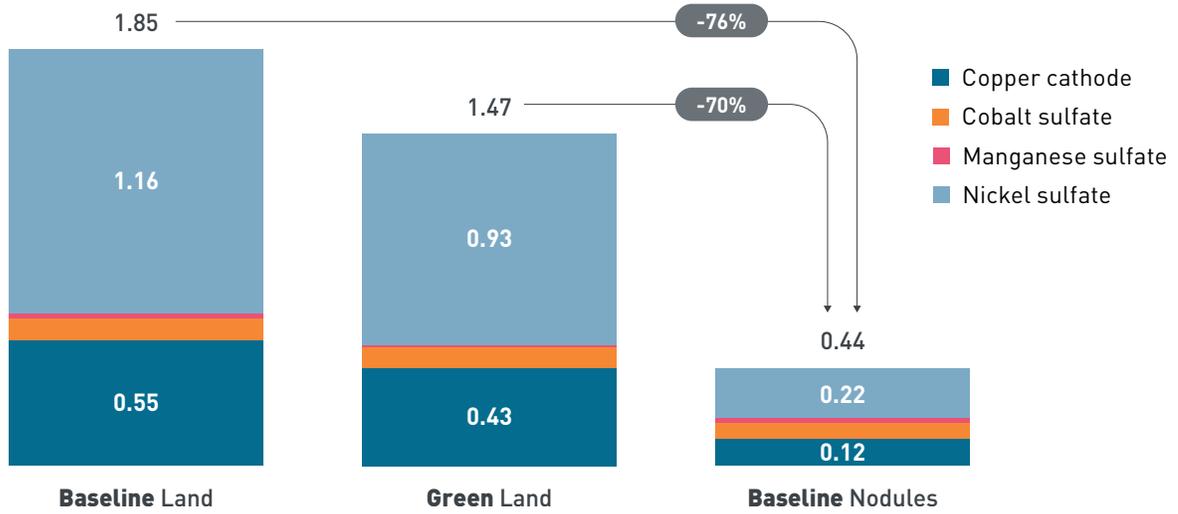
Carbon Sequestration Impacts at a Glance

IMPACT SUB-CATEGORY
Carbon Sequestration
• On land, mining puts at risk significant amounts of carbon. Forests, vegetation, and soil are disrupted for mining as well as for processing. As much as nine gigatonnes of carbon dioxide is at risk of release in order to generate battery metals for one billion EVs.   • The total amount of stored carbon at risk is >90% lower when using deep-sea nodules. Seabed sediments contain vastly lower amounts of carbon, little of which can reach the ocean surface even if sediment is disturbed. Meanwhile, higher-CO$_2$, pressurized seawater is pumped to the surface and will have brief atmospheric exposure, but modeling shows the quantity of CO$_2$ this operation risks releasing is low. For onshore operations, processing plants are location flexible and may be placed within areas of minimal trees and vegetation, further mitigating impact.

Below, we describe the mechanisms by which carbon sequestration may be impacted by land mining and deep-sea nodule collection across all phases of production. Potential impacts are quantified for both metal-production types. The section proceeds as follows:

• Carbon sequestration impact from terrestrial mining and production

• Carbon sequestration impact from deep-sea nodule collection (offshore)

• Carbon sequestration impact from deep-sea nodule production (onshore)

Carbon Sequestration Impact from Terrestrial Mining and Production

Using light from the sun and CO_2 from the air, plants photosynthesize the carbon-based chemicals they need for growth. Trees store a substantial part of their production as wood in their trunks and branches, effectively sequestering the contained carbon from release to the atmosphere for very long periods (decades, centuries, and even millennia, depending on species). Carbon not used for above-ground growth is stored in roots, and some is disbursed to mutualistic fungi. Over time, carbon from dead roots, fallen leaves, and dead trees or other vegetation also enters the soil. If undisturbed, soil sequesters its carbon for similarly long periods.[163] The result is that terrestrial soils are the world's second-largest carbon sink (~2,300 Gt), 15 times larger than surface sediments of the abyssal seabed (~150 Gt) and second only to the intermediate and deep ocean (~37,100 Gt).[164]

Mining can interact with the carbon-sequestration process through two primary mechanisms: land transformation and pollution. First, some of the stored carbon is released when forests and soils are cleared and disturbed for the mines and processing plants. Carbon can also be released when the land is debilitated by contamination with toxic water, dusts, or air emissions. Second, physical damage and contamination may impede revegetation of habitats, which reduces the future capability for the ecosystem to sequester carbon. Habitat damage may happen through land and water contamination, land use for tailings dams, tailings dam collapses, and other mechanisms described in the Nonliving Resources section. The damage to carbon sequestration caused by terrestrial mining will vary by mine type, location, size, mining methods, local habitats and ecosystem, and other factors. No estimates are available for overall impact by mining sector or for individual mines. However, typically the area of damage will exceed the geographical area of the mine per se, as a result of water and air pollution, construction of access roads, and impacts of mining communities.

An extreme example is illustrated by the nickel mining and smelting complex in Norilsk, Russia: emissions of cadmium, copper, lead, nickel, arsenic, selenium, zinc, and sulfur dioxide caused widespread respiratory illness and mortality, and turned an area twice the size of Rhode Island into a dead zone of lifeless tree trunks, mud, and snow, earning Norilsk a listing in 2007 as one of the world's 10 most polluted sites.[165]

We constructed a rough estimate of the amount of sequestered carbon at risk of release from clearing vegetation and soil from land used for terrestrial mining. The starting point for this estimate is the life cycle land use for mine sites, refining sites, plant infrastructure, and road construction for terrestrial mines—estimated at 156,000 square kilometers needed to obtain the metals for one billion EVs (see Physical Damage to Habitats subsection for discussion of method and assumptions). An average organic carbon content of 16,200 tonnes per square kilometer was calculated as stored in the soil and vegetation across all biomes.[166] This yields about 2.53 gigatonnes of stored carbon at risk within the area needed for one billion EVs. When exposed to air, oxidation plus microbial metabolism will eventually convert that 2.53 gigatonnes of carbon to 9.3 gigatonnes of carbon dioxide—see Figure 48. We estimate this to be the maximal risk for sequestration loss associated with terrestrial mining for the one billion EV battery scenario. That risk could be reduced somewhat if mines separated out some portion of the removed soil, or cut vegetation from air through either stacking or burial.

While mines sit unremediated and infrastructure, roads, and other land disruptions persist, future carbon sequestration services are impacted. We calculated a scenario of cessation of carbon sequestration services from all affected soil and vegetation needed for one billion EVs. If services in all disrupted areas ceased for 100 years, an estimated 0.56 gigatonnes of carbon would not be sequestered, equivalent to 2.1 gigatonnes of CO_2.[167]

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163   (EEA, 2015)

164   (World Ocean Review, 2010a).

165   See 2017 New York Times article on Norilsk's impacts on the environment: (Ponomarev, 2017); (Blacksmith Institute, 2007).

166   Carbon content was calculated as the average of three estimation methods, using, respectively, biome-by-biome estimates from (1) (Trumper, et al. 2009); (2) vegetation, soil, and detritus organic carbon estimates by (IPCC, 2007); and (3) soil estimates by (Zomer, et al. 2017) and vegetation estimates by (Erb, et al. 2018), (Lal, 2004), and (FAO, 2010).

167   Annual U.S. carbon sequestration rates from (Lu, et al. 2015) yield an estimate of 104 tonnes of carbon/km² sequestered per year in forested areas and 2.1 in non-forested areas. Annual global sequestration rates from (Keenan and Williams, 2018) yield an average all-terrain estimate of 27 tonnes of carbon/km² sequestered per year. Applying these rates to LCIA land areas for one billion EVs and extending to 100 years yields 0.7 gigatonnes and 0.42 gigatonnes of carbon, respectively, or an average of 0.56 gigatonnes.

Figure 48. Sequestered Carbon Release From Land-Mining Operations for 1B EVs
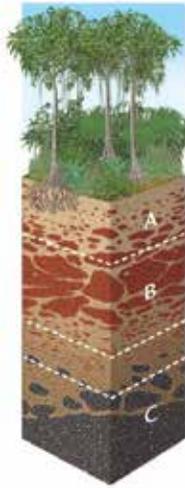
9.3 gigatonnes
of CO_2 is at risk of release from removing vegetation and soil ("overburden")

156,000 km²
land area impacted by mining for 1B EVs

~16,200 tonnes of organic carbon
stored on average per km² of soil and vegetation across all terrestrial biomes

Carbon Sequestration Impact from Deep-Sea Nodule Collection (Offshore)

Offshore nodule-collection operations, in contrast, are unlikely to release substantial amounts of already-sequestered carbon to the atmosphere, while significant, though probably temporary impact to the ongoing carbon-sequestration process could occur. Each of these is described in detail below.

Release of already-sequestered carbon by offshore nodule-collection operations could occur through two broad mechanisms. The first is by stirring up carbon embedded in sediments, whereby previously-trapped particulate organic carbon, organic or inorganic carbon dissolved in pore water, or carbon from methane or carbon dioxide clathrate reservoirs might rise to the ocean surface. The second is by release of carbon dioxide from deep seawater as it is slightly warmed and briefly exposed to air in a decompressed setting. We look at each of these in turn.

Carbon embedded in sediments

To estimate the carbon at risk of release from sediments, we need to consider three things: the size of the seabed disturbed for nodule collection, the density of carbon content on or within the seabed, and the mechanics of this carbon physically rising to the ocean surface.

The footprint impacted by nodule collection is much larger than for land mining—508,000 square kilometers of seabed compared to 156,000 square kilometers of land. Although the area of disruption is larger, the sequestration impact will not be equivalent, since carbon concentrations in CCZ sediments are on average at least an order of magnitude less than in terrestrial soil.

Despite its vast area, the total seabed surface contains up to 15 times less carbon than all vegetation and soil on land. Data from World Ocean Review indicates that globally, 150 gigatonnes of carbon are stored in 354 million square kilometers of seabed surface (424 tonnes/km²), while 2,300 gigatonnes of carbon are stored in 130 million square kilometers of vegetation, soil, and detritus on the planet (17,700 tonnes/km²).[168] Ciais et al.[169] state a higher total value of 1,750 petagrams for marine surface sediments, yielding a global average of 4,940 tonnes/km², but even this is much lower than the value for land. The lower quantity of carbon in surface sediments occurs in part because most carbon is metabolized in the water column before it reaches the bottom, as microbes decompose particles during their long voyage downward.

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168 (World Ocean Review, 2010a).
169 (Ciais, et al., 2013).

As a result of low primary productivity in its surface waters plus microbial degradation of organic detritus as it slowly sinks to the bottom, the total amount of organic carbon stored per area within the top 10 centimeters of CCZ abyssal sediments is far less than in terrestrial soil.

In all CCZ areas sampled by Volz et al., total organic carbon contained in sediment ranged from 0.2% to 0.6 % by weight, decreasing with depth and remaining constant below 30 centimeters at <0.2 %.[170] In contrast, soil carbon values in the Unified North American Soil Map range from 0.87% to 51%.[171] The median value for soil, 17%, is more than 300 times higher than for CCZ sediments.

Sediment samples from the CCZ NORI Area D seafloor averaged 1.17 grams/cm^3 wet weight; 0.31 grams/cm^3 dry weight; 0.49% carbon; and 151.9 grams of total organic carbon per square meter (151.9 tonnes/km^2). Scaling up to the 508,000 square kilometers of CCZ seafloor that would be disturbed to a depth of 10 centimeters in order to produce the metals for one billion EV batteries and connectors,[172] the total amount of material displaced would be 59.6 gigatonnes wet, or 15.9 gigatonnes dry, and 0.08 gigatonnes of carbon. However, essentially none of that carbon at 4-6 kilometers depth can reach the sea surface and the atmosphere. Even when sediments are disturbed, plumes are expected to rise no more than 100-200 meters from the seafloor, and 99% of the material is expected to resettle back to the bottom within one to two months and within 100 kilometers.[173] The residual 1% would still only reach the surface after decades or centuries of thermohaline circulation in the unlikely event that it were still afloat. The maximum amount of carbon at risk is therefore less than 1% of 0.08 gigatonnes, or <0.0008 gigatonnes of carbon for one billion EVs. Thus, essentially none of the seabed carbon, whether dissolved or particulate, is lost to the atmosphere; it all remains sequestered on the seabed.

Responding to concerns that DSM could harm the global climate by releasing carbon stored by the seafloor, we also investigated whether nodule collection on the CCZ seafloor risks disturbing reservoirs of liquid or clathrate methane or CO_2.[174] Intense ambient pressure and cold temperature in CCZ sediments (5,700–8,500 psi) at mining depth (4,000–6,000 meters) would normally keep such reservoirs intact in liquid or solid form.[175] In any case, no such reservoirs are known to exist in the CCZ, and it is not the type of place where they typically form. Methane clathrates occur in shallow water sediments and under permafrost in polar regions and in deeper sediments along the margins of highly-productive continental slopes.[176] Reservoirs of methane clathrates usually require anaerobic bacterial decomposition of organic matter, while surface waters overlying the CCZ seabed are nutrient poor with low primary production. Insufficient amounts of organic matter reach the bottom to support large accumulations of methane. Furthermore, sediments are fine grain clay, which typically supports only diffuse and dilute clathrate formation. Finally, CCZ sediments are oxic to at least two meters, so any clathrate that did form would be below that level and would not be disturbed by nodule harvest, which is limited to the top 10 centimeters. Regarding carbon dioxide clathrates, these usually occur near active hot water vents or cold seeps,[177] which are not known to occur in the CCZ. In sum, it seems very unlikely that either methane or carbon dioxide clathrate reservoirs occur in the CCZ or would be disturbed by nodule collection there.

Nodule collection should also not significantly impact long-term ocean buffering by existing carbonaceous marine sediments. The top ~10 centimeters

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170 (Volz, et al. 2018).

171 (Liu, et al. 2013).

172 As with other analyses in this study, the required nodule seafloor area has been calculated by performing economic allocations of land areas to specific metals, then aggregating to one billion EVs—just as in any LCA byproduct allocation. The calculation of 508,000 square kilometers reflects this allocation process.

173 (Jones, Kaiser, & Sweetman, 2017).

174 See, e.g., (Greenpeace, 2019) and (Howard, Parker, Jenner, & Holland, 2020).

175 A typical phase diagram for carbon dioxide indicates that at temperature of 4°C and pressure ⩾~60 atmospheres, CO_2 remains in a liquid state soluble in water until pressures ⩾~5,000 atmospheres, after which it forms a solid. See phase diagram at https://www.researchgate.net/figure/A-typical-phase-diagram-of-carbon-dioxide_fig1_232085696

176 (USGS). Processes by which methane clathrates form are described by (You, Flemings, Malinverno, Collett, & Darnell, 2019).

177 (Hester & Brewer, 2009) and (Stott, 2019).

of sediments would be disturbed and partially redistributed over tens of kilometers, but essentially none would be removed, all would eventually settle, and their ocean buffering as well as carbon sequestration services would remain available.

In sum, the large seabed disruption is offset by the other two factors: very low carbon density, and the inability for carbon to rise to the surface. To alter this consequence, sediments would have to contain vastly more carbon (by over an order of magnitude), and additionally, carbon would need a way to rise toward the surface for release into the atmosphere. Even if these circumstances did occur, deep-sea nodule-collection operations would be unlikely to significantly alter oceanic carbon sequestration services by seabed sediments or atmospheric concentrations of heat-trapping gases, in part because the relative scale of nodule-collection areas to the total oceanic ecosystem is miniscule. The overall area of oceanic abyssal sediments, about 270 million square kilometers, is orders of magnitude larger than the area likely to be mined in the CCZ—3.1 million square kilometers that may be set aside for mining, of which about 0.5 million square kilometers supply the base metals for one billion EVs.[178]

Given the above, release of previously-sequestered carbon by stirring up sediments during deep-sea nodule collection seems extremely unlikely. If it does occur, it should be small relative to carbon-sequestration impacts from land mining.

Pressurized seawater brought to the surface

The second possible pathway of release of previously-sequestered carbon arises from cold, pressurized seawater being pumped to the surface. In bringing the nodules to the surface, large volumes of seawater are sourced from below the carbonate compensation depth, where solid carbonate is dissolved into the seawater under pressure. As it is brought to the surface, the depressurized seawater could release some CO_2 to the atmosphere. The water will be exposed to air bubbles for 300 seconds or less during the final 1,600 meters of its air lift to the surface; and then to ambient air for another 300 seconds in the hold of the surface-production vessel.

We can estimate the maximum CO_2 that could be directly exchanged with the atmosphere during this time. Calculations show that an operation harvesting 6.4 megatonnes of wet nodules per year would release approximately 170 tonnes of CO_2 annually into the atmosphere under this extreme case.[179] Scaling this up to one billion EVs gives 0.00015 gigatonnes of potential CO_2 release.

To put this number into context, nodules' potential carbon-sequestration impact via this method is less than 0.1% of the total life cycle CO_2e calculated earlier in the GWP discussion.

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178 Assumes an average of 15 tonnes of wet nodules per square kilometer in the CCZ, metal concentrations as surveyed by (AMC Consultants (A), 2019), and 85% nodule area harvested.

179 Assumes deep tropical water (0-20°N, ~4°C) containing dissolved inorganic carbon (DIC) of ~2340 μmol/kg; alkalinity of ~2380 μmol/kg seawater; and surface water containing an estimated pCO_2 of ~910 μatm, or 985 μatm if the water warms to 6°C (during its upward passage and brief residence within the hold of the collection ship). Under the extreme case that the 6° C water is equilibrated fully with present-day atmospheric CO_2, the resulting DIC quantity becomes ~2220 μmol/kg, or a change of ~120 μmol/kg. Raising nodules from the bottom using a lift pump requires an amount of seawater that is ~5 times the wet weight of the nodules, or ~32 million cubic meters of water for 6.4 Mt of wet nodules. Assuming a pumping rate of ~1 cubic meter per second, the maximum annual CO_2 release to the atmosphere calculates to 3.84×10^6 mol CO_2. That is equivalent to 170 tonnes of CO_2, or less than 27 grams per wet tonne of nodules. Allocating this release economically and scaling up to one billion EVs yields a total maximum release of 0.00015 Gt of CO_2 from pumping water.

Figure 49. Potential Sequestered Carbon Release from Nodule Offshore Operations for 1B EVs

~0 gigatonnes

of CO_2 at risk from pumping water
or disturbing the seabed sediments

~0.00015 gigatonnes of CO_2
at risk from depressurization of
deep seawater pumped to surface
for 1B EVs

508,000 km²
seabed impacted by mining for 1B EVs
(0.1% of global seabed)

~424 tonnes of organic carbon
stored on average per km² of seabed
surface sediments—but, these
carbon-containing sediment particles do
not reach the surface

Realistically, the release to the atmosphere is likely less than this, because the kinetics of gas/water exchange are very slow. Only a tiny amount of the dissolved inorganic carbon is in the form of aqueous CO_2 gas that can be directly exchanged between water and air. Because of this, CO_2 gas exchange is roughly an order of magnitude slower than that of other gases like O_2 and N_2; timescales for mixed-layer gas exchange with the atmosphere from wind-driven turbulence and bubbles are on the order of months. The oceanographic community has developed special equilibrators, with seawater showers mixing with air to measure surface-ocean CO_2 levels; even these equilibrators have e-folding timescales of roughly 30 minutes.[180]

A number of engineering techniques could further reduce CO_2–atmosphere exchange during the few minutes that water resides in the ship's hold, including: (1) limiting the ratio of air–water surface area to seawater volume, (2) limiting formation of bubbles that enhance gas exchange, and (3) limiting the turbulence on the water side (CO_2 air–water exchange is limited by water-side turbulence because

the solubility of CO_2 in water is low). Notably, if the seawater's resident time in the ship's hold extends significantly beyond five minutes, it would become necessary to consider chemical equilibration timescales of the hydrolysis reaction between aqueous CO_2 and the larger inorganic CO_2 pool.

After nodule extraction, seawater is pumped out of the collection ship's hold and injected back into the ocean in mid-water, at a depth to be determined that is well below the euphotic zone and below the oxygen minimum layer. Any excess CO_2 contained in this returned seawater would later be released into the atmosphere at the ocean ventilation rate. The lack of any chlorofluorocarbons in water below 1,000 meters as well as radiocarbon $\Delta 14C$ values below -180 indicate that the water is quite old; ventilation rates are over 100 years. Any CO_2 release would therefore presumably occur well after substantial reductions in anthropogenic emissions had occurred. CO_2 release from nodule lift water, therefore, does not present a serious environmental impact risk for nodule collection.[181]

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180   E-folding refers to the time interval in which an exponentially growing quantity increases by a factor of e. E-folding is often used as the timescale characterizing a process evolving toward equilibrium.

181   We thank marine chemist and geochemist Scott Doney of Woods Hole Oceanographic Institution and University of Virginia for his preliminary evaluation of the risk from CO_2 release by lift water.

Impact on future carbon sequestration offshore

Sweetman, Smith, Shulse et al.[182] reported that benthic bacteria were principally responsible for carbon metabolism on the abyssal seafloor of the CCZ, both by consuming and metabolizing phytodetritus and also by directly converting dissolved inorganic carbon (CO_2) into biomass by a still-unknown chemosynthetic method. Rates for the two processes were statistically indistinguishable. Bacteria, rather than macrofauna, were thus responsible for most carbon recycling on the CCZ abyssal seafloor.

Nodule collection itself may not kill individual bacteria, because they are probably too small to be crushed by the collection machines and the marginal pressure created by the machine's weight. Bacteria would also probably survive dispersal in plumes created by those machines. On the other hand, bacteria transported to the surface in nodule riser-water might die as a result of lysis caused by changes in pressure or temperature.[183]

Carbon cycling by abyssobenthic bacteria could be disrupted if they require any particular spatial or structural organization to carry out their identified functions. If, for example, the bacteria need to be in an assembled layer, or in contact with other organisms in some mutualistic way, then nodule collection could disrupt their function more than if they are able to function independently.

As part of environmental impact studies required by the ISA prior to any applications for commercial exploitation of nodules, Sweetman and colleagues will carry out several years of *in situ* experiments in the CCZ, using respirometers and ^{13}C-labelled algae and CO_2 to quantify: the amount of phytodetritus and CO_2 fixed by bacteria and archaea; the amount of bacteria grazed by fauna; and the role of bacteria as a food source for grazing or deposit-feeding meiofauna, macrofauna, and megafauna.

Experiments will also explore how quickly bacterial functions may recover after disturbance caused by nodule collection. If Sweetman et al.'s initial findings that bacteria provide approximately half of abyssobenthic carbon through chemosynthetic fixation of dissolved CO_2 are confirmed, then future carbon sequestration in the disturbed area could be substantially reduced during the years or decades needed for recovery of full bacterial function.

We again estimated the impact of 100 years' cessation of carbon sequestration services, this time from all affected seabed areas as well as soil and vegetation needed for one billion EVs using nodules. Assuming there were no recovery of vegetation on mined land and no recovery of chemosynthetic bacterial flora on the CCZ seafloor for 100 years, the amount of carbon sequestration sacrificed to make metals for one billion EVs would be 8 times higher using land mining (0.56 gigatonnes) compared to nodules (0.065 gigatonnes).[184]

Carbon Sequestration Impact from Deep-Sea Nodule Processing (Onshore)

The risk of release of sequestered carbon associated with nodule processing and refining is anticipated to be very low. Carbon release will occur primarily as a result of land cleared for construction of processing and refining plants. Additional land impacts accrue from indirect life cycle contributions, including metals to build the plant, coal for reduction, and other material, energy, and infrastructure inputs.

The total LCA land footprint associated with nodule production, as detailed in the Nonliving Resources section, is calculated at 9,800 square kilometers. Of this, 7% is associated with the offshore operations and shipping phases, while the remainder is associated with onshore processing. Again, using the average carbon content of 16,200 tonnes of organic carbon contained in soil and vegetation per square kilometer, sequestered carbon at risk is 0.148 gigatonnes of carbon, or 0.54 gigatonnes of CO_2. The total sequestered carbon at risk from nodule onshore operations is illustrated in Figure 50.

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182   (Sweetman, et al., 2018).

183   (Hall, et al., 2007).

184   If services in all disrupted seabed areas ceased for 100 years, an estimated 0.025 gigatonnes of carbon would not be sequestered, equivalent to 0.09 gigatonnes of CO_2. This assumes the flux of phytodetrital particulate organic matter continues falling to the CCZ bottom at the current rate of 1 gram carbon/m² per year, with an assimilation rate of inorganic carbon by abyssobenthic bacteria of 50% (Sweetman, et al. 2018). Land disruptions would add an additional 0.04 gigatonnes of carbon not sequestered—greater than the disruption from seabed disturbance—for a total of 0.065 gigatonnes.

Figure 50. Potential Sequestered Carbon Release from Nodule Onshore Processing for 1B EVs

0.54 gigatonnes
of CO_2 at risk from land use
for processing and refining nodules

9,200 km²
land area impacted by processing
and refining nodules for 1B EVs

~16,200 tonnes of organic carbon
stored on average per km² of soil
vegetation across all terrestrial biomes
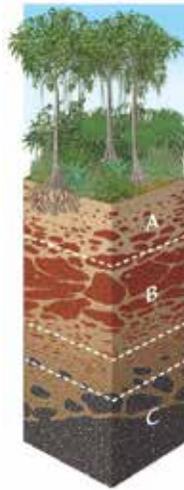
The remaining 7% representing indirect land area attributable to offshore operations adds 0.04 gigatonnes of CO_2 to the above estimate of about 0 gigatonnes from offshore processing, not moving the needle of that estimate.

In summary, the estimated total amount of previously stored carbon at risk when producing metals for one billion EV batteries and connectors:

- For metals production from land ores:
  ~9.3 gigatonnes of carbon dioxide

- For metals production from nodules:
  ~0.6 gigatonnes of carbon dioxide

Combining this with the GWP results detailed above, we see that sourcing the nickel, cobalt, manganese, and copper needed to construct one billion EVs using land ores could therefore release up to 10.8 gigatonnes of CO_2: 9.3 gigatonnes from disturbing carbon stored on land, plus 1.5 gigatonnes from operations and material inputs, as detailed in the GWP subsection.

Sourcing the metals from nodules on the CCZ seafloor could in contrast release about one gigatonne of CO_2: 0.54 gigatonnes from disturbing carbon stored on land, plus 0.04 gigatonnes from offshore operations, plus 0.44 gigatonnes of emissions from operations and material inputs, as detailed in the GWP subsection. This yields a total climate change impact reduction potential of up to 90% compared to land mining.

CATEGORY 2: NONLIVING RESOURCES

Nonliving Resources Impacts at a Glance

IMPACT CATEGORY
Nonliving Resources
• Land mining industry uses and significantly alters nonliving resources. Mining is characterized by substantial physical land alteration, water pollution, chemical pollution, air pollution including toxic dusts, and high quantities of waste. Mine sites are difficult to restore, and mine reclamation is not always performed. Mine disasters and tailings dam failures cause further environmental harm. High water usage can also be problematic on local scales. • Collecting nodules from the deep seabed disrupts the seafloor ecosystem. It disturbs sediments, removes nodules, and risks blanketing the habitats adjacent to collection sites with plumes. Onshore processing also has a minor land, water, and emissions footprint. Under zero-waste design, no tailings streams are produced, and there is limited chemical pollution. Water usage is also relatively lower. Total energy resources utilized are comparable to land mining.

Here, we consider several environmental/ecosystem impacts that fall within the category of nonliving resources. This section contains the quantification of several LCIA indicators and quantitative metrics: freshwater usage, waste and tailings, land competition, forest use, seafloor use, SOx and NOx emissions, ecotoxicity (terrestrial and freshwater), eutrophication potential, and cumulative energy demand (CED).

The section is subdivided as follows:

- **Physical damage to habitat,** including land, forest, and seafloor resources used or disturbed

- **Tailings and chemical pollution,** including waste quantification and several LCIA indicators

- **Water withdrawal** quantification

- **Water pollution** drivers

- **Air pollution,** including quantification of SOx and NOx emissions

- **CED** LCIA indicator results

Physical Damage to Habitat

All forms of mining of virgin resources unavoidably change habitats that contain targeted minerals. To access ore bodies on land, topsoil is removed, and forests and other vegetation are cleared. Landscapes are changed by creating very large pits, waste-rock piles, tailings ponds, and/or vertical shafts and extensive networks of underground tunnels. In the case of nodule mining, nodules—hard surfaces

used by some wildlife for critical life functions—are removed, and the top layer of sediment is temporarily suspended above the seabed.

Land ores targeted for mining tend to present as three-dimensional ore bodies, often stretching for hundreds of meters and even kilometers underground (e.g., copper and nickel sulfides), or several-meters-thick flat sheets covering a much larger land area (e.g., nickel laterites). In contrast, nodules present as a thin nodule field—often just one nodule thick, with 90% of the nodules found in the top five centimeters of the sediment. Intuitively, this suggests that nodule collection would impact much larger areas of seabed habitat in the deep ocean than land habitats impacted by mining on land.

Below, we estimate the total habitat areas—including land, forests, and seabed—that would be removed or disturbed in order to supply metals for one billion EVs from both resource types.

First, it is important to understand how the polymetallic nature of the nodules impacts the total amount of ore that needs to be collected. One tonne of polymetallic nodules contains 290 kilograms of manganese, 13 kilograms of nickel, 11 kilograms of copper, and 2 kilograms of cobalt. To get the same amount of contained metal from land ores, three different types of ore bodies would need to be mined—nickel-cobalt, copper-cobalt, and manganese ores. When average grades of mined ore on land are

applied (35% for manganese, 1.25% for nickel, 0.5% for copper, and 0.08% for cobalt as a byproduct of nickel and copper mining), about four times as much ore (4,068 kilograms) needs to be extracted on land to get the amount of metal contained in 1,000 kilograms of nodules. The polymetallic nature of nodules thus effectively reduces the total required tonnage of ore by a factor of four. Note that this represents the difference in metal-containing ore only. To access the ore on land, miners often have to break much more surrounding and overlaying country rock, with the ratio of this additional stripped rock to mined ore typically ranging from 1:1 to 5:1 (and even as high as 12:1). After adding in this additional country rock, the total tonnage of rock that needs to be drilled and blasted on land is higher by a factor of 8 to 24 when compared to collecting one tonne of nodules.

Using the Ecoinvent database and land-ore literature sources, the standard land-usage footprint "land competition" LCIA indicator using the CML standard was computed. This is a life cycle computation including direct and indirect impacts across all production phases. A static-supply scenario is provided by these data sources, but we know that, as ore grade halves, the amount of ore needed to produce the same metal doubles, thereby increasing the land impact. This allows us to add ore-grade impacts and estimate the land-usage impact for one billion EVs under a dynamic scenario. A simple model shows that life cycle land use increases by 14% once incorporating projected ore-grade declines.[185]

Estimated total life cycle land usage, given by the "land competition" indicator representing land impact, needed for metals for one billion EVs and connectors:

- For metals produced from land ores:
  ~156,000 square kilometers of land

- For metals produced from nodules:
  ~9,800 square kilometers of land

For land ores, the two main factors driving this land usage, as viewable in an LCA analysis tool like SimaPro, are forest clearance and the land required for hosting tailings. For nodules, these two drivers are mostly absent, and no material tailings are produced during nodule processing and refining. The impact is primarily driven by land required for onshore processing and refining facilities.

Focusing specifically on forest use, we compute this by first assessing the "land use" ReCiPe LCIA indicator, isolating the softwood, hardwood, and forest subcategories. These are then scaled up linearly to create "land competition" CML indicator values, using the same indicator type for better intuition against land impact without altering relative results. The same 14% adjustment for ore-grade dynamics is applied.

Estimated total life cycle forest usage needed for metals for one billion EV batteries and connectors:

- For metals produced from land ores:
  ~66,000 square kilometers of forest

- For metals produced from nodules:
  ~5,200 square kilometers of forest

To estimate the use and disturbance of the seabed, we first examine land-ore mining. Land mining can harm the seabed through "deep-sea tailings placement" (DSTP)—now a more common practice in nickel laterite mining projects, where around 170 tonnes of tailings and waste material may be placed into the ocean for every tonne of nickel produced.[186] In DSTP, finely ground rock slurry containing residual heavy-metal elements is passed through pipes to an outfall point below the base of the surface mixed layer (more than 100 meters deep). From this point, the tailings flow freely down the sloped seabed until settling in a deposition zone, typically more than 1,000 meters deep, at rates that may vary from 450 tonnes per day to 100,000 tonnes per day, and forming deposition piles often tens of meters thick.[187] With DSTP,

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185 With some assumptions on the relative contribution of land mass mined to the total "land competition" indicator, one may adjust the impact for ore-grade dynamics. The mining and concentration phases contribute around 50% of life cycle land impact for the two main nickel-processing paths studied (Verboon, 2016). Presuming that 80% of land-usage impact is directly attributable to ore mass and scales linearly by ore grade, applying the nickel and copper ore-grade projections from the LCSA, and assuming the same 50% breakdown for copper, under dynamic demand the total impact increases by 14% relative to the static scenario.

186 Based on estimates from the Ramu nickel mine near Madang, Papua New Guinea, given a DSTP disposal rate of 14,000 tonnes per day and an approximate average production rate of 30 kilotonnes of contained nickel per year.

187 (Hughes, Shimmield, Black, & Howe, 2015); (Morello, et al., 2016).

output is stored farther from human communities, and there is less active management required. However, significant environmental risks with DSTP include wildlife smothering, toxicity, community composition changes, productivity changes, sublethal effects, bioaccumulation, and biomagnification.[188] Furthermore, since the equipment extends far undersea, it is difficult to maintain should there be a failure. DSTP projects may include efforts to find less invasive patches of seabed for disposals, although they are constrained to areas relatively near the coast and with a steep seafloor angle for deposit. As proximity to a coast is the key enabler for using DSTP, it is only used in a small subset of mining projects.

For the purposes of estimating seabed use, we assume that, at present, 3% of mined nickel, cobalt, and copper output is associated with a DSTP disposal process, and that this will grow to 6% by 2047. Using averages of comparables from Lihir, Misima, and Vancouver Island projects, which vary considerably in tailings density from <10 megatonnes to about 600 megatonnes of waste per square kilometer, in the dynamic scenario about 2,000 square kilometers of seabed would be used for DSTP in supplying metals for one billion EVs.

Nodule collection operations are expected to cause direct impacts to the seabed by removing 85% of the nodules in the operational area. These operations would remove nodule-dependent habitats, disturb the top 10-30 centimeters of sediment, and generate plumes that risk being carried by eddies and resettling outside the operational area. Specific risks to marine wildlife are later discussed in the section on Biodiversity, and impacts on stored carbon are discussed in the section on Climate Change.

We sized the total seabed area of the CCZ that would be needed to produce one billion EVs using the same life cycle economic allocation standards as used for estimating land usage. Land or seabed use was allocated based on the economic value of all coproduct and byproduct streams (some of which are not needed for supplying EVs). The same technique was used in the more complex GWP LCA model described above.

Estimated total seafloor area impacted by sourcing metals for one billion EV batteries and connectors:

- For metals produced from land ores: **~2,000 square kilometers (deep-sea tailings placement)**
- For metals produced from nodules:
  ~508,000 square kilometers

In summary, producing the metals required to build one billion EVs using land ores would remove at least 156,000 square kilometers of land habitats and would impact about 2,000 square kilometers of seabed through deep-sea tailings placement. Although some level of damage restoration as part of the mine-closure process is possible and indeed mandated in some parts of the world, in practice this process is extremely costly and hence not widely practiced, especially in the developing world.

Producing the same amount of metals from the CCZ would impact 508,000 square kilometers of seabed during nodule collection, as well as 9,800 square kilometers of land during processing and refining. Risks of a wider area of impact on the seabed are also possible through plumes carried by eddies outside the mining area; modeling and environmental assessment work to ascertain whether this risk is present and whether it will constitute habitat damage is currently ongoing by several contractors with exploration contracts in the CCZ area. Physical habitat damage on the seabed is expected to be partial and non-monolithic; 15% of nodule cover is expected to be preserved in the mining zones (though plumes may bury them to some extent), 10%¬–30% of mining areas are expected to be designated as no-take zones with 100% nodule cover preservation, and some measures to restore removed nodule cover (e.g., by placing artificial ceramic nodules) are in the research phase.

Tailings and Chemical Pollution

Tailings are, broadly, the materials left over after separating valuable ores from uneconomic rock. Their largest volume comes from the mining and concentration phases, when excess rock and waste are collected, as well as from processing steps such as leaching.

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188   (Morello, et al., 2016).

It is telling that synonyms for tailings include mine dumps, slimes, refuse, and leach residue. Tailings may be toxic, as in sulfidic tailings from copper and other sulfides, and may become acidic if exposed to air and water. The quantity of tailings and waste produced by mining is massive. According to a 2011 study, mine waste along with its environmentally acceptable storage was the largest waste problem on earth, with 350 billion tonnes produced yearly.[189] For metals like copper, every kilogram of metal produced is accompanied by 10 to 50 times as much tailings mass, or up to several hundred times as much according to some reports.[190]

In the discussion that follows, we first describe and quantify the relative volumes of tailings and waste generated by the two production methods. Then we discuss the nature and scale of impacts of tailings and chemical pollution from metal production.

Producing metals for one billion EVs from land ores will generate more waste rock and tailings than nodules for several reasons. First, with land ores, a large amount of waste rock needs to be drilled and blasted just to gain access to the ore body—this is particularly true in the case of open-pit mines with spiraling terraced access for mining trucks. Nodules, in contrast, can be collected directly. The nodule-collection process does suck up seafloor sediment; most of the sediment is separated from nodules and discharged back into its environment.

Second, due to ore-grade differences as described earlier, four times more ore is required on land to get at the same amount of metal contained in one tonne of nodules (see Figure 51).

Figure 51. Four Times More Ore Required for Land-Ore Metal Production; Nodules Zero Waste

Land

Average grades of mined ores
% of mined tonnage

1.25% Ni   0.08% Co byproduct

35% Mn

0.70% Cu   0.08% Co byproduct

99% waste, primarily discarded

65% waste, primarily discarded

99% waste, primarily discarded

Ocean Nodules

Average grades of CCZ nodules
% of total tonnage

29% Mn   1.30% Ni   1.10% Cu   0.2% Co

68% all producticized, no solid waste

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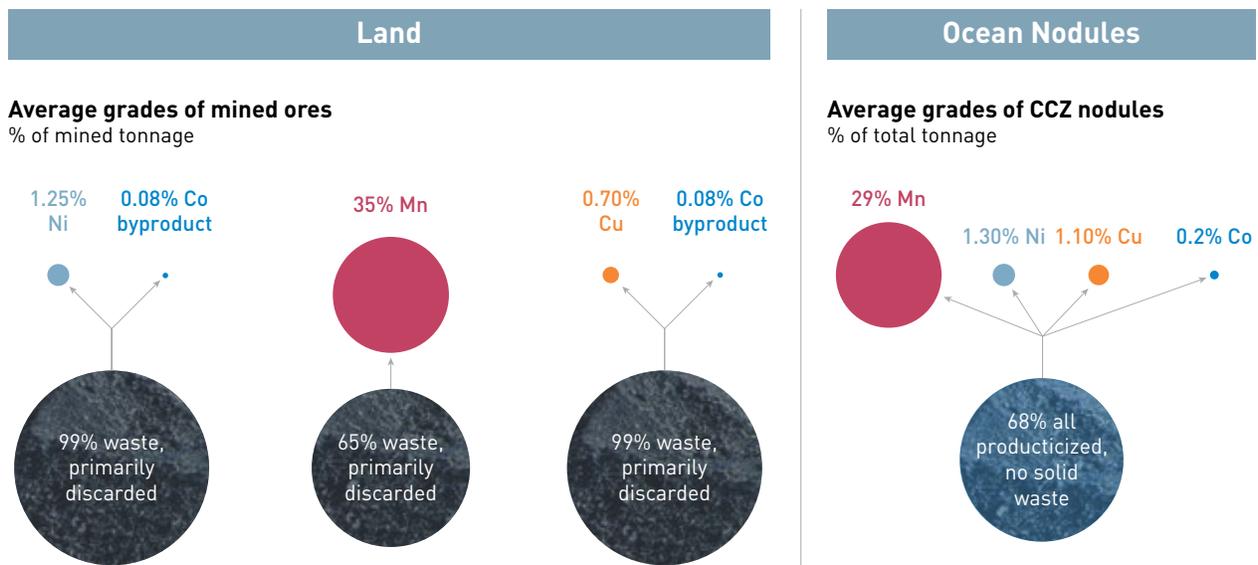
189   (Blight, 2011).

190   (Nagaraj, 2005). The Island Copper Mine on Vancouver Island produced 136 kilograms of tailings per kilogram of copper (Skei, 2019). Antofagasta produced 322 kilograms of tailings per kilogram of copper (Macquarie Research, 2019). A typical copper mine using froth flotation may produce 444 kilograms of waste and 219 kilograms of tailings per kilogram of copper produced, assuming a strip ratio of 2:1, an average ore grade of 0.5%, 90% recovery rate, and 26% concentrate.

Third, tailings are a necessary byproduct in most land-ore processing, whereas the mineralogy of nodules enables zero-tailings processing from beginning to end. With nodules, smart-processing design can enable any presumed waste to be reused or productized: residues can be recycled into the processing, converter slag can be reused as a raw gravel material by the market, and fertilizer-grade ammonium sulfate is produced as a useful byproduct. Land-ore processing may benefit from design for reduced waste, but the common presence of heavy minerals in toxic concentrations (e.g., antimony, arsenic, cadmium, chromium, lead, and mercury) as well as lower ore grades makes this much more difficult.

A rough estimate was made for the total tailings and waste (including overburden) that would be produced when generating metals for one billion EV batteries and connectors from land ores. This estimate considers direct impacts from the mining stage as well as tailings and residues produced during processing and refining. The median of two estimation methods was taken. First, a literature review yielded several estimates of tailings and waste quantities per kilogram of metal output for several nickel and copper mines. Scaling this up statically to produce metals for one billion EVs yielded an estimate of between 38 and 52 gigatonnes of waste and tailings. Second, a bottom-up model was created, starting with the inverse of expected ore grades to give the excess rock mass needed to mine a bit of metal. These were economically allocated among byproducts as done for land and seafloor areas, then scaled by an estimated addition of masses of chemicals, fluids, and other materials that contribute to the final tailings and residues. The ratio of residues-to-ore masses is around 1.5 for nickel laterites processed by HPAL—meaning that each tonne of ore excess leads to an additional 150% of waste mass.[191] We calculated a bottom-up estimate of 47 gigatonnes of waste and tailings to produce metals for one billion EV batteries and connectors.[192]

The median from these methods yielded an overall static estimate of 47 gigatonnes of waste and tailings for one billion EVs. Adjusted with ore-grade projections for nickel and copper through 2047, the bottom-up estimate increases by 34%. The driver for this dramatic change is the inverse relationship between ore grades and the amount of rock mass required to produce the same kilogram of metal. We scaled up the median estimate by this same amount to yield a final dynamic estimate of 64 gigatonnes.

Estimated total land tailings and waste directly generated in producing metals for one billion EV batteries and connectors:

- For metals produced from land ores:
  ~64 gigatonnes of waste and tailings

- For metals produced from nodules:
  ~0 gigatonnes of waste and tailings

In order to keep tailings away from habitats and human environments, they are typically dammed into tailings ponds—massive stores of water, waste, and byproducts of mining and metal production. Managing tailings is an intensive process of site selection, dam and disposal methods design, water management, monitoring, sampling and analysis, and processes to control and prevent acid drainage.[193] Poor management or disposal of tailings can result in toxic dusts causing diseases like lung cancer, acid seepage into water supplies, and even worse, tailings dam collapses can lead to human deaths and local habitat destruction. Tailings facilities must be monitored and maintained indefinitely after the closure of the mining operation, which can be problematic if the operator is not financially viable. Lower-ore grades increase the scale of production, the amount of tailings, and the likelihood of accidents. The risk potential of tailings storage failures has increased by a factor

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191 Analysis by Hatch estimates a residue-to-ore ratio of 1:5 for nickel. Data from ERIAS Group shows that the Ramu mine in Papua New Guinea produces a residue-to-ore ratio of 1:5 for nickel, and Vale New Caledonia produces an average of 1.25 tonnes of wet residue per tonne of nickel-ore feed.

192 Average ore grades for nickel laterites, nickel sulfides, copper, and manganese were used for the static model. Cobalt allocations presumed average nickel-cobalt and copper-cobalt grade combinations, weighted as 55% of cobalt co-mined with nickel, of which 70% was with sulfides. Manganese received full allocation, and copper and nickel each 70%. Ore-grade decline rates used in the LCSA were applied.

193 (Ritcey, 1989).

of 20 every 1/3 century. Of the 52 recorded incidents in 1990–2010, 63% were "serious" (>100,000 cubic meters of tailings released, and/or loss of life) or "very serious" (>1 million cubic meters of tailings released, and/or release that traveled >20 km, and/or ≥20 deaths). The total costs for just seven of these 16 large failures was $3.8 billion, at an average cost of $543 million per failure.[194] In the past century, tailings dam and ash pond failures cost nearly 3,000 human lives.[195] As of the writing of this paper, the lives of around 100,000 people are threatened in Brazil: 27 vulnerable tailings impoundments sit uphill from cities or towns, following two significant collapses of similarly constructed Brazilian dams since 2015 that killed hundreds and collectively released more than 50 million cubic meters of toxic sludge.[196] Tailings dam collapses furthermore harm animal habitats, wildlife preserves, soil, and vegetation; impact coastal marine environments and coral reefs; and can destroy all ES within a stream or river.

Issues associated with tailings are eliminated when producing metals from deep-sea nodules. During the nodule-collection phase, the primary physical discharge back into the environment during operations is return water and sediment—mostly the same, chemically unprocessed material collected from the environment. Within the processing and refining phases (e.g., when leaching could result in tailings), nodule mineralogy and nodule-plant locations uniquely allow for an optimized plant design that produces no tailings, residues, or solid-waste output.

Looking more broadly to chemical pollution caused by land-based mining, the quantity is significant. Even in the United States, where environmental regulations are fairly robust, metal mining releases more chemicals to the land and air than any other industry. In 2017, metal mining accounted for 50% of total toxic substances released and 72% of on-site land disposal across all American industries. These releases from the extraction, beneficiation, and processing of

metal ores resulted in large amounts of on-site land disposals, primarily of metals included on the Toxic Release Inventory (TRI) list of chemicals and contained in the ore and waste rock.[197] The nature of mining—the necessary movement and disposal of TRI chemicals present in large volumes of earth to access the target ore—does not lend itself to source reduction, unlike in manufacturing. In a single year, 1.954 billion pounds (97% of the metal mining sector's production-related waste) were disposed of or otherwise released in the US, primarily on-site.[198] These data are indicative of the best-case chemical pollution levels that may be expected in developing nations, where regulations are often less strict, and where most of the four metals are mined today.

In contrast, chemical pollution from nodule collection and processing is orders of magnitude lower in scale and scope. It is primarily limited to emissions and discharge during regular ship operations in offshore nodule collection and transport, as well as the processing and refining steps, which use and produce some chemicals. Nodules processing's optimization for zero tailings and zero waste significantly reduce the potential for chemical pollution to land and water.

Three CML LCIA indicators related to chemical pollution have been quantified to illustrate these chemical-pollution differences between land ores and nodule processing: terrestrial ecotoxicity, freshwater ecotoxicity, and eutrophication potential. Terrestrial ecotoxicity and freshwater ecotoxicity both measure the toxic effects of chemicals, including emissions and heavy metals, can have on the ecosystem. These are both midpoint LCIA indicators that can lead to biodiversity loss and/or extinction of a species. They are calculated using the Uniform System for the Evaluation of Substances for LCA purposes (USES-LCA), which characterizes the fate, exposure, and effects of toxic substances. Both are measured in 1,4-dichlorobenzene (DB) equivalent units. Eutrophication potential reflects the accumulation of

194   BowkerChalmers. 2015. The risk, public liability & economics of tailings storage facilities failures. Online at: https://earthworks.org/cms/assets/uploads/archive/files/pubs-others/BowkerChambers-RiskPublicLiability_EconomicsOfTailingsStorageFacility%20Failures-23Jul15.pdf

195   See (Sanamarina, Torres-Cruz, & Bachus, 2019).

196   See (Chega) and (Miranda & Marques, 2016).

197   (EPA, 2019).

198   (EPA, 2019).

a concentration of chemical nutrients, which can lead to abnormal productivity, potentially causing severe reduction in water quality and animal populations, due for example to emissions of ammonia, nitrates, nitrogen oxides, and phosphorous to the air and water. Eutrophication potential is measured in phosphate (PO4)-equivalent units.

The same data sources as for the GWP LCA model were used, under a static one billion EV demand scenario. Using Ecoinvent and the same literature sources for land ores, along with the LCA model developed for nodules, we therefore estimate the cradle-to-gate direct and indirect impacts of these three measures.

Estimated total terrestrial ecotoxicity measure for producing metals for one billion EV batteries and connectors:

- For metals produced from land ores:
  33 megatonnes 1,4-DB eq.
- For metals produced from nodules:
  0.5 megatonnes 1,4-DB eq.

Estimated total freshwater ecotoxicity measure for producing metals for one billion EV batteries and connectors:

- For metals produced from land ores:
  21 gigatonnes 1,4-DB eq.
- For metals produced from nodules:
  0.1 gigatonnes 1,4-DB eq.

Estimated total eutrophication potential measure for producing metals for one billion EV batteries and connectors:

- For metals produced from land ores:
  80 megatonnes PO4-eq.
- For metals produced from nodules:
  0.6 megatonnes PO4-eq.

Water Withdrawal

Land mining requires withdrawal of large amounts of freshwater from lakes, streams, and groundwater. A high volume of freshwater withdrawal can deplete supplies available to humans for drinking, food preparation, sanitation, irrigation of fields, and watering livestock. It can decrease or eliminate the streamflow needed for fish used as food by humans and wildlife. Ramifications are particularly significant when local sources are scarce, in dry regions such as Australia, Chile, China, Peru, Southern Africa, and the Southwestern United States. Losses of streamflow, lakes, or watering holes can have serious effects on biodiversity, with knock-on effects on ES and human communities and cultures.

Water consumption or water loss can stem from all phases of the metal production life cycle: milling, flotation, and separation of ores, hydraulic and slurry transport, dust suppression, leaching, heating, cooling, electrorefining, tailings management, granulation, revegetation, wastewater, and of course, employee needs.

To illustrate the magnitude of water withdrawal, Table 14 lists the water requirements for extracting one kilogram of copper from five different mines. Differing methods, locations, climate, uses for water, and attention to water conservation contribute to wide variations in the amounts of water used.

In contrast to land mining, the process of collecting nodules from the ocean does not require any freshwater directly. Water necessary for employee needs during collection would be "made" from seawater, typically using reverse osmosis; the energy to do this is already considered in the analysis. Some water consumption is required for the processing and refining stages, particularly for heating and cooling, granulation, and employee needs. There would also be second-order contributions in a full life cycle assessment.

Table 14. Quantity of Water Used to Create 1 kg of Copper, Representative Mines[199]

NAME	LOCATION	MINE TYPE	WATER USED
Kamoto Industrial Mine (Glencore)	DRC	Cu/Co	3,010 liters/kg Cu
Several Arizona mines	USA (Arizona)	Cu	1,892 liters/kg Cu
Chilean mines w/ conservation	Chile	Cu	375 liters/kg Cu
Tenke Fungurume Mine (Freeport)	DRC	Cu/Co	189 liters/kg Cu
Minera Esperanza Mine	Chile (Atacama Desert)	Cu	102 liters/kg Cu (untreated pumped seawater through 145 km pipeline)

While there is no single standardized database for average life cycle water consumption for all the four metals studied in this paper, we approximated the total freshwater used to produce the metals for one billion EV batteries to gauge any order-of-magnitude differences. For nickel and cobalt, life cycle water usage estimates were used from the same published sources as the earlier GWP analyses. For copper, a rough median of a number of sample mines was taken: 400 liters of water per kilogram of copper. For manganese, a comparable number from silicomanganese production was used. In aggregate, the estimate for freshwater requirements to mine and process land ores covers full life cycles for three of the metals, and the mining phase only for copper, which may produce a slight underestimate. Note that, in general, the result is sensitive to the modeling estimates of copper, as copper comprises the majority of the mass for batteries plus connectors.

For modeling water consumption of production from nodules, we used data from the detailed metallurgical plant design completed by mining and metallurgical engineering firm Hatch. We accounted for direct impacts from the processing and refining phases. Employee needs during nodule-collection operations are not accounted for, and second-order life cycle impacts are not included. Note that second-order effects typically amplify overall life cycle computations by a fraction of the first-order effects. Allocation of freshwater usage by nodule processing and refining used economic allocation, as with the other life cycle assessments.

Estimated total freshwater usage for one billion EV batteries and connectors:

- For metal production from land ores:
  ~45 cubic kilometers

- For metal production from nodules:
  ~5 cubic kilometers

In summary, metal production from nodules would result in an order of magnitude reduction in freshwater usage. Given its flexibility in processing-facility location, it also provides the possibility of prioritizing sites that are not water stressed.

Water Pollution

Land mining is often a chronic source of freshwater pollution, with harmful impacts that can include illness and death in humans and wildlife. Pollutants can enter the water at every stage of land mining. Surface water and groundwater can be contaminated through acid-mine drainage, toxic-metal leachate from pits, waste-rock piles, tailing ponds, and flooding of underground tunnels, among other mechanisms. Table 15 provides a summary of the wide variety of potential water-pollution issues present throughout the life cycle of a mine.

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199   Sources: Cobalt-Copper DRC: (Dai, Kelly, & Elgowainy, 2018); Mineral Esperanza Mine: (ICMM, 2012); Arizona mines and Chile: (Singh, 2010).

Table 15. Potential for Water Pollution During Land-Ore Mining Phase[200]

STAGE	POTENTIAL ISSUES
Exploration and site preparation Surveying, drilling, trench blasting, camp/road/mine construction	• Sediment runoff, increased suspended sediment load to surface waters • Spills of fuels and other contaminants
Mineral extraction Blasting, ore stockpiling, waste piling	• Chemical contamination of surface water and groundwater • Toxicity impacts to organisms (terrestrial and aquatic plants and animals) • Altered landscapes from mine workings (e.g., open pits, changes in stream morphology) • Increased erosion and siltation • Altered patterns of drainage and runoff • Water consumption: dust suppression, mine camps, evaporative losses from clean water storage dams, water used to cool equipment • Decreased groundwater resources due to dewatering • Reliance on power from water-dependent sources (hydro and thermal)
Processing and refining Concentration, smelting, refining	• Discharge of chemicals and other wastes to surface waters • Water consumption: water used in mineral separation and beneficiation, slurry lines • Reliance on power from water-dependent sources (hydro and thermal)
Mine closure/post-operation Revegetation, fencing, monitoring seepage	• Persistent contaminants in surface water and groundwater • Expensive, long-term water treatment • Persistent toxicity to organisms • Permanent landscape changes

Polluted water can harm or kill plants and wildlife, and is not potable for humans. Pollutants in water can bioaccumulate in plants and in the milk and meat of livestock, leading to elevated levels in humans. Water pollution becomes catastrophic when tailings dams collapse; a tailings dam or ash pond failure can cause hundreds of deaths. Given the number of such impoundments around the world, more failures can be anticipated.[201]

Philippine nickel mines are known to stain rivers, rice fields, and watersheds with nickel laterite, and contaminate water and soil with heavy metals. In 2016, the president of the Philippines shut down 28 of the country's 41 mining companies, including about half of the country's nickel production, with the stated reason to protect the environment.[202]

Another example illustrates how seriously such events can impact water resources and the wildlife and people who depend on them. A gold-copper mine in Southeastern China, owned by Zijin Mining Group, leaked 2.4 million gallons of wastewater from a copper smelter. The acidic, copper-laced water leaked into the Ting River, killing 2,000 tonnes of fish—said to be enough to feed the 72,000 residents of Bitian village for a full year. Chronic pollution from this and other mines rendered the river nearly lifeless. Village residents are afraid to eat any fish caught. Water wells are unusable, as the water is not potable. Cancer rates in the area are very high.[203]

In contrast to land-ore mining, which presents significant potential for freshwater pollution, ocean-nodule collection has no impact on freshwater during collection operations. None of the risks and issues shown in Table 15 apply. Rather, pollution of seawater is the more relevant issue with nodule collection. This pollution is mostly limited to the typical operations of large ships, as previously described. Ocean pollution

200 Source: (Sauer & Miranda, 2010).

201 See, e.g., (Chega, 2019) and (Sanamarina, Torres-Cruz, & Bachus, 2019).

202 (Almendral, 2017).

203 (Chuanmin, 2011).

could occur by accidental spills of bunker fuel, transfer of alien species on ship hulls, release of ballast or bilge water, release of low concentrations of biocides contained in antifouling hull paint, and pumping of holding tanks for toilets or gray water.

Air Pollution

With land-ore mining, air pollution poses great risk to miners and nearby populations. Air pollution from land-ore mining can consist of airborne emissions, toxic dusts from blasting, evaporated tailings ponds, and soil contaminated by leachate from waste-rock piles. Dusts containing particles of silicon as well as potentially toxic metals from mined rocks are generated during drilling, blasting, excavation, loading, transport, crushing, and cleaning phases. Exposure to these dusts and other air pollutants can irritate the eyes, skin, and respiratory tract. Lung diseases such as asthma, silicosis, chronic obstructive pulmonary disease, and lung cancer may result from prolonged exposure. People in surrounding areas may also suffer from harmful effects of windblown dust. Beyond the direct harmful effects from inhalation, the dust-based contamination of soil, food, plants, and animals raised in surrounding communities can also affect health and food supplies.

With deep-sea nodules collection, air pollution is generated by combustion of bunker fuel, mostly around extremely low-populated areas as most fuel is burned offshore during nodule collection and transport. Air pollution includes CO_2, SOx, NOx, and particulate matter emitted by ships. Some risk of human harm is present for ship operations personnel. There are no surrounding communities to harm. With recent IMO 2020 regulations, emissions of SOx and NOx will decrease across the shipping fleet as new standards for low-sulfur fuels and/or scrubbers are implemented.

Using a selection of comparables, Ecoinvent, and the nodules model, we calculated an inventory of SOx and NOx for land ores and nodules. For land ores, we calculated a static one billion EV scenario.

Comparables from Ecoinvent were used for a conservative estimate. For nodules, for offshore processing we calculated a dynamic one billion EV scenario by including a slight trajectory of the expected emissions improvements. Offshore emissions were modeled separately based on fuel-consumption models. For modeling SOx emissions, the global fleet average was used as an initial starting point of emissions, while the maximum sulfur content of 0.5% as of 2020 based on IMO regulations was set as the 2047 target. For NOx, the global average, Tier 3 min, and Tier 3 max were calculated; a linear dynamic trajectory was assumed from the global average in 2017 to midway between the Tier 3 min and Tier 3 max by 2047. The inventory for onshore processing was obtained directly from the nodules LCA model.

Estimated total SOx directly and indirectly emitted by producing metals for one billion EV batteries and connectors:

- For metals produced from land ores:
  173 megatonnes

- For metals produced from nodules:
  17 megatonnes

Estimated total NOx directly and indirectly emitted by producing metals for one billion EV batteries and connectors:

- For metals produced from land ores: **8 megatonnes**

- For metals produced from nodules: **1 megatonne**

Cumulative Energy Demand

Energy sources can be categorized along three different dimensions: whether the source is renewable versus nonrenewable, primary versus secondary (extracted from nature, like coal, versus commodity forms, like fuels), and intent of use as an energy versus material (e.g., a fuel or as a solvent).[204]

A number of energy indicators exist to quantify this information, yielding substantially different answers. Cumulative energy demand (CED) is frequently used in LCA studies of metals, and is therefore used by this paper for consistency with land-ore metal LCA

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204 As discussed at the Society of Environmental Toxicology and Chemistry Europe's 20th LCA Case Study Symposium. Also see (Arvidsson & Svanstrom, 2015).

literature. CED notably includes energy flows for both material and energy purposes—which means it will count energy-derived materials even if not utilized as combusted fuels.

Figure 52 summarizes the CED for cradle-to-grate production of Ni, Co, Mn, and Cu using the two different sources under both economic and mass-based allocations. Typically, CED LCA results tend to track closely with CO_2e, as seen in a study of 63 metals.[205] But for cobalt, while CO_2e was much lower with nodules, here their CEDs are comparable. This

is likely because the significant amount of natural gas and electricity fueling the reduction process is, in the model, economically allocated to nickel, cobalt, and copper. In actuality, the most of this is used to reduce manganese molecules rather than to power the processing. Therefore, in this model, cobalt demands substantially more energy when produced from nodules, only if in the model the pyro process infrastructure is economically allocated. The trend switches under mass allocation. The mass-based sensitivity analysis provides a useful view in this particular case.

Figure 52. Cradle-to-Gate CED Comparison, Land Ores versus Nodules (MJ per kg Metal)[206]

Economic allocation (Primary result)

	Nickel sulfate	Cobalt sulfate	Manganese sulfate	Copper cathode
Land ores	239	260	140	98
Nodules	229	587	217	82

Mass-based allocation (Sensitivity analysis)

	Nickel sulfate	Cobalt sulfate	Manganese sulfate	Copper cathode
Land ores	165	148	140	98
Nodules	27	27	227	27
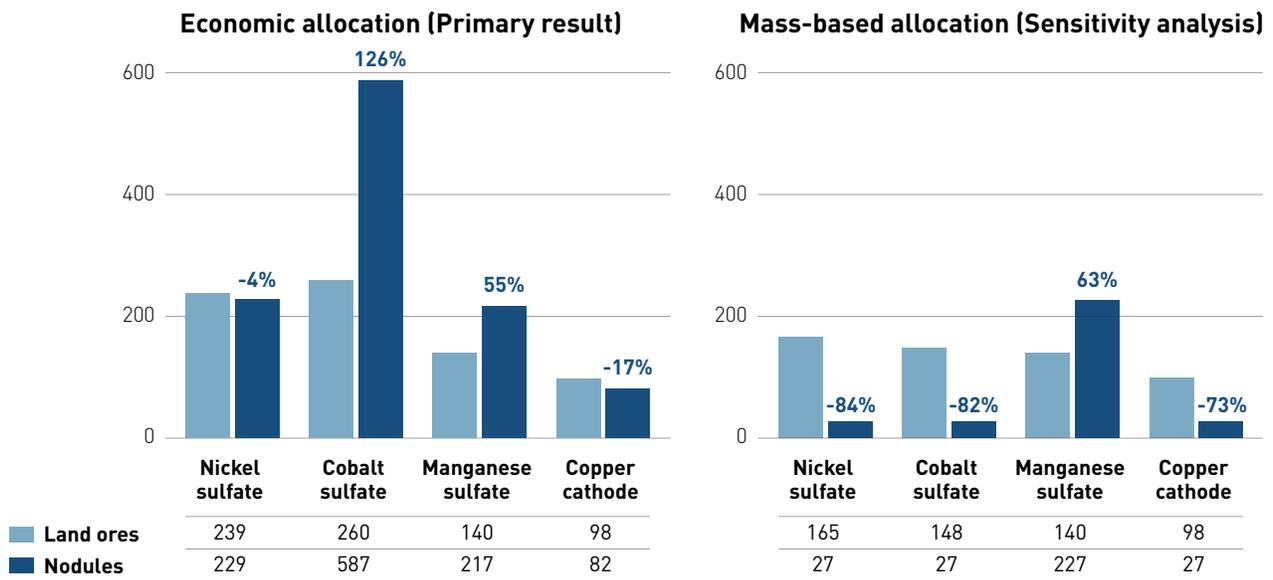
205 (Nuss & Eckelman, 2014).

206 Sources: For land-based values, see note 11. For nodules-based values, see technical appendix for LCA model.

Nickel and copper each demand less energy when produced from nodules, regardless of the allocation method.

For both the economic and mass allocations, the CED of manganese from nodules is judged to be within the margin of error of land ores. As was the case with GWP, CED estimate for manganese under land ores has greater uncertainty and may be underestimated due to scarcity of data and inconsistencies in the published literature; a similar analysis to that of CO_2e shows a 2x discrepancy in CED estimates for ferromanganese between Ecoinvent and the recent Hatch study.[207]

Of the total CED involved in processing a nodule, 35% is natural gas, 34% is due to coal used as a reductant, and 16% is hydropower electricity used in processing and refining. The remaining 15% comes from sulfuric acid and other material inputs, as well as offshore operations (5%). Energy savings in the collection phase are partially offset by the endothermic nature of nodule processing, as natural gas and electricity are required for heating and powering the reduction reaction. Land-ore processes may be endothermic or exothermic, depending on mineralogy; the land-ores aggregate baseline reflects a mixture of both types.

Applying the per-kilogram values to the one billion EVs demand case, we see the following values of CED (see Figure 53):

- Metals produced from land ores: **24,600 petajoules (mass sensitivity: 19,600 petajoules)**
- Metals produced from nodules: **25,300 petajoules (mass sensitivity: 5,500 petajoules)**

Figure 53. CED Contributions to 1B EVs by Metal, As-Is Land Ores and Nodules (×10⁹ MJ)

207   (Westfall, Davourie, Ali, & McGough, 2016); (Hatch, 2014).
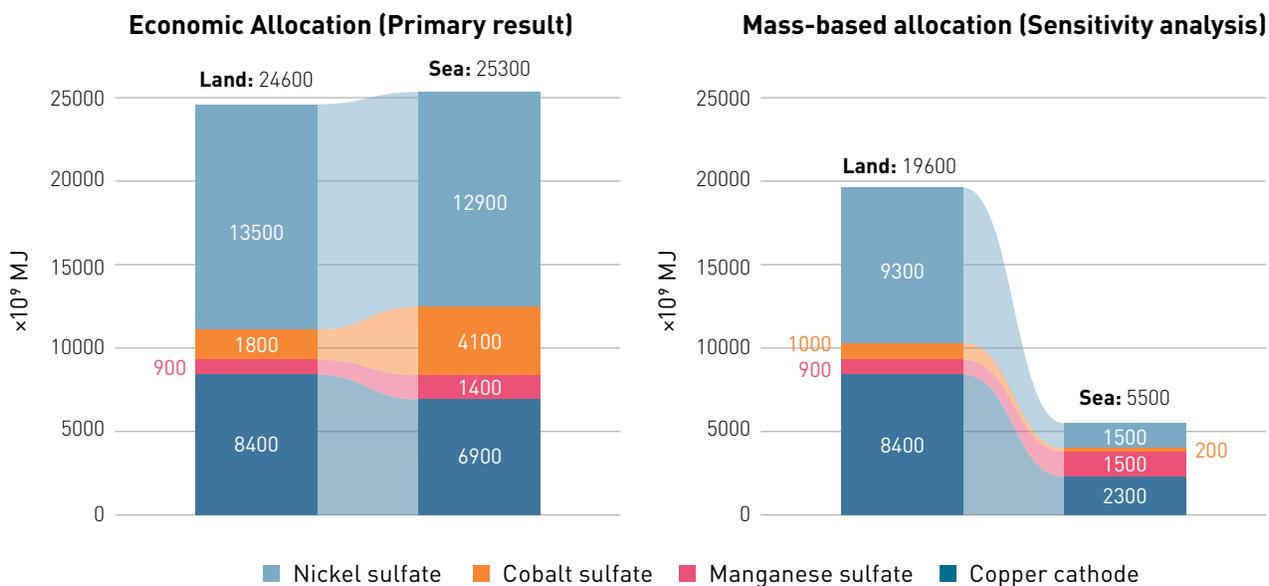
Applying the dynamic scenarios for land ores, the CED for producing battery precursor metals for one billion EVs for the baseline land ores scenario versus planned nodules project becomes:

- Metals produced from land ores: **26,200 petajoules (mass sensitivity: 21,000 petajoules)**

- Metals produced from nodules: **25,300 petajoules (mass sensitivity: 5,500 petajoules)**

For the green land-ores scenario versus planned nodules project:

- Metals produced from land ores: **24,500 petajoules (mass sensitivity: 19,700 petajoules)**

- Metals produced from nodules: **25,300 petajoules (mass sensitivity: 5,500 petajoules)**

Table 16. Nonliving Resources Impacts of Metal Production

	PRODUCTION FROM LAND ORES		PRODUCTION FROM OCEAN NODULES	
Physical Damage to Habitat	Med	Three different types of mines with falling average mined grades are required to supply the four metals. As a result, four times more ore mass needs to be processed to get the metals needed for one billion EVs compared to polymetallic nodules. 156,000 km2 of land habitats, including forests, are removed. Landscapes are altered and receive a significant quantity of waste and tailings. In addition, tonnage of tailings is placed into deep sea, covering 2,000 km2 of seabed.	Med–Low	Due to their polymetallic nature, four times less nodule mass needs to be processed to get the metals needed for one billion EVs compared to land ores. 508,000 km2 of seabed surface lose nodule cover. Plumes generated by seabed machines are at risk of resettling outside the mining area and blanketing deep-sea wildlife. Use of land, forests, water are low.
Tailings and Chemical Pollution	High	64 gigatonnes of waste and tailings are generated, leading to substantial amounts of chemical pollution.	Med–Low	Near zero solid waste and tailings are produced on land. Pollution to seawater is limited to typical ship operations.
Water Withdrawal	Med–High	45 km3 of freshwater are withdrawn for mining operations.	Low	5 km3 of freshwater are withdrawn for onshore processing and refining.
Water Pollution	High	Substantial pollution from routine operations, tailings dam collapses, and insufficient mine reclamation has resulted in large-scale human and wildlife illness and deaths.	Med–Low	Nodule collection does not use or pollute freshwater.
Air Pollution	High	Toxic dusts are produced in the mining phase. CO_2, SOx and NOx emissions are produced from kilns, furnaces and converters during the processing and refining phases. Lung cancer and other diseases sometimes result from long exposure.	Med–Low	Ship combustion releases SOx and NOx toxins into unpopulated areas only. No toxic dusts from tailings dams are produced. Process emissions from kilns, furnaces, and converters are similar to that for land ores, however with four times less ore tonnage processed to get the same amount of metal along with environmentally optimized flow design, overall air pollution is lower.
Cumulative Energy Demand	Med	24,500 petajoules of energy are extracted from the earth to produce battery precursor metals for one billion EVs.	Med	25,300 petajoules of energy are extracted from the earth to produce battery precursor metals for one billion EVs. A substantial portion of this is hydropowered or energy used for material purposes only (e.g., coal reductant).
Overall	**Med–High**	**Medium to High Impact**	**Med–Low**	**Medium to Low Impact**

CATEGORY 3: BIODIVERSITY

Biodiversity Impacts at a Glance

IMPACT CATEGORY
Biodiversity
• There is exquisite diversity and richness of species affected by land mining sites. Land mining unavoidably causes habitat destruction and biodiversity loss, with future expansion of land-based production putting more habitats and wildlife at risk in some of the most biodiverse regions of the planet, home to rare local species. Mine site restoration is mandated in some countries but is not stringently enforced in jurisdictions producing most nickel, cobalt, manganese and copper. Few jurisdictions mandate habitat restoration and biodiversity offsets beyond the mine site area.
• Due to a low flux of particulate organic carbon from the surface, there is little food availability on the CCZ seafloor. As a result, the abundance of life at the abyssal seafloor is low and limited to fauna (no flora present). Some organisms attach to nodules, others need the hard surfaces of nodules for critical life functions. Nodule removal will lead to habitat loss and reduction of nodule-dependent wildlife populations. If disturbed sediment plumes travel outside the collection areas, they will pose an additional risk of damage to habitats in a wider area. There is a need for more study of deep-ocean ecosystems and future impacts of nodule collection on ecosystem function and recovery.

We next turn to an exploration of the wildlife populations and ecosystems at risk of harm by land-based mining and deep-sea nodule collection. To understand the impact of metal production on biodiversity loss, we discuss the following topics:

• Measuring biodiversity loss

• Wildlife populations found on terrestrial mining sites

• Mechanisms of impact from terrestrial mining

• Wildlife populations found in deep-sea nodule collection sites

• Mechanisms of impact from deep-sea nodule collection

Measuring Biodiversity Loss

'Biodiversity' is often used as an umbrella term for the diversity within species, between species, and of ecosystems (IPBES 2019). Biodiversity underlies the delivery of many ecosystem services. Harming a system's biodiversity compromises its ability to deliver resources and benefits to people and nature; greater biodiversity increases the benefits an ecosystem provides, as well as bolsters the ecosystem's resilience to disturbance.

In contrast to impacts like carbon dioxide emissions or ecotoxicity, biodiversity does not lend itself to easy quantification or comparability using simple metrics. Measurement complexity arises in part because impact on biodiversity is context specific; just as extracting excessive water may be more damaging in a rain-poor area, transforming one square kilometer of land into a mine in a tropical rainforest often leads to the extinction of more unique species than does land use in other ecosystems.[208] Furthermore, how does one decide which species are more valuable to an ecosystem, or to people? What is the relative importance of different habitats?

Biodiversity loss may be quantified as "global species loss," or the fraction of global species committed to extinction due to habitat loss, compared to undisrupted habitats.[209] A comparative biodiversity study might break the problem into three pieces: (1) What is the nature and quantity of wildlife occupying a habitat? (2) How do the actions in question cause disruptions to that population? (3) Can we "value" or quantify the negative impacts of those disruptions? The first question has to do with measuring species richness and populations in the impacted habitats. The second question relates to the underlying

208   (Global Resources Outlook 2019).
209   (Chaudary et al 2015).

mechanisms through which human actions translate to damage or harm to species or habitats. The third question is the trickiest—it implicitly asks us to compare the impact difference between harming organisms A in location 1 versus organisms B in location 2.

We start by reviewing these three questions at a high level. Then, we explore each of the two habitat types more deeply.

First, we consider the species and populations residing in each habitat. We will see that terrestrial ecosystems generally have greater species richness, organism abundance, and biomass per unit area than the abyssal seafloor.

The number of species on earth is only approximately known, but estimates range from 8.7 million to 20 million plants, animals, and fungi. Only 1.8 million have been formally identified, although new barcoding techniques are certain to increase that number, especially for insects.[210]

Although life evolved in the ocean, which covers 70% of our planet and contains 95% of the volume where higher life can occur, the number of species is much higher on land. This is because the fragmentation and physical diversity of landforms provided increased opportunities for evolution to occur, and the three-dimensional "architectural diversity" provided by the evolution and diversification of flowering plants on land created a multitude of new niches, fueling further diversity and coevolution, with increased primary productivity and new sources of food (e.g., pollen, nectar, fruit). As a result, there are six times more species on land than in the ocean, even though the deep-seabed area is more than twice as large as terrestrial land.[211] At least two-thirds of marine and terrestrial species have been described, and

new descriptions and discoveries are not likely to change those proportions across taxa and environments.[212] In aggregate, average per-area species richness is an order of magnitude higher on land than in the deep seabed.

As discussed in the Nonliving Resources section, the total seabed area impacted by nodule collection required to supply one billion EVs is 3.26 times larger than the total land area impacted by land mining (508,000 square kilometers versus 156,000 square kilometers). Given that species richness is an order of magnitude greater on land, the total species at risk should be higher with terrestrial mining. A simple calculation applying average species densities to the land and seabed usages in the one billion EV scenario shows 70% fewer species would be touched by nodule collection and processing than by using land ores. A more robust analysis would consider the specific geography of global base metal mine sites on land and associated biodiversity. Given that the bulk of current metal production and reserves on land are found in some of the most biodiverse areas on the planet (e.g., Indonesia, Philippines, DRC, South Africa), we expect this analysis would drive the number of species impacted by land mining even higher and the difference between land and nodules wider.

Terrestrial ecosystems also tend to have comparable or higher total individual wildlife populations. Figure 54 compares average minimum and maximum fauna populations in the two habitat types, measuring per-square-meter populations within the top centimeter of terrestrial soil and abyssal seabed sediments. The numbers below represent global average minima and maxima and do not account for the site-specific biodiversity of base metal production on land. No flora is indicated because plant life does not exist in the deep sea—photosynthesis is not possible without sunlight.

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210 (Pennissi, 2019).
211 (Costello & Chaudhary, 2017); (Zhang, 2017).
212 According to (Costello & Chaudhary, 2017).

It is also important to understand that abyssal seabed in the CCZ is a food-poor environment that produces wildlife that is physically much smaller than what we encounter on land. As a result, the definitions of what constitutes megafauna, macrofauna, and meiofauna in the abyssal plains is of a different scale. For example, "megafauna" on land include mammals, birds, reptiles, and amphibians, while deep-sea megafauna includes baited fish and shrimp that are larger than 2 cm.[213]

Figure 54. Organisms per Square Meter: Land Ores versus Nodules[214]

MICROBES

361		**100000**
Max **190**		
Min		
51	**34**	
		0.2 **100**
ABYSSAL	SOIL	ABYSSAL SOIL
Prokaryotes (×10¹² per m²)		**Protists** (×10⁶ per m²)

FAUNA

9461		**300**		**4**	
Max **3270**					
Min **217**	**232**	**0.23**		**0.0004**	
ABYSSAL	SOIL	ABYSSAL	SOIL	ABYSSAL	SOIL
Meiofauna and Macrofauna (×1000 per m²)		**Megafauna in situ** (per m²)		**Megafauna mobile** (per m²)	
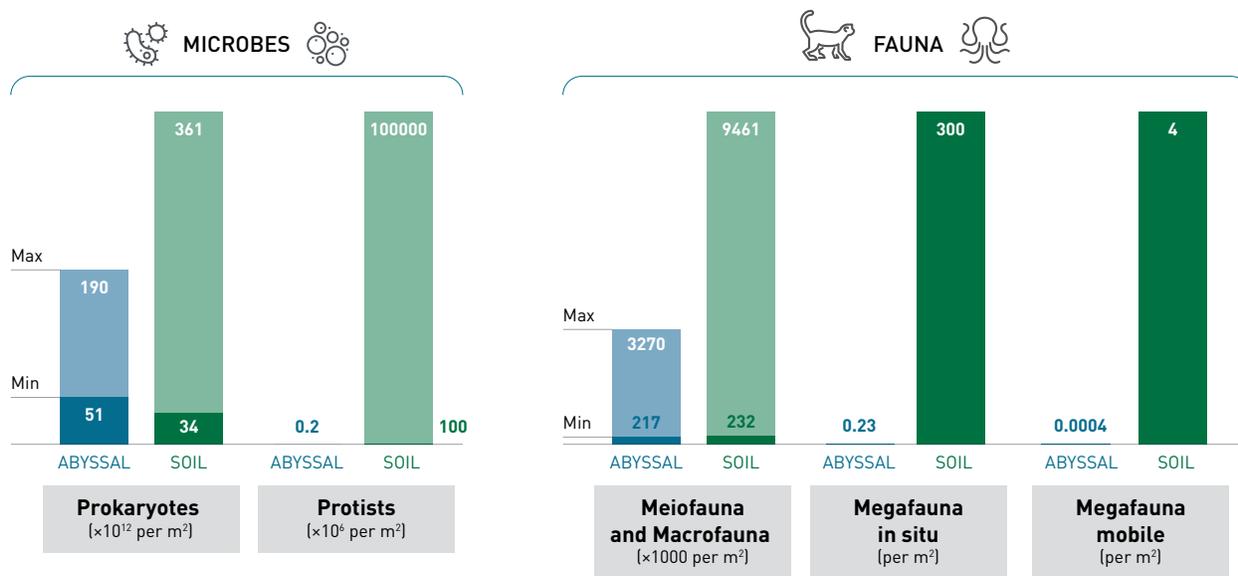
213 Confusion arises from the fact that scientists use the same terms to classify organisms by size on land and on the abyssal seafloor, but with different criteria for size. On the abyssal seabed, "megafauna" describes organisms longer than two centimeters, but on land it commonly refers to animals weighing more than 40–44 kilograms (90–100 lbs.), while in soil science, the term is used for animals such as earthworms and small vertebrates (e.g., moles, mice, hares, rabbits, gophers, snakes, and lizards). On the abyssal seabed, "macrofauna" describes organisms smaller than two centimeters and retained on a sieve of mesh size 250 µm, but on land it describes organisms longer than one centimeter. "Meiofauna" describes the very small (<1 mm) organisms that live in spaces between sediment particles. "Microfauna" on the abyssal seabed describes organisms that pass through a mesh size of 32 µm (0.032 mm), whereas on land it describes soil animals smaller than one millimeter. Abyssal definitions from International Seabed Authority can be found at: https://www.isa.org.jm/scientific-glossary/m.

214 Population numbers have been compiled from numerous literature references. For terrestrial prokaryotes, see (Bardgett and Van Der Putten 2014), (Soil Biology, 2019), (Raynaud & Nunan, 2014), and (Bar-On, Phillips, & Milo, 2018). For terrestrial protists and meiofauna, see (Bardgett and Van Der Putten 2014). "In situ" terrestrial megafauna include soil-occupying creatures such as earthworms, while mobile terrestrial megafauna include amphibians, reptiles, birds, and mammals. For terrestrial megafauna and vertebrates, see (Bardgett and Van Der Putten 2014), (Reagan, Camilom, & Waide, 1996), (Ishwar, Chellam, & Kumart, 2001), (Gaston, Blackburn, & Goldewijk, 2003), and (Yalden, 2002). For abyssal prokaryotes, see (Wei, et al., 2010) and (Rex, et al., 2006). For abyssal protists, see (Gooday A. J., et al., 2017) and (Giere, 2009). For abyssal meiofauna, see (Pape, Bezerra, Hauquier, & Vanreusel, 2017), work by (Coul et al., 1977), (Tietjen, 1992), and (Shimonaga et al., 2007) referenced within (Giere, 2009), and (Rex, et al., 2006). For abyssal macrofauna, see (De Smet, et al. 2017) and (Rex, et al., 2006). For abyssal megafauna, see (Rex, et al., 2006), (Simon-Lledó, Bett, & Veerle, 2019), and (Leitner A. B., Neuheimer, Donlon, Smith, & Drazen, 2017).

The total populations at risk when scaling to one billion EVs vary depending on taxa. Figure 55 compares individuals at risk within each taxon when using nodules compared to using land ores. Land and seabed usage numbers calculated previously are taken into account. Under the billion EVs scenario, slightly more individuals within the prokaryote and meiofauna categories are put at risk if using nodules. For protists and megafauna, far more individuals within these categories are at risk if using land ores, by roughly a factor of 14.

Notably, when environmental impact assessment studies are conducted on land for new mining projects, they typically consider impacts on megafauna and keystone species only. If we follow that protocol to compare impacts of nodule collection to impacts of land ore mining for producing metals for one billion EVs, 93% fewer megafauna would be at risk when using nodules—47 trillion organisms would be at risk if using land ores while 3 trillion would be at risk when using nodules. In both cases, the vast majority of organisms are "in situ" megafauna. Focusing on mobile megafauna only, again we see 93% fewer individuals at risk if using nodules—41 billion with nodules versus 630 billion with land ores. Figure 56 illustrates the mobile megafaunal populations at risk under the one billion EV scenario, using average population estimates.

Figure 55. Wildlife Populations at Risk, One Billion EVs[215]

	Prokaryotes at risk	Protists at risk	Meiofauna and macrofauna at risk	Megafauna in situ at risk	Megafauna mobile at risk
Units	$\times 10^{24}$	$\times 10^{20}$	$\times 10^{17}$	$\times 10^{12}$	$\times 10^{10}$
% more individuals at risk — Nodules	103%		23%		
% more individuals at risk — Land		1487%		1428%	1436%
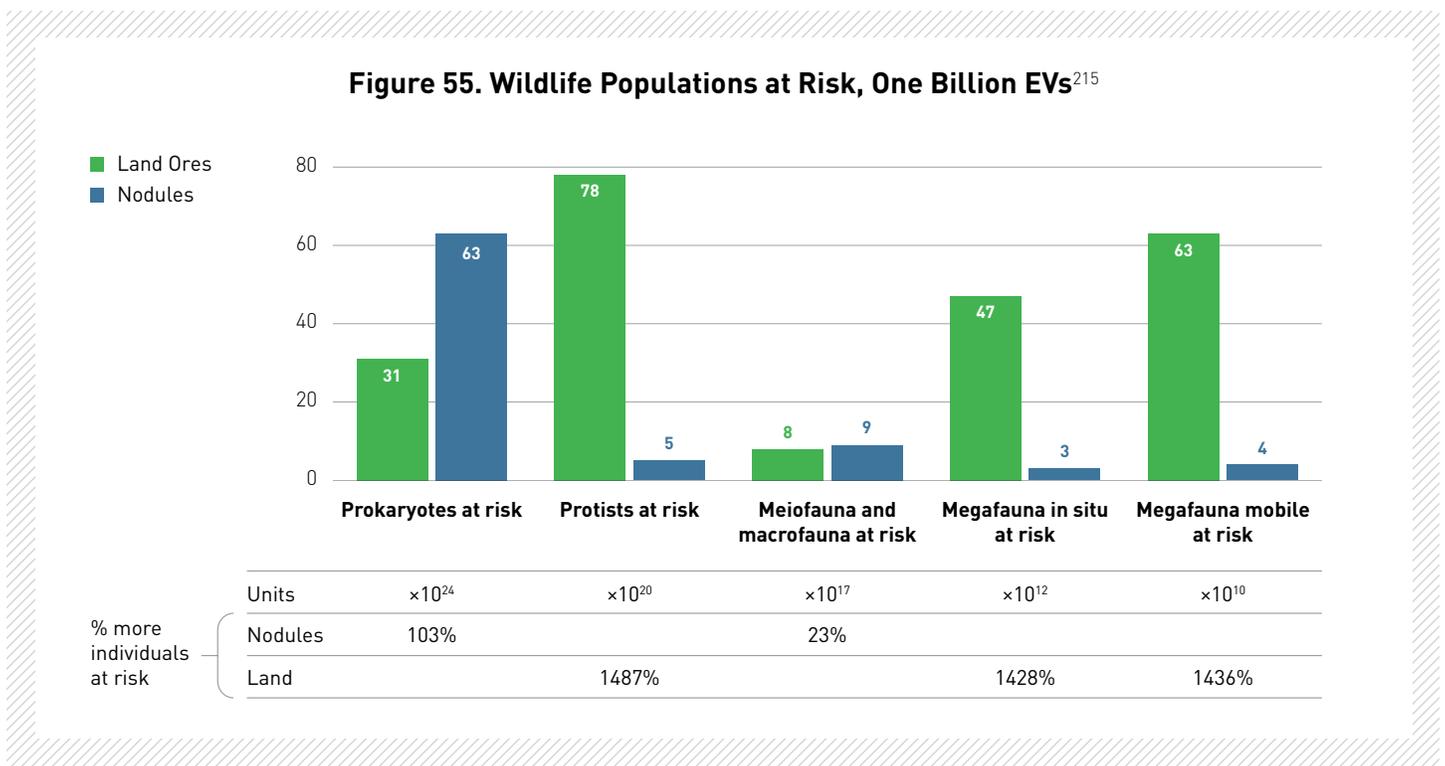
215 Sources are given in Footnote 192. Assumes average between minimum and maximum estimates for each taxon, scaled to the land and seabed areas impacted for one billion EVs. Table indicates the percentage difference in estimated populations at risk; for instance, 103% more prokaryotes are at risk with nodules, while 1487% more protists are at risk with land ores.

Figure 56. Mobile Megafauna Individuals (Billions) At Risk, One Billion EVs[216]

	Mobile (abyssal)	Amphibians	Reptiles	Birds	Mammals
Land Ores	0.1	348	284	0.3	0.2
Nodules	1	22	18	0.02	0.01
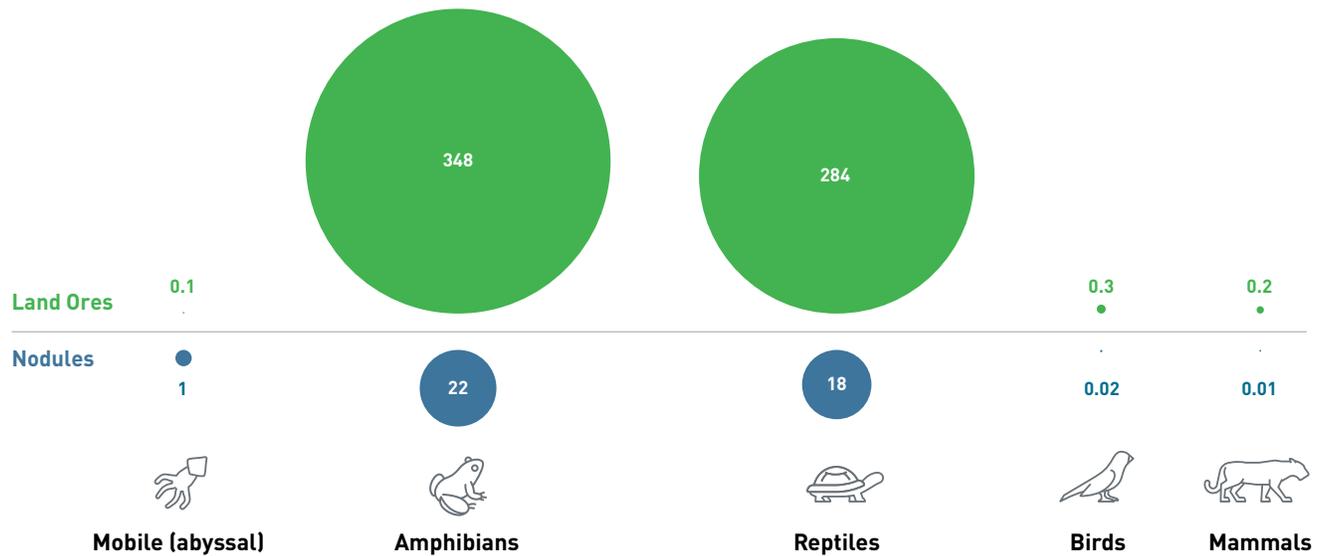
Estimated megafauna at risk by mining and processing metals for one billion EV batteries and connectors:

- For metals produced from land ores:
  ~47 trillion megafauna (including 0.6 trillion vertebrates and other mobile megafauna)

- For metals produced from nodules:
  ~3 trillion megafauna (including 0.04 trillion vertebrates and other mobile megafauna)

Biomass, or the total quantity of organisms in a given area, may be another lens for comparing the total wildlife present within the two habitat types. Calculated as the average biomass of living organisms (i.e., sequestered carbon is excluded), biomass is two orders of magnitude higher in terrestrial habitats than on the abyssal seabed. Average biomass is 3.64 kilograms of carbon per square meter on land, compared to 0.0128 kilograms of carbon per square meter on the abyssal seabed.[217] Scaled up to one billion EVs, the impacted biomasses are 568 megatonnes when using land ores versus 42 megatonnes when using nodules; note that 85% of the biomass value for nodules comes from its processing footprint on land and only 15% comes from collecting nodules from the CCZ seabed.

Estimated biomass of living organisms impacted by mining and processing metals for one billion EV batteries and connectors:

- For metals produced from land ores:
  ~568 megatonnes of biomass

- For metals produced from nodules:
  ~42 megatonnes of biomass

While these estimates are of some value when it comes to making sense of the scales of relative impacts, they are fundamentally reductive. They don't tell us anything about the fascinating species inhabiting impacted ecosystems, or how these

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216 Sources are given in Footnote 192. Assumes average between minimum and maximum estimates for each taxon, scaled to the land and seabed areas impacted for one billion EVs.

217 Drawing primarily on data from (Bar-On, Phillips, & Milo, 2018). The seafloor-biomass value incorporates an estimate of seamounts and hydrothermal vents attributed to (Wei, et al., 2010). It is also an overestimate because it includes all fish in the water column, rather than focusing only on the seafloor, but there was not a simple way to extract this from the data. The overall biomass of earth's ice-free terrestrial area was 472.7 gigatonnes of carbon, compared to 2.49 gigatonnes of carbon for the abyssal seabed.

ecosystems function, or the ecosystem services they deliver for our planet. In the subsections that follow, we explore in greater depth these fauna populations and ecosystems that will be disrupted by land-ore mining and nodule collection.

But first, to understand how land mining or nodule collection operations cause disruptions to wildlife populations, it is necessary to understand the mechanisms by which industry actions lead to biodiversity loss. This brings us to the second overarching question—how do the actions in question cause disruptions to wildlife populations. The most important drivers of biodiversity loss are habitat change and degradation (including land and seabed use and transformation), pollution, climate change, natural resource exploitation, and invasive species.[218] These can directly or indirectly cause habitat loss or degradation and drive species loss. LCA impact-evaluation frameworks contain several metrics that directly correspond to most of these drivers, including land use, climate change, ecotoxicity, and water extraction.

Examining LCA midpoint indicator results is probably the best way to understand drivers of biodiversity loss. Several indicators we measured and discussed earlier in this paper are leading indicators of biodiversity loss; biodiversity loss in the LCA is represented as an "endpoint," designating potential species loss, fed by these many midpoint indicators. As Figure 57 shows, higher values of land use, climate change, ecotoxicity, and water use, among others, contribute to higher risk of species extinction. Reexamining the results presented under Nonliving Resources, we see a higher number associated with land ores across most categories, implying a greater risk of biodiversity loss with land-ore mining than with nodules.

Mining requires felling trees and disrupting habitats. Nodule collection requires removing nodules and any organisms attached to them. In the subsections below, these mechanisms of biodiversity harm from mining land ores and the deep seabed are more fully explored.

Figure 57. ReCiPe LCIA Indicator Taxonomy including Biodiversity Endpoint[219]

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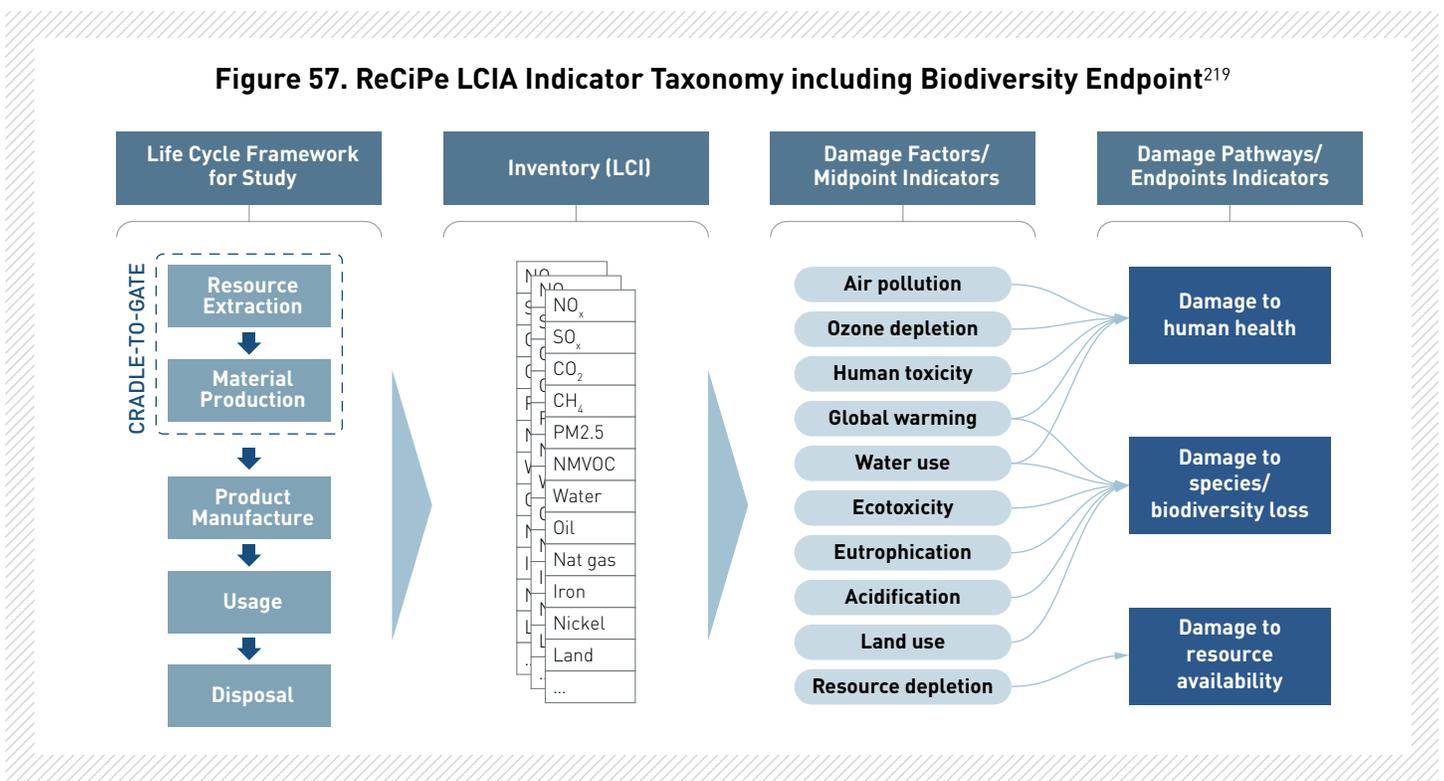
218 See (IPBES, 2019) for top drivers of biodiversity loss as described by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services.

219 Framework reflects LCIA standard ReCiPe model, as depicted in (Water Matters, 2016), (RIVM, 2018), and many others.

Finally, when comparing relative impacts, we have to ponder difficult value questions, such as "Which species is more valuable to the ecosystem, a beautiful abyssal sea cucumber or a majestic snow leopard?" or "How many nematodes equal a Chinook salmon?"

Many characteristics can factor into the answer: Is the species in question more endangered? Is it more integrated into critical ecosystem services? Is it genetically unique, or endemic? Is one species more valuable for scientific study, or more intangibly beneficial, aesthetically or spiritually? Is there an exceptional iconic value placed on the species, due to its great age (the "Methuselah" bristlecone pine or the Japanese koi "Hanako"), reproductive success (Laysan albatross "Wisdom"), intelligence (western lowland gorilla "Koko"), touristic importance (African lion "Cecil"), or symbolic importance (Sumatran rhinoceros "Tam")?

Indeed, 180 UN-recognized currencies can be valued with respect to each other at the push of a button, enabling us to know that one Albanian lek buys 0.12 Zambian kwacha, but there is not yet a simple standard value comparison process for species or individual organisms.[220] Understanding how to create such preferences for organisms is at the heart of ongoing biodiversity impact research. Some geospatial databases have been developed, allowing the LCA practitioner to weight a habitat by vulnerability metrics such as endemic richness or species threat levels, though the emphasis so far has been primarily on land habitats.

Another approach to determining the comparative value of biodiversity loss is to examine the aggregate impact on ecosystem services. Arguably one of the most direct links between biodiversity and impact to humans comes through impacts on ecosystem services. Groups of individual organisms can be measured and flows to ecosystem services and other benefits can be qualitatively predicted and valued. For instance, changes in fish population can help us understand food flows, which also further impact tourism and recreation. In aggregate, relative biodiversity impacts might be understood through further research of the ecosystem services value provided by local organisms. As discussed in the earlier Ecosystem Services results overview, studies to date suggest that the impacts of nodule collection seem significantly lower for most services—implying that disruptions would consequently be of lower magnitude than terrestrial habitats. However, with less accessibility to the deep seabed, there are more knowledge gaps in cataloging all present species and their roles and contributions to ecosystem services—so this conclusion is tentative at best and more research into CCZ abyssal plain ecosystems is required.

In aggregate, comparing biodiversity impacts requires more than just localized species richness and population data. It requires localized measures of value or vulnerability (e.g., endemic richness and species threat levels), and can be aided by a better understanding of the ecosystem services impact from local organisms.

In the subsections that follow, we provide a deeper exposition of the terrestrial and CCZ deep-seabed wildlife populations, explore known species vulnerabilities, and describe the mechanisms through which land mining and nodule collection can cause harm.

Wildlife Populations Found on Terrestrial Mining Sites

Among the approximately 85% of species inhabiting land are about 352,000 species of flowering plants, 1,000 species of coniferous trees, 15,000 species of ferns and horsetails, 23,000 species of mosses, 15,000 species of freshwater fish, 15,000 species of amphibians, 10,000 species of reptiles, 10,000 species of birds, 5,500 species of mammals, and 5 million species of insects.[221] Studies contend that large and endemic species are the most vulnerable to extinction.[222]

Figure 58 depicts a sample of creatures currently threatened by copper- and nickel-mining operations on land. The jaguar is one of several species

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220   Exchange rate as of July 16, 2019.

221   (Chapman, 2009); (IUCN, n.d.).

222   (Costello & Chaudhary, 2017).

threatened by the proposed Rosemont copper mine in Arizona's Santa Rita Mountain. A mile-wide pit nearly 900 meters deep and thousands of acres of waste rock piled several hundred feet high would disrupt an important wildlife corridor between Mexico and the US and decrease water availability for wildlife. The Canada lynx is one of many species threatened by a planned copper-nickel mine near Ely, Minnesota, adjoining Boundary Waters Canoe Area Wilderness.

The Dinagat-Caraga tarsier, discovered in the 1970s, lives only on Dinagat Island in the Philippines, and is threatened by 10 companies that mine nickel ore on the 60-kilometer-long island. The Chinook salmon in Alaska is one of five salmon species threatened by a large-scale copper and gold mine in the Bristol Bay watershed. Tribal communities that have depended on salmon for thousands of years are also threatened.

Figure58. Four Animals Threatened by Terrestrial Copper or Nickel Mining[223]

a) Jaguar in Rosemont Copper Mine, Arizona

b) Canada Lynx near planned Cu-Ni mine, Minnesota

c) Danagat-Caraga Tarsier in the Philippines

d) Chinook salmon in Alaska near Bristol Bay

223 (a) Photo credit: National Geographic (Main, 2019). (b) Photo credit: Erwin and Peggy Bauer, USFWS (Pearson, 2019). (c) Photo credit: Futurity.org (Catoto, 2017). (d) Photo credit: wildsalmoncenter.org (Mordant, n.d.).

In general, a mine's potential biological and ecological impact will tend to be proportional to its size and the biodiversity of the region in which it is situated. The sixfold greater abundance of species on land, along with the variety of habitats impacted and imperfect oversight quality prevailing in terrestrial mining, therefore provides significant opportunities for damage to biodiversity. When mines are clustered in an area, their effects are additive and cumulative.[224]

Seventeen countries are identified as "megadiverse" because they each contain at least 5,000 species of endemic plants and also border marine ecosystems. Together, these countries host approximately 70% of earth's species. The list includes Australia, Brazil, China, Colombia, the DRC, Ecuador, India, Indonesia, Madagascar, Malaysia, Mexico, Papua New Guinea, Peru, the Philippines, South Africa, the United States, and Venezuela. Some fascinating creatures populate these areas.

Notably, one activity shared by all the megadiverse nations is mining (see Table 17).

Table 17. Top 17 Megadiverse Countries and Presence in Mining

COUNTRY	RANK	NICKEL	COBALT	MANGANESE	COPPER	OTHERS
Brazil	1			Yes	Yes	Yes
Colombia	2	Yes			Yes	Yes
United States	3				Yes	Yes
South Africa	4	Yes	Yes	Yes		Yes
Philippines	5	Yes	Yes		Yes	Yes
Papua New Guinea	6				Yes	Yes
Malaysia	7					Yes
DRC	8		Yes		Yes	Yes
Australia	9	Yes	Yes	Yes	Yes	Yes
Indonesia	10	Yes			Yes	Yes
China	11	Yes		Yes	Yes	Yes
Mexico	12				Yes	Yes
Venezuela	13					Yes
Ecuador	14					Yes
Peru	15				Yes	Yes
India	16			Yes	Yes	Yes
Madagascar	17	Yes	Yes			Yes

Physical features such as complex topography, mountain ranges, isolated watersheds, and islands enabled evolution of the myriad distinctive plant and animal species—and, in time, the human cultures and traditions unique to each country. Many of these nations joined in 2002 as the Group of Like-Minded Megadiverse Countries to conserve biodiversity, ensure its sustainable use, and ensure fair and equitable sharing of benefits.[225]

As examples of potentially affected habitats, below are biodiversity profiles for four countries that are the world's major producers of the metals contained in nodules from the CCZ (see also Table 18).

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224 See, for example, (Wesley, Infante, & Hughes, 2014), (EPA, 2014).
225 (UN, 2010).

Table 18. Biodiversity (Species Richness) in Major Producers of Ni, Co, Mn, and Cu[226]

Taxon	SOUTH AFRICA (MN)			INDONESIA (NI)			CHILE (CU)			DRC (CO)		
	Rank	Species	%	Rank	Species	%	Rank	Species	%	Rank	Species	%
Mammals	22	297	5	1	670	12	N/A	119	N/A	10	430	8
Birds	29	755	8	4	1,615	16	N/A	530	N/A	11	1,087	11
Reptiles	13	447	4	6	728	7	N/A	87	N/A	23	294	3
Amphibians	10	315	2	12	347	5	N/A	43	N/A	16	244	3
Fish	13	2,059	6	2	4,682	14	N/A	43	N/A	23	1,480	5
Flowering Plants	6	23,420	9	4	29,375	11	N/A	4,295	N/A	20	1,107	4
Overall Species Richness Rank	13			3			N/A			14		

Indonesia, the world's largest producer of nickel, also mines copper and gold, is the world's 10th-most megadiverse country and ranks third in overall biodiversity, behind Brazil and Colombia. With more than 17,000 islands, its many ecosystems hold species found nowhere else. It hosts the world's largest number of mammal species (670), second-largest number of fishes (4,682), and fourth-largest numbers of flowering plants (29,375) and birds (1,615). The part of Indonesia where most nickel laterites are found furthermore coincides with the Wallace Line, a habitat unique on the planet in which Australian mammals naturally coexist with Asian mammals. Indonesia also forms a major part of the global epicenter of shallow-water marine diversity: the Coral Triangle, a 4 million square mile area of ocean and coastal waters in Southeast Asia and the Pacific. This area surrounds Indonesia, Malaysia, Papua New Guinea, the Philippines, Timor Leste, and the Solomon Islands. The Coral Triangle is home to:

- Highest coral diversity in the world: 76% (605) of the world's 798 coral species.

- Highest diversity of coral reef fishes in the world: 37% (2,228) of the world's 6,000 coral reef fish species, and 56% of coral reef fish species in the Indo-Pacific region (4,050).

- Some of the highest numbers of endemic reef fish species in the world—particularly in Indonesia, Papua New Guinea, and the Philippines.

- Consequent richness in every other category of marine life.[227]

The DRC, the world's largest producer of cobalt, is the world's eighth-most megadiverse country and 14th in overall biodiversity. The DRC is home to 430 species of mammals (10th) and 1,087 birds (11th). As the second-poorest country in the world, the DRC lacks sufficient funds or institutions to regulate mining or enforce existing regulations, much less to investigate the impacts of mining on biodiversity.[228] It is also sufficiently dangerous that outsiders cannot accurately assess biodiversity impacts. A land challenged by poverty, poaching, and lawlessness, the DRC's abundant resources of cobalt, copper, diamonds, tantalum, tin, and gold have had both positive and negative impacts. There is strong evidence that resource wealth has caused conflicts to have greater frequency, last longer, and produce more casualties.[229]

Furthermore, exploitative artisanal miners have moved into national parks, bringing more deforestation, poaching, and environmental pollution not only to the DRC, but elsewhere, such as in Gabon's Minkébé National Park, where gold mining has spawned prostitution, drugs, arms trafficking and the slaughter of tens of thousands of forest elephants;[230] and in Madagascar, where deforestation caused by up to half a million illegal gemstone miners has destroyed some of the last remaining habitat for the country's endangered lemurs.[231]

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226 Data sources: (Butler, 2016) for rainforests; (IUCN, n.d.) for freshwater fish; (Minter, et al., 2004) for South African amphibians; (Royal Botanical Gardens, 2019) for Chilean vascular plants.

227 (Veron, De Vantier, & Turak, 2007).

228 (World Atlas, n.d.).

229 (Ross, 2004); (Heath, 2014).

230 (Yong, 2017).

231 (Tullis, 2019).

South Africa, the world's largest producer of manganese, is the world's fourth-most megadiverse country and ranks 13th in the world in overall biodiversity. It is especially rich in vascular plants with 23,420 species, ranking sixth in the world. A new survey of frogs found 315 species in South Africa alone, raising its global rank for amphibian species richness to 10th.

Chile, the world's largest producer of copper, while not as species rich as the other three countries in this group, has among the highest percentages of endemism anywhere in the world. Evolution of discrete populations has occurred throughout Chile's extremely long, mountainous, fragmented landscape. As a result, more than 50% of all its species are endemic. For example, 2,124 (49%) of its 4,295 vascular plants are found nowhere else on earth; that endemism includes not only species, but also 467 genera and 134 families.[232]

The above descriptions of biodiversity only include macroflora and macrofauna. Millions of insects and spiders, and tens of thousands of lower plants (ferns, horsetails, mosses), fungi, meiofauna, and bacteria also play key roles in land ecosystems.

Notably, taken together, the richness of terrestrial biodiversity along with its architectural diversity has engendered exquisitely coevolved relationships to an extent not possible on the abyssal seafloor. As one example, each of the world's approximately 25,000 orchid species (of which Indonesia hosts about 5,000) has an exclusive and intricately coevolved relationship with a single species of either bee, wasp, fly, moth, butterfly, gnat, or bird, to ensure cross-pollination.[233]

Equally extraordinary is the coevolution of wasps, fig trees, orangutans, and human cultures in the rainforests of Borneo and Sumatra.[234] The wasps pollinate the figs and lay their eggs in the fig fruit, one of the main foods of orangutans. Orangutans distribute the fertile seeds in their feces, insuring widespread reproduction of the figs. The trees have evolved to fruit asynchronously, so that somewhere there are always figs for the wasps to pollinate (the flower is inside the fig) and figs for orangutans to eat.

Orangutans have evolved high intelligence to recall locations of trees that will be in fruit at any given time. The intelligence and human-like appearance of orangutans have inspired numerous beliefs, taboos, stories, and traditions among human inhabitants of Borneo and elsewhere. Ancestral Dayak traditions profess that orangutans taught humans how to assist in the delivery of babies and how to use medicinal plants to soothe mothers after giving birth. Others regard them as reincarnations of respected members of the community and let them feed in their fruit gardens undisturbed. Tales of orangutans that protected a boy from a crocodile or a woman from a leopard lead to traditional beliefs and knowledge systems that facilitate protection of orangutans and their habitats, such that poaching—a major threat to this endangered species—is lower in areas where orangutans are incorporated into human belief systems.[235] That wasps, fig trees, orangutans, and people mutually support each other in a virtuous cycle is one of the many wonders of terrestrial biodiversity.

The case of orangutans illustrates another difference between challenges to terrestrial biodiversity and marine biodiversity. Orangutans' continued existence is threatened by mining, but also by deforestation to construct oil-palm plantations, conflict with subsistence farmers, illegal logging, forest and peat fires, hunting and poaching, illegal wildlife trade and ignorance and fear.[236] They, like many (perhaps most) terrestrial species, face a compounded impact of human-caused pressures.

Mechanisms of Impact from Terrestrial Mining

Depending on geographic location and whether the mine is open pit or underground, mining can directly impact biodiversity in several ways, including:

- Clearing, deforesting and excavating the natural habitat.

- Creating noise from blasting and machinery.

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232 (Royal Botanical Gardens, 2019).

233 (Horak, 2004).

234 (Webster, 1977).

235 (Yuliani, Adnan, & Bakara, 2018).

236 See (savetheorangutan.org, 2019).

- Polluting air with toxic dusts.

- Polluting water by release of chemicals.

- Draining acidic, toxic-metal-contaminated water into streams, rivers, lakes, or groundwater.

- Tailings dam failures, causing catastrophic damage to adjoining natural habitats and human communities from the release of toxic mud and sludge.

Deforestation and vegetation impacts can extend far beyond the mine site. Transport roads are constructed; communities where miners and workers live require clearing of forests for living space, fuel, and crops; water is contaminated with human wastes. Indirect impacts can include changes at the landscape level, removal of native vegetation and soil, opening of roads, secondary accesses and supply chains, urban expansion, deforestation for charcoal production, and mine waste discharge and spills. In Brazil, mining caused extensive deforestation in the Amazon rainforest between 2005 and 2015. Within lease areas, deforestation directly related to mineral extraction, processing, and infrastructure development resulted in three times the average Amazon clearing rate. But due to indirect impacts, deforestation extended up to 70 kilometers beyond lease boundaries, with total induced deforestation 12 times greater than within lease areas alone. In all, mining caused 11,670 square kilometers of deforestation in Brazil between 2005 and 2015, representing 9% of all deforestation within Brazil's Amazon rain forest.[237]

Land mining can have profound species impact in areas with high endemism. For instance, the Espinhaço mountain range of Eastern Brazil has the highest rate of plant endemism in South America, as well as high levels of endemism and diversity of anurans (frogs and toads) and birds. Intense mining for gold, iron, and other minerals has directly or indirectly affected 36% of the range of 32 anuran groups and 29% of the range of eight bird species endemic to the Eastern Brazil mountaintops. Range impact was more than 50% for eight anurans and more than 40% for two bird species. Since all the species studied are endemic to the Espinhaço mountains, local extinction also means global extinction.[238]

Reduction of water availability for wildlife and people is another indirect effect of terrestrial mining, because mines typically require large amounts of water to extract and process ore. This is particularly true when nearby water sources are scarce. Water withdrawal by the Oyu Tolgoi copper and gold mine in Mongolia's southern Gobi desert, one of the world's largest copper-gold mines, endangers species such as the Asiatic wild ass, black-tailed gazelle, argali sheep, ibex, Mongolian gazelle, corsac fox, cinereous vulture, steppe eagle, and grey wolf, while also impacting traditional herding communities, some of whom have already forsaken their heritage and taken menial jobs at the mine or in a nearby coal plant.[239] Even the iconic and endangered snow leopard was threatened by numerous mining leases until a community campaign persuaded the government to buy back the leases, prohibit mining, and create the 8,169-square-kilometer Tost Tosaonbumba Nature Reserve in South Gobi.[240] Conflicts will probably become more numerous and severe as one-fifth of Mongolia has been designated for mineral exploration. The International Monetary Fund predicts that, by 2021, mining will account for more than half of the economy, with the Oyu Tolgoi mine alone making up a third of Mongolia's GDP.

In cases where land mines impact coastal marine environments, fish, birds, turtles, reef corals, and other species may be harmed. For example, Brazil experienced its worst-ever environmental disaster on November 5, 2015, when a huge tailings dam collapsed at the Mariana mining site in the state of Minas Gerais. A three-meter tidal wave containing 55 million cubic meters of toxic mining waste sludge and clay killed at least 19 people, destroyed hundreds of homes, devastated livelihoods, contaminated drinking water, and flowed 650 kilometers down the River Doce to the Atlantic Ocean. Fisheries in the river were destroyed and aquatic life buried in toxic mud. Coastal marine life, including a nesting area for the endangered leatherback turtle, was threatened, as were coral reefs at Abrolhos National Marine Park, which includes a humpback whale breeding site.[241]

237 (Sonter, Herrera, & Barret , 2017).

238 (Pena, Goulart, & Fernandes, 2017).

239 (Woods, 2016).

240 (Snow Leopard Trust, 2018). See also (Bayarjargal Agvaantseren, 2019 Goldman Environmental Prize, Mongolia, 2019).

241 (Miranda & Marques, 2016).

To summarize, mining in or near any highly biodiverse area, such as Indonesia or the DRC, poses direct and indirect threats to large numbers of species, including high-visibility vertebrates (mammals and birds) as well as reptiles, amphibians, and fish. Many of those species are endemic, and some are already threatened by other factors, including deforestation, hunting, poaching, and climate change. High-visibility marine invertebrates, such as reef corals, already face serious threats from climate change, and any harm from terrestrial mining can compound that challenge, not only to corals, but to the rich fish and invertebrate communities that depend on them.

The rich biodiversity of terrestrial ecosystems, representing the vast majority of the world's species, is directly impacted by ongoing mining operations within the most biodiverse areas on earth, adding to the cumulative impact of even more extensive pressures, particularly land conversion for crops, pasture, fiber, biomass, and extraction of fossil fuels and other resources, and placing at risk complex examples of coevolution and the range and volume of ecosystem services provided by terrestrial biodiversity.[242]

Wildlife Populations Found in Deep-Sea Nodule-Collection Sites

Only 15% of the world's species reside in the ocean. All but three marine phyla (Echinodermata, Ctenophora and Hemichordata) have relatives on land. Many of the species on the abyssal seafloor are new to science, but all are related to taxa found elsewhere in the ocean. By most qualitative assessments, the biodiversity of the deep ocean is deemed significantly lower than terrestrial biodiversity. The millions of plants, insect and vertebrate species known to comprise terrestrial biodiversity are absent, and the numbers of multicellular species and individuals per square meter are much lower in the deep sea than on land.

Like other abyssal ecosystems, the CCZ has a number of characteristics that need to be considered to understand local biodiversity. Compared to land, abyssal plains such as the CCZ have traditionally been described as relatively homogenous areas, formed by a steady "rain" or "snow" of sinking particles that cover the underlying crustal geomorphology with a thick layer of silt.[243] In ocean basins near continental margins, particles from terrestrial erosion delivered via rivers and submarine canyons form important components of bottom sediments. Farther offshore, as in the CCZ, the primary component is detritus from production in the overlying euphotic water layer.[244] The silt is typically soft for the first 10–30 centimeters, gradually hardening by about 50 centimeters, and extending downward sometimes for hundreds of meters.

While the term "abyssal plain," first used in 1880, suggests a vast and unchanging area, modern studies reveal considerable heterogeneity at smaller scales. High-resolution images show that the depth of the CCZ seafloor surface ranges from 3,950 meters to 5,150 meters, and that the area contains numerous shallow ridges and troughs, small depressions, and seamounts 200–500 meters high.[245] The topography of the CCZ can be seen in Figure 59.

Figure 59. Sample Seafloor Topography in the CCZ[246]

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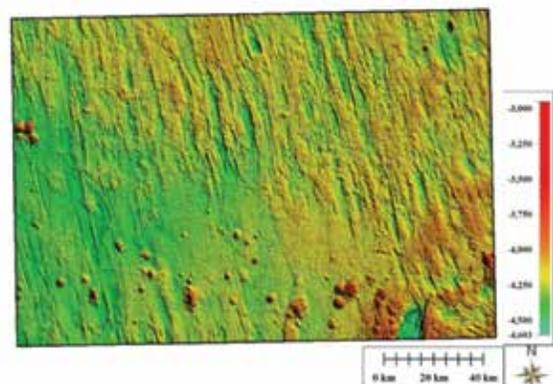
242 (Oberle, et al., 2019).

243 See https://en.wikipedia.org/wiki/Marine_snow. See also (Harris, 2012), chapter 6, p. 130.

244 (Simon-Lledó, Bett, & Veerle, 2019).

245 (Glover, Dahlgren, Wiklund, Mohrbeck, & Smith, 2016).

246 Bathymetry data for NORI Area D area of the CCZ. Seamounts and plateaus appear in dark red. Ridges and troughs visible as straight lines. Source: (AMC Consultants (A), 2019).

In general, currents at the seabed are slow. Sediment erosion and redeposition from physical processes are uncommon in the natural environment. However, there is evidence from the eastern CCZ that on geological time scales, and possibly annually, re-suspension and sediment transport events may be occurring (Smith C. R., 1999). According to (Smith C. R., 1999), the most ecologically relevant structures in seabed ecosystems are biological (e.g., formed by animal tracks or the tubes of animals) or the nodules themselves. Nodules host a distinct community, much different from that found in the surrounding sediments.

An unknown number of species—possibly as many as 100,000—of small animals, mostly crustaceans, worms, echinoderms, nematodes, and others are estimated to live on or in the top 30 centimeters or so of the seabed. Anemones, hydroids, sponges, and others, some very beautiful, are obligate residents on nodules that form in and on the top layer of sediment (see Figure 60).

In contrast to terrestrial habitats, the abyssal seabed of the CCZ contains no plants, mammals, birds, amphibians, or reptiles, and relatively few species of fish. Such vertebrates do inhabit overlying waters, to varying degrees and depths, where deep-sea mining operations are unlikely to directly interact with them at a material level. Indirect effects related to nodule collection (e.g., turbidity, sediment load, harm to marine food organisms, noise, light) could impact some pelagic or planktonic species, with intensities dependent on species, location, and other factors.

Figure 60. Fascinating Creatures in the CCZ Seabed[247]

247 *Top left:* Examples of megafauna found in the CCZ: (a) Holothurian, (b) Serpent star, (c) E Multi-nucleate, test-building single-celled organisms, (d) Soft coral, (e) Relicanthus, new order of Cnidaria, (f) & (h) Soft corals, (g) Photo credit: (Amon, et al., 2016).
Top right: Examples of meiofauna found in the CCZ include tiny species that live in between grains of sediment or sand. Photo credit: (McClain, 2010).
Bottom left: A close up of a relicanthus anemone moving across the bottom of the CCZ. Photo: Craig Smith and Diva Amon / ABYSSLINE Project.
Bottom center: Specimen of Plenaster craigi sponge attached to a nodule. Retrieved from a box-core sample at sampling site S04 in Ocean Mineral Singapore exploration area of the CCZ. Scale bar is 1 millimeter. Source: (Lim, Wiklund, Glover, Dahlgren, & Tan, 2017).
Bottom right: A sea cucumber on a bed of polymetallic nodules (credit: Diva Amon and Craig Smith). Source: (Grabowski, 2016).

Two deep-sea octopus species (not yet scientifically named, but probably vulcanoctopus) discovered in a nodule-abundant region of the Peru Basin abyssal seabed and on the deep Ka'ena and Necker Ridges of the Hawaiian Archipelago, use the stems of dead sponges attached to nodules for egg laying and brooding.[248] No deep-sea octopuses have been reported in the CCZ so far.

Roughly similar numbers of bacteria, archaea, and protista inhabit the top centimeter of terrestrial soil and abyssal sediments, on the order of 10^{14} cells per square meter, although it is not known whether all seafloor cells are functional.[249] Fungal cells appear to be much more abundant in soil than in abyssal sediments, and the many arbuscular mycorrhizal cells found in soil do not occur in abyssal sediments.[250]

Despite apparent equivalence in microbial numbers, the number of metazoan animals inhabiting the abyssal seafloor is several orders of magnitude lower than that of land, with far fewer total individuals and (likely) total species. Across 10 deep-ocean study sites reviewed, the mean total abundance of "large" organisms (those that can be seen without the aid of magnification) was 604 individuals per square meter, with a maximum of about 1,000.[251] In contrast, the abundance and diversity of terrestrial soil fauna seems to be more than a hundred times greater: the minimum estimated numbers of nematodes, enchytraids, colembolans, mites, isopods, diplopods, and earthworms yield a total of 232,420 organisms per square meter, as depicted earlier in Figure 54.

The reason for this difference in species abundance is a confluence of several factors present in the deep sea: great hydrostatic pressure, low temperature, perennial darkness, and limited sources of food. Each of these factors can slow animals' physical growth and reproductive rates. Together, these factors have caused the exponential decrease in the number and types of organisms living on the seafloor per unit area. Furthermore, no plant life exists on the CCZ seabed.[252]

The actual number of species present on or in the CCZ seabed and their geographic ranges remain unknown due to limited sampling. Furthermore, some taxa cannot be distinguished visually or morphologically and must be separated—or even discovered—using genetic techniques.[253] Investigations of the seabed are still revealing features of physical diversity in the CCZ bottom that enhance speciation, including slope, depth, and proximity to seamounts. Differential food availability owing to clines in surface productivity also contribute.

Land habitats and the abyssobenthic zone are so distant from each other, both in geography and in depth, that ore harvesting in one region is unlikely to affect biodiversity in the other. Only 60 types of flowering plants (seagrasses in shallow inshore waters), two types of crocodiles, one type of lizard (marine iguana), seven species of turtles, 60 species of snakes, about 360 species of seabirds, and 40 species of insects (all water striders of the genus Halobates) live in or on the ocean. None of these live at the abyssobenthic depth of the planned nodule collection. A small number of other flowering plants (mangroves, salt marsh grasses), euryhaline fish, amphibians (crab-eating toad and cane toad), reptiles, shorebirds, and mammals live in coastal habitats or sometimes enter shallow saltwater or brackish waters. None of these are found at abyssal depths or are impacted by events there, other than natural events such as a submarine earthquake.

No vertebrates are known to live on the abyssal seabed in an obligate manner, although there are some interdependencies among species from the different habitats. For instance, epifauna, dead organisms, and carcasses that fall from above are important sources of food for deep-sea fish such as rattails (grenadiers) and some sharks, although dietary information is not yet available for most.[254] Animals killed by nodule collection may provide benefit to scavengers, while simultaneously reducing food supply for predators.

248 (Purser, et al., 2016).

249 See (Bardgett and Van Der Putten 2014).

250 (Bardgett and Van Der Putten 2014).

251 (De Smet, et al. 2017).

252 See (Grosberg, Geerat, & Wainwright, 2012) and (Costello and Chaudhary 2017).

253 See, e.g., (Sinniger, Pawlowski, & Harii, 2016).

254 (Leitner, Neuheimer, Donlon, Smith, & Drazen, 2017).

Transient vertebrate species not resident in the specific nodule collection areas could be harmed by deep-sea nodule collection:

- About 120 species of mammals (e.g., whales, dolphins, porpoises, seals, sea lions, walruses, manatees, dugongs, and sea otters) live in the ocean. Given the low productivity of its surface waters, CCZ waters are probably not a primary feeding site for any of these, although deep-diving species such as sperm whales, beaked whales, and elephant seals might feed over seamounts.[255] Some species may transit the area during migrations, although the common pathways are closer to the coast. Loud noises from seabed collection machines, nodule-lift devices, and surface ships could affect the behavior of any marine mammals in the vicinity, though they can easily move out of range.

- Seabirds are often attracted to the solid surface and lights on surface ships, which could possibly result in collisions, injuries, or death. Birds can also feed on plankton or fish drawn to such lights.

- Sea turtles may rest underneath any stationary ships, endangering themselves if the ships begin to move.

The biodiversity of the abyssal plain has been on occasion described as "high," "distinctive," and "rivaling rainforests."[256] It is remarkable that so many species in the CCZ have been able to adapt to intense hydrostatic pressure, low food availability, low temperature, and perpetual darkness punctuated only by bioluminescent flashes. Because both the number of species present and the distribution and numerical abundance of their populations are still poorly known, definitive quantitative comparisons of biological diversity are difficult to make. However, qualitatively, current research on the CCZ ecosystems does not support these descriptions—the abundance and diversity of life on the abyssal seabed is not "high" when compared with that of a tropical coral reef, tropical rainforest, or indeed most coastal or terrestrial habitats.

The number of ecological niches available on the deep seabed is far more limited than on land. Conditions of the physical environment are much more intense, albeit relatively constant. Food supplies are much more limited, either in quantity trickling down from the euphotic zone, or in type (e.g., hydrogen gas, hydrogen sulfide, ammonia used by chemosynthetic bacteria that form the base of hydrothermal vent ecosystems). It is therefore not surprising that the kinds and numbers of multicellular organisms present are much lower than on land. Overall, it seems reasonable to conclude that wildlife in terrestrial habitats is more diverse and abundant than in the deep sea.

Diversity at local habitat and regional scales has been studied in the CCZ with focused investigation of specific animal groups at both organism and genetic level. Diversity and genetic preservation have been identified as a key issue by the International Seabed Authority in managing mineral development within the CCZ. This has led to the establishment of nine preservation zones (Areas of Particular Environmental Interest or APEIs) covering 34% of the CCZ area. The intent behind the APEIs is to protect CCZ biodiversity from possible future impacts from nodule collection and to create connecting habitats to aid recovery of mined areas (ISA 2011a, 2012b).

Mechanisms of Impact from Deep-Sea Nodule Collection

The dependence of CCZ deep-ocean fauna on nodule presence is significant. Video surveys found eight major groups living on top of the seabed, both sessile and mobile: hydrozoa (jelly-like organisms), anthozoa (e.g., anemones, stony corals), echinodermata (e.g., starfish, sea cucumbers), and porifera (sponges). Apart from nodule obligate species, most of the creatures were observed in both nodule-rich and nodule-free areas, but abundance was strongly dependent on the presence of polymetallic nodules; when nodule coverage was absent or sparse, abundance dropped to between one-half and one-

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255 Multibeam echosounder surveys using autonomous underwater vehicles revealed sequential depressions of indeterminate age ('recent geological past') at depths down to 4,258 meters on the abyssal seafloor of the CCZ similar in morphology to those inferred to be made by beaked whales in other areas (Marsh, et al. 2018). That depth is 1,200 meters deeper than any whale has been reported to dive, though biometric evidence suggests that beaked whale skulls could withstand that pressure. Nevertheless, the amount of food known to be available on or in the bottom would not provide adequate reward for diving 2.65 miles, so based on current knowledge, whale foraging would not appear to be an ecologically significant function for the CCZ bottom.

256 (Ramirez-Llodra, et al., 2011); (Miller, Thompson, Johnston, & Santillo, 2018); (Dybas, 1996).

fourth compared to nodule-rich areas.[257] Some species of xenophyophores, a poorly understood but probably ecologically important group of large (up to ~15 centimeters) agglutinated multinucleate foraminiferans found only in abyssal areas such as the CCZ, may also be dependent on nodules as attachment sites.[258]

Nodule collection is therefore anticipated to have both direct and indirect impacts on wildlife habitats in the deep ocean. It will impact all populations within a mined area and potentially beyond, as detailed in a recent summary.[259] Impacts will differ for different species and functional guilds (e.g., epifauna, infauna, deposit feeders, suspension feeders, predators, scavengers).[260]

Complete removal of nodules will kill the attached animals (e.g., anemones, sponges) as well as any eggs attached to the nodules or to the animals themselves. Partial removal of nodules will also reduce or slow down recolonization of mined areas for animals requiring hard surfaces for attachment, egg laying, or other purposes. As nodule collection machines are expected to disrupt the top 10 to 15 centimeters of seabed sediments, many megafauna, macrofauna, and some meiofauna and microfauna organisms (detailed above) in the path may be disturbed, smothered, or crushed.

Separate from but related to damage to the sea bottom and its inhabitants is the possibility of impacts to creatures living in the water column. Near-bottom water will be sucked into the riser pipe, and organisms will be harmed or killed by the approximately eight-to-twelve-kilometer round trip (depending on the collection site location within the CCZ) to the surface and back.

The most significant potential indirect impact relates to plumes. The nodule-collection process disrupts and suspends the top layer of seabed sediment ("plumes"). Plumes eventually resettle but the precise spread

area and resettling time is currently under study. This is important to understand for two reasons. First, if plumes spread outside the mining area, the total area impacted by nodule collection increases. Second, depending on the thickness of the plume blanketing, the impact of plumes could range from negligible to lethal to marine wildlife living in the impacted area.

Small-scale tests and modeling offer a range of estimates and predictions: earlier studies indicated that over half of suspended particles would resettle within several kilometers of the source region within 10 days, with the remaining particles transported outside the model boundaries. A 2013 study predicted that 99% of the plume mass would resettle within one or two months and at maximum within 100 kilometers of the mining head, with only the finest particles at risk of prolonged suspension.[261] A more recent 2019 study modelled plumes generated at fast discharge rates and current flow conditions to more realistically approximate the impact of a large nodule-collection machine.[262] This modeling showed that the greater turbulence increased particle aggregation and settling rates, with most of the suspended mass expected to spread between four kilometers under normal flow conditions to nine kilometers during the passage of an eddy.

Sediment plumes may smother or bury seabed organisms, cover nodules, hinder larval settling and survival, harm the feeding apparatus of filter feeders or mucous feeders, impact the ability of jelly organisms to remain neutrally buoyant, and reduce visual predators' abilities to hunt luminescent organisms.[263] Sedimentation rates from plumes are expected to exceed the normally low sedimentation rates characteristic of nodule-forming areas in the CCZ. It is possible that abyssal organisms occasionally experience elevated scouring or sedimentation caused by internal waves or passage of eddies. The existence of "benthic storms" lasting 2–20 days, with bottom currents up to 20 centimeters per second and

257 (Varnreusel, Hilario, Ribeiro, Menot, & Arbizu, 2016).

258 (Gooday, et al., 2017).

259 (Christiansen, Denda, & Christiansen, 2019).

260 See (Jones, Kaiser, & Sweetman, 2017) and (Secretariat of the Pacific Community, 2013).

261 (Wedding, et al., 2013).

262 (Gillard, et al., 2019).

263 (Robison, 2009).

sediment loads up to five grams per liter, has also been discussed. However, a review of previous studies of bottom currents found no evidence for resuspension of sediment particles, including in currents of 20 centimeters per second.[264] If they did occur, such natural sedimentation events could affect fauna positively, by maintaining sediment-free surfaces on nodules necessary for egg laying or for attachment of sessile organisms, or negatively, by burying nodules and epifauna and infauna. Existing adaptations, if any, that enabled abyssal benthos to endure such events could possibly help them survive mild sedimentation caused by nodule collection.

Current research shows that the maximal theoretical thickness of sediments precipitating from plumes would be about 30 millimeters.[265] The near-field sedimentation of above 20 millimeters is expected to drastically impact the deep-sea ecosystem.[266] Three millimeters' burial monthly for six months has variable effects, but instantaneous burial of one millimeter does not affect microfaunal species richness or abundance. Based on a precautionary approach, a one-millimeter ecological blanketing threshold value has been proposed, with the understanding that such threshold levels can only be reached if massive blanketing effects are accepted in smaller fallout areas of a few square kilometers inside designated collection areas.

Another concerning question is whether disturbance of sediments during nodule collection would release toxic metals into the water just above the seabed. This will likely not be the case in the CCZ. Diffusion of metal ions into water is limited by the oxic depth of the sediment layer, and the bottom sediments in the CCZ are oxic down to 200 centimeters.[267] Within these oxic sediments, manganese oxide efficiently binds other metal ions, including the potentially toxic ions of Co, Ni, Cu, Zn, Pb, and Cd, preventing buildup to toxic levels. Since only the top 15 centimeters are expected to be disrupted, it is unlikely that nodule collection

will disturb the reduced or anoxic sediments that lie far beneath. While nodules themselves also efficiently bind such ions (given their high manganese oxide content), the extensive oxic sediment layer remaining after their collection is anticipated to prevent levels of concentration of metal ions that would be toxic to fauna.

As sediment-bearing water from the riser is returned to the ocean, turbidity will also temporarily increase at the release point and ultimately above the seabed as particles settle. Returned water will have warmed by approximately 2°C during transport to the surface and will temporarily warm the local region around the outflow pipe. The chemical content of returned water may also differ from the water contents at its reinjection site. There will likely be small differences in the concentration of nutrients (N and P) and trace metals. Injection will take place at >1,600 meters, far below the euphotic zone, so nutrients will not affect primary productivity and are unlikely to harm any marine life. The concentration of potentially toxic positively charged metal ions is also likely to be low, since most will have been bound by manganese oxide in oxic sediments and nodules as discussed above.[268] Small differences in the relative concentrations of carbon dioxide, carbonate, bicarbonate, and calcite can be expected due to the changes in temperature and hydrostatic pressure experienced as lift water is pumped up and down, but this is not likely to harm mid-water or deep-water animals after water is reinjected. In all cases, local effects will be reduced by the constant forward motion of the ship. The very small amount of CO_2 released to the atmosphere as nodules are strained out on the collection ship will not harm marine animals (note these numbers are included in this paper's calculations of life cycle CO_2e emissions for metals sourced from nodules – see section on Climate Change).

Damage to surface waters (euphotic zone) is unlikely to occur, since sediment plumes created by nodule-collection machines cannot reach them, and since nodule lift water will be returned into deeper water.

264   (GSR, 2018); (Smith, Amon, Altamira, & Thurnherr, 2017).

265   (Jones, Kaiser, & Sweetman, 2017).

266   (Gillard, et al., 2019).

267   (Paul, Gaye, & Haeckel, 2018).

268   See (Paul, Gaye, & Haeckel, 2018).

In addition to potential damage from sediments, some water-column residents will be exposed to noise, vibrations, and artificial light, which could affect food finding and even cause deafness or blindness in some fish and invertebrates.[269] Lights can potentially repel, attract, or blind some organisms, or disrupt behavior in species that rely on bioluminescence for communication or interaction. Noise and vibration can attract or repel some organisms, and mask communication, navigation, prey detection, predator avoidance, or other responses.[270] Fish, sharks, turtles, and other organisms might aggregate under ships, as often occurs with floating objects. Trips to and from ports pose the risk of ship strikes on marine mammals, turtles, or other animals. Such risks might be mitigated via deck watches during daylight hours and reduced ship speeds when animals are sighted or when transiting sensitive areas.

The impact of nodule collection on CCZ seabed habitats would be material, even if difficult to size at this time. Researchers believe the vast majority of deep-sea animals have yet to be identified. We cannot predict how long the populations of different species will take to recover, or how effectively regional marine protected areas (MPAs or APEIs), local contractor no-take zones, partial removal of nodule cover, and other mitigation strategies can prevent potential species extinctions. Species most vulnerable to extinction will be the sessile megafauna that use nodules as holdfasts, sites for egg laying, or other purposes, though some mobile species, such as serpent stars, may recover quickly or even benefit from some disturbance.[271] Inhabitants of the deeper parts of the water column, which include thousands of species of jelly organisms, ctenophores, larvaceans, swimming mollusks, larval fish, and others, will be vulnerable to sediments extending upward from plumes (probably no more than 200 meters) or released in returning lift water. Given the significant volume of deep water and the difficulty of sampling it or retrieving specimens without damage, a complete biological inventory might

never be established. The situation is not dissimilar even on land where habitats are much easier for scientists to access. So impacts on biodiversity cannot be completely and definitively known.

Of further concern is that a future biodiversity loss may impact ecosystem function. A study of 116 deep-sea sites worldwide found an exponential increase in the rates of deep-sea ecosystem processes and efficiency as the number of nematode individuals (worms) and species increased.[272] The researchers hypothesized that bioturbation (reworking of sediments through burrowing, ingestion and defecation) caused by nematodes—and by extension, other infauna whose abundance correlates with that of nematodes—underlies benthic fluxes and redistribution of food within the sediment, increasing ecosystem functioning in mutually beneficial ways. If deep-sea sediments, which cover 65% of the world's surface, play an important role in global ecological and biogeochemical processes, loss of deep-sea biodiversity could impact sustainable ocean function.

This is speculative and of unknown scale, and it seems unlikely that nodule collection in an area accounting for less than 0.1% of the global seabed (for the one billion EV demand scenario) could damage whole ocean systems or earth's climate system, but environmental-impact studies compiled by nodule-collection companies as part of their application process for nodule exploitation contracts will have to address this issue.

Nodule cover in collection areas is not expected to be removed completely, with about 15% of nodule areas left unharvested and available for recolonization, albeit to varying degrees partially covered by mud or plumes. And while humans have impacted the deep sea in many ways, it currently does not seem likely that the CCZ seabed would be used for any other purpose after nodule collection.[273] Habitats may remain undisturbed in perpetuity, allowing unlimited time for recovery. In general, some species will recover quickly (years)

269   See (Miller, et al. 2018).

270   (Preston, 2019).

271   (Jones, Kaiser, & Sweetman, 2017).

272   (Danovaro, Gambi, & Dell'Anno, 2008).

273   See the comprehensive summary in (Ramirez-Llodra, et al., 2011).

from above impacts, while many, in particular species dependent on nodules, will likely require much longer time scales. But with the exception of global climate-heating effects, which will gradually become significant, the collection zones in the CCZ would probably remain undisturbed during the very long time needed for recovery.[274]

With further research, it may also be possible to design an effective substitute substrate for nodules. Nodules left behind by nodule-collection machines or those gradually raised by bioturbation would speed recolonization. Nodule cover does not need to be high to enhance species richness; once nodules were present, even in small numbers, they were colonized by numerous hard-substrate-obligate morphotypes.[275] Colonization by larvae could occur from up to 110 kilometers.[276]

The UN Convention on Biological Diversity and Sustainable Development codified the protected areas of representative marine ecosystems (Goal 14) at 44% as of 2018.[277] As nearly all of the abyssal plains are still undeveloped, it should be possible to preserve at least 50% of the area worldwide as part of the "half-earth" plan to avoid widespread biodiversity decline and prevent the risk of ecosystem services' collapse.[278]

Key measures already in place or currently being researched to minimize damage and speed recovery include:

- ISA-established network of large-scale protected areas as reserves for all representative species and habitats and sources for repopulation of damaged areas.[279]

- Mandated ecological set-asides ("no-take zones") by nodule collection companies. Provision of a sufficient network of large-scale protected areas and smaller-scale set-asides would reduce (though not necessarily eliminate) the risk that nodule collection could cause species extinctions. The relatively large ranges of most species studied so far support this statement.

- Leaving residual nodule cover behind in nodule collection areas. For example, DeepGreen expects to collect with 85% efficiency, leaving 15% on the bottom as loci for recolonization.

- Distributing artificial hard substrates, such as cobbles or artificial structures (e.g., ceramic, cement, or other), to accelerate recolonization by abyssal sessile organisms, as have been employed for shallow-water organisms such as oysters or coral.

- Smart design of collection gear to reduce plumes.

- Smart collection patterns to include areas to serve as refuges from nodule collection and plumes.

- Smart lift devices to minimize sediment uptake and thermal change.

- Smart lift-water discharge protocols to minimize thermal and turbidity effects on the euphotic and mid-water zones.

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274 See (Sweetman, et al., 2019). Their models predict that, by 2100, the abyssal zone (>300m) of the equatorial Pacific will experience a rise in temperature, slight reduction in dissolved oxygen content and pH, and substantial reduction in downward flux of particulate dissolved carbon, resulting in a threefold decline in microbial and nematode biomass and consequent fivefold decline in macrofaunal biomass.

275 (Amon, et al., 2016).

276 Based on data cited in (Wedding, et al., 2015).

277 (UN, 2018).

278 (Watson & Venter, 2017).

279 Expert-designed marine protected areas (MPAs) will allow at least 34% of representative habitats and biota to thrive and repopulate mined areas over time. Representatives from ISA and the scientific and international ocean law communities used geospatial analysis and expert opinion to design a system of MPAs to protect CCZ habitats and biota from unacceptable harm caused by nodule collection. They recommended to the ISA a network of nine replicated MPAs, each 400 by 400 kilometers, covering over 30% (1,440,000 square kilometers) of the total CCZ planning region. This system met ISA responsibilities for a precautionary approach to protect the marine environment; minimize socioeconomic impacts; protect all life stages and critical habitats for deep-sea biota; protect a full range of habitat types found within each subregion within an MPA; maintain minimum viable population sizes for each species; surround each MPA with a sufficient buffer zone; and demarcate each MPA boundary with straight lines for ease of recognition, monitoring, and enforcement. See (Wedding, et al., 2013).

Summary of Impacts to Biodiversity

Table 19. Biodiversity Impacts of Metal Production

		PRODUCTION FROM LAND ORES		PRODUCTION FROM OCEAN NODULES
Diversity	Med-High	Typical mining locations can be home to some of the most biodiverse areas of the planet.	Med-Low	The deep ocean contains substantial wildlife diversity, but far fewer species and less biomass than land habitats impacted by mining today.
Potential impacts	Med	Mine building and operations cause direct habitat loss at mine site and habitat damage at regional scales.	Med	Nodule removal translates to animal deaths (e.g., anemones, sponges) and habitat damage.
Severity of impacts	Med-High	Habitats are destroyed by mine development, pollution, and disasters. Species extinction risk present. By virtue of higher diversity and abundance of wildlife, impact severity may be higher.	Med	Some animals are killed in mining areas (and could be impacted outside direct mining areas by plumes). Species extinction risk present. By virtue of lower diversity and abundance of wildlife on the abyssal plains, impact severity may be lower. LCIA midpoint indicators linked to risk of biodiversity loss are all lower. More studies are forthcoming on long-term ecosystem impacts.
Overall	Med-High	**Medium to High Impact**	Med	**Medium Impact**

CATEGORY 4: SOCIAL IMPACTS

Social Impacts at a Glance

IMPACT CATEGORY
Social
• Land-ore mining has inherent dangers. Mining remains one of the most hazardous occupations in the world. This has historically led to significant levels of human fatalities, illness, and financial costs. Vulnerable populations are disproportionately affected, including children exploited by artisanal mines and underprivileged people in developing countries. By the nature of displacement of physical land sources, land-ore mining often affects indigenous cultures. • Producing metals from ocean nodules eliminates or reduces the social risks presented by land-ore mining. The primary inherent dangers with nodule production are those related to operating production vessels at sea. The only vulnerable populations affected may be those whose countries' GDPs are heavily dependent on mining cobalt, manganese, or nickel. There is no risk of cultural displacement.

Here we consider four broad categories of social impact:

• Human fatalities and illness

• Vulnerable populations

• Financial and social costs of human death and injuries

• Cultural disruption

Human Fatalities and Illness

At the highest level, land-based mining poses a wide variety of risks that are not present in nodule collection. Commercial deep-sea nodule collection operations have not yet begun, so there is no data on fatalities, injuries, or illness, but there is a reason to believe that the rate of fatalities, illness, and injuries will be less for deep-sea nodule collection. The closest proxy that could be used to approximate the impacts of offshore nodule collection, explored below, is offshore oil and gas—a sector that already has a much better safety track record than land mining. Unlike offshore oil and gas, nodules are inert and are not pressurized which makes them easier and safer to handle, leaving reason

to believe that the future track record of offshore nodule collection could be better than what is accomplished in offshore oil and gas today.

Below, we explore land-ore mining risks through documented historical sources, then compare these to estimated predictions of fatalities that could result from nodule collection and processing operations.

Mining is one of the world's most hazardous occupations, with typical fatality rates of 50 to 100 deaths per 100,000 workers globally.[280] In more highly regulated countries, like Australia and the United States, that number can range from 4 to 15.[281] Mining on land accounts for about 1% of the world's workforce (about thirty million workers), of which about 66% mine metals or other non-coal products. This 1% of the workforce accounts for about 8% of fatal accidents at work. Some estimates put the death rate at 12,000 to 15,000 officially reported mining-related deaths globally each year.[282]

Mining has historically been a source of injury and death:

- In 2016 and 2017, across all South African mines, an average of 7.15 miners died each month.

- In September 2015, in the Mabaya mine in the DRC, a mine collapse killed 13 people. Just a week prior, 18 others had died in a separate incident.

- In 2012, South Africa reported a fatality rate of 0.2% of workers who worked an average of 10 years, while 6% of such workers were injured. A mine collapse killed 20 people in the Makungo mine in the DRC. A shaft collapse killed at least 60 in Pangoyi in the DRC.

- In 2011, in an illegal mine in the DRC, 15 people died due to suffocation.

- A 2005–2007 study of a Zambian copper-mining company employing 15,000 people documented a fatality rate of 1.1% of workers who worked an average of 10 years, while 5.5% of such workers were injured.[283]

As suggested by these examples, most work-related deaths and nonfatal occupational accidents occurred in low- and middle-income countries, which typically have a high proportion of workers in risky jobs and low levels of automation. The International Labor Organization estimates the fatality rate in Central and Eastern Europe, China, and India is twice as high as in advanced industrialized economies, and selected hazardous jobs, including mining, can be 10 to 100 times riskier.[284]

Nevertheless, high-income countries also have a significant number of work-related fatalities. Between 1960 and 2005, across all mining sectors globally, there were 43 mine disasters with five or more fatalities, including 35 disasters in the United States, eight in Australia, and four in the United Kingdom. Beyond these disasters, in 2004 within the United States alone, "minor" incidents with fewer than five fatalities contributed 55 fatalities across 54 accidents.

Recent safety improvements have significantly reduced but not eliminated deaths and injuries. In the United States, deaths in the non-coal mining sector decreased from 233 fatalities per year in the 1930s to twenty-four fatalities per year by 2006, holding steady through 2010.[285]

The persistence of the mining risk is partially reinforced by the sheer quantity of potential hazard types given the nature of mining. The primary causes of deaths in underground mine disasters included flooding, underground gas, shaft collapses, ground collapse, asphyxiation, fires, and explosions. In the Zambian

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280 The estimate of 50 was arrived at by assuming ~15,000 mining deaths per year (The world counts, 2019) against a global mining industrial workforce of approximately 30 million, inclusive of non-hazardous job types. The estimate of 100 is an aggregation of statistics reported across several mines and countries, as described in detail below, corresponding to a fatality rate of 0.1%.

281 Australian mining employment and safety statistics available at: (Government of Australia, 2019), (Safe Work Australia, 2019). Safety records of 10.0 (2016) and 15.5 (2017) reported by the United States Bureau of Labor Statistics (BLS, 2018) for mining.

282 (Lang, 2010); (Earthworks and Oxfam America, 2004).

283 See (International Manganese Institute Risk and Policy Analysts, 2015), (Department of Mineral Resources, South Africa, 2017), (ENCA, 2015), and (ILO).

284 (University of Bergen, 2019).

285 (Mine Safety and Health Administration, 2019)

study, rockfalls were the main cause of death, and underground workers were the most vulnerable. Additional persistent dangers include handling heavy machinery and transport. Though most disasters occur in underground mines, risks cannot be eliminated by focusing on surface mines. In 2004, surface mines contributed three-fourths of US deaths from minor accidents.[286]

To estimate the potential mining-related deaths that could result from producing metals for one billion EVs using land ores, we compiled published statistics on mining deaths from numerous sources.[287] Death rates in developed countries ranged from 0.005% in Australia to 0.02% in US for non-coal mining; rates in other countries ranged from 0.02% in some South African mines to 0.1% in the Chinese coal industry, one Zambian copper mine, and South African gold mines. (Even the United States had a rate around 0.2% in the 1930s, a less-regulated era.)

Using representative rates with the top 10 copper-producing countries weighted by production volume, we estimate an aggregate fatality rate for copper mining of 0.09%, or five deaths per allocated megatonne of copper produced. Nickel and manganese are approximated as having the same rate, while estimating cobalt's fatality rate was more difficult due to lesser data transparency. The estimate for cobalt was divided into DRC artisanal mining (17% of DRC volume), DRC non-artisanal mining (the remainder of DRC volume), and non-DRC (40% of global volume). Non-DRC output was conservatively assigned the lower end of copper-fatality rates.

DRC overall and DRC non-artisanal fatality rates were extrapolated based on single-year statistics: at least 82 reported cobalt artisanal mine deaths over 13 months in 2014–2015, and at least 63 reported deaths in DRC mines in the first half of 2019.[288] The DRC cobalt data hints at a fatality rate comparable to copper ranges, but with a workforce population orders of magnitude larger

due to the nature of artisanal mining, the number of fatalities from cobalt dwarfs the other metals.

After allocating these numbers economically and scaling them to one billion EVs' worth of metal, in the static case we estimate around 4,500 fatalities using land ores, of which 83% are attributed to cobalt, 10% to copper, 6% to nickel, and 1% to manganese. We then assumed that the safety track record of the land mining industry would keep getting better as a result of technological and operational improvements over the next 30 years. Between 50%–66% reductions in fatality rate per metal output were assumed, as was a 50% workforce reduction in risky jobs per metal output due to technology improvements that increase productivity. These improvements offset any counter-effects from ore-grade decline. Under this dynamic case, we calculated 1,800 fatalities to produce metals for batteries and connectors for one billion EVs using land ores.

Fatality risks for the collection phase of deep-sea nodules will likely derive from two types of operations: at-sea production vessel operations (similar to the offshore oil and gas industry); and shipping operations to transport the nodules to shore. These two operational segments will likely face slightly different hazards, so we partitioned the nodule-mining fatality rate estimate into two parts to account for these differences.

First, we used statistics of marine fatalities and ship disasters from shipping operations as a proxy for nodule-shipping operations. Marine statistics were taken from Allianz and the European Marine Safety Agency (EMSA).[289] For shipping intensity of nodule collection, we assumed that a nodule collection operation producing and shipping 6.4 million wet tonnes of nodules per year 2,000 km for processing would require a nodule shipping fleet consisting of four ships, each with 18 crew. We then estimated the fatality rate in three ways: (1) Bulk carrier loss data from Allianz

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286   See (Seymour, 2005) and (Bråtveit, Moen, & Michelo, 2009).

287   See (Government of Australia, 2019), (Safe Work Australia, 2019), (Statista, 2019), (The world counts, 2019), (Hao, 2017), (Barrera, 2019), (Republic of South Africa, 2018), (Lang, 2010), (Earthworks and Oxfam America, 2004), (International Manganese Institute Risk and Policy Analysts, 2015), (Department of Mineral Resources, South Africa, 2017), (ENCA, 2015), and (ILO).

288   For 2014-2015, see (Amnesty International, 2016). On February 20, 2019, 20 deaths were caused by a truck collision resulting in sulfuric acid spillage (Patterson, 2019). On June 27, 2019, 43 deaths resulted from a landslide at Glencore's largest copper and cobalt mine (Hume, 2019).

289   See (EMSA, 2018) and (Allianz, 2015).

over 2005–2014 implies the risk of losing an individual bulk carrier is 0.0009, putting expected fatalities for a deep-sea nodule-shipping fleet at roughly one death every 16 years. (2) EMSA data reported 405 accidents with 683 fatalities in 2011–2017, translating to one death from the nodule-collection operation every 24 years. This may be an underestimate since not all ships in EU waters reported. (3) EMSA data showed 279 injuries and 25 fatalities during 2017 among 1,584 cargo ships, translating to one death every 16 years as an upper limit, as an unknown number of incident-free ships were not included in the cargo ships estimate. Note that these statistics may overestimate the fatality rate: marine-loss statistics skew high for older ships, whereas nodule-operation ships will mostly be newer builds. The average of the conservative first and third comparables is a fatality rate of one death every 15 years. For a dynamic estimate, a conservative long-term estimate assumes the second comparable with a 33% safety rate improvement by 2047.

Second, we used fatality statistics from the oil and gas industry as a proxy for likely fatalities resulting from nodule collection operations in the CCZ, i.e., for the crew of the collector ship and a support vessel. Three sources of data were used to estimate the likely fatality rates during nodule collection.[290] Based on global data on offshore operations from 46 producing companies, from 2009 to 2018 the fatality rate declined from 2.78 fatalities per 100 million worker hours to 0.97. UK oil and gas industry offshore-worker safety data shows an average of 124 fatalities per 100 million worker hours between 1996 and 2017, but with marked improvement in recent years due in part to technological and procedural improvements; the average from 2008 to 2017 was 0.98 fatalities per 100 million worker hours. The US oil and gas industry averaged 16 offshore oil and gas industry operation fatalities per year from 2003 to 2010, or an average of about 20 deaths per 100 rigs each year. Given an average crew estimate of 144 crew per rig, this amounts to 16 fatalities per 100 million worker hours. Almost 40% of these incidents were helicopter related, and another 10% or more were related to an oil and gas explosions. After adjusting for

these types of incidents (neither of which would occur in nodule collection operations), the relevant comparable figures are eight fatalities per 100 million worker hours. Notably, this calculation is from an earlier time frame than the most recent numbers reflected in UK and global data, so it is likely an overestimate.

These three comparables—0.98, 2.78, and 8 fatalities per 100 million worker hours—show that, most recently, globally and for the UK, the fatality rate has reduced, while in the previous decade, the proxy fatality rate was around eight times greater in the US and perhaps even higher globally. We adopt a conservative estimate starting at four fatalities per 100 million worker hours, with a total crew of 82 manning the collection ship and support ship. Given the marked safety improvements in the past two decades, this may be an overestimate.

Using these comparables, a single nodule operation may result in one fatality roughly every ten years. To put this number into context, 1,000 nodule operations would result in less than 1% of the current global death rate of the mining industry.

Allocating these statistics to each metal and scaling up to one billion EVs, we estimate 83 fatalities in the static case. Taking the assumption that, as with land ores, fatality rates may continue to improve in the next 30 years, we constructed a dynamic case for nodules. We set the 2047 rate of the first proxy, shipping, to the most optimistic comparable of one fatality every 24 years, and set the 2047 rate of the second proxy, oil and gas, much closer to the recent UK and global rates—1.3 fatalities per 100 million worker hours. Under this dynamic case, we estimate 47 fatalities to supply metals for one billion EVs using nodules.

Calculated total projected fatalities as a result of producing metals for one billion EV batteries and connectors, leveraging historical fatality data but projecting safety and productivity improvements:

- For metals produced from land ores:
  1,800 human lives

- For metals produced from nodules:
  47 human lives

290   See (IOGP, 2018), (Oil & Gas UK, 2018), and (Centers for Disease Control and Prevention, 2013).

Finally, in addition to accident-related death and injury, significant illnesses can result from land-based mining. Mining-related disabling diseases included pneumoconiosis, cancer, hearing loss, and the effects of vibration.[291] In contrast, illnesses resulting from nodule-collection operations are expected to be mostly limited to sea sickness and contagious diseases brought aboard by crew members.

The life cycle human toxicity CML LCIA indicator is one quantifiable metric that aggregates relative toxic impacts to the human environment related to the fate, exposure, and effects of toxic substances. Toxicity can result from ingestion, touch, or inhalation. This quantification takes into account releases of toxic materials into the air, water, and soil. Just as climate change impact is expressed as an equivalent CO_2e, with various emissions quantities converted into the CO_2 that would produce the same impact, human toxicity is expressed in units of 1,4-dichlorobenzene (DB) equivalents per kilogram of emissions. The human toxicity potential of biodiesel, as an example, is 0.487 kilograms 1,4-DB eq. per kilogram. Using Ecoinvent and the same literature sources for land ores, along with the LCA model developed for nodules, we estimate the direct and indirect human toxicity impacts. Due in large part to the zero-waste, zero-tailings design of nodule processing, its human toxicity measure is far lower than that of land-ore mining.[292]

Calculated total life cycle human toxicity impact as a result of producing metals for one billion EV batteries and connectors:

- For metals produced from land ores:
  37 gigatonnes 1,4-DB eq.
- For metals produced from nodules:
  0.3 gigatonnes 1,4-DB eq.

Vulnerable Populations

Ore mining and processing ranks as the second-most harmful industry to human health. It is estimated that the health of nearly 7 million people is at risk from mining and ore-processing sites in the low- and middle-income countries investigated. Exposures to lead and chromium alone result in 450,000 to 2.6 million disability-adjusted life years (DALYs), but owing to data limitations those estimates do not include health outcomes associated with other metals. The real DALY impact of mining is likely much larger.[293]

Several types of vulnerable populations are particularly exploited and exposed to these risks of illness and death. A majority of mining operations occur in developing countries, leading to disproportionate exposure for children and underprivileged workers in these countries. Industrial fatalities and injuries, including in the mining sector, are furthermore most common in these countries.[294]

Such risks in developing countries arise in part from a lack of well-enforced regulations. In addition to the 30 million people officially employed in mines, another 6 million people (20%) work in small-scale artisanal or informal mines, which do not tend to comply with national or international labor standards.

For instance, informal mining in the DRC, producing 17% of the country's cobalt, is carried out by untrained workers, thousands of whom are children, with no regulation of labor or environmental impacts.[295] Workers are exposed to unsafe conditions, with mining areas often controlled by militias. Injuries, fatalities, lung problems from dust inhalation, ingestion of polluted water and food, and skin diseases from direct contact with polluted water are common. Miscarriages and infant deformities are associated with fathers who work in mines.[296] In a recent study, blood levels of cobalt in the urine of children from a cobalt mining area were 10 times higher than in a control group. DNA damage was also found.[297]

Artisanal mines experience accidents at a rate six or seven times higher than organized company operations. A group of 180 miners studied for one year in the artisanal mining area of Lupoto in the province of

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291 (ILO) n.d.

292 (Science Direct, 2019).

293 See report by (Pure Earth and Green Cross Switzerland, 2016).

294 (Vidal, 2015)

295 (Hitzman, Bookstrom, Slack, & Zientek, 2017).

296 (Sadof, Mucha, & Frankel, 2018).

297 (Nkulu, et al., 2018).

Katanga, reported 392 injuries, and 72% of the miners were affected.[298] The problem is pervasive, as in some countries more people work in artisanal mines than in the formal mining sector.

As described in the Economic Impacts section, entire countries whose economies are resource dependent are also vulnerable to shifting commodity prices. Variability and uncertainties in resource supply and production costs and volume have a substantial impact on such countries. Land-based mining also experiences variability due to the risky nature of prospecting.

In comparison, metal production from nodules would likely employ no child labor; nodule-collection operations will not suffer from the human health hazards of mining; and nodule-based production is expected to experience greater predictability, and therefore less harmful impacts on vulnerable mining-dependent countries.

The introduction of nodule collection would affect the geographies of countries supplying the metals today. If this new supply is introduced into a market that does not grow quickly enough, there is some risk of displacing or challenging the current highest-cost producers. In particular, economies dependent on mining manganese could be impacted—although production in the most dependent nations is currently in the bottom half of the cost curve, hence less vulnerable. This is further addressed in the Economic Impacts section.

Financial and Social Costs of Human Deaths and Injuries

Human lives are not fungible, and it is impossibly difficult to assign a numeric value to a single life. There is however a body of work that attempts to do so: the "value of statistical life" (VSL) method. The VSL may be defined as "the amount that a group of people is willing to pay for fatal risk reduction in the expectation of saving one life."[299] It attempts to recognize the wages, standards of living, and other variables prevailing in different countries.

Using country-specific data, estimates of total financial costs of some land-based mining deaths include:[300]

- 143 deaths in 20 months of mining in South Africa (2016–2017): **~$150 million**
- 20 deaths at a copper-mining company in Zambia (2005–2007): **~$5 million**
- 19 deaths in Brazil tailings dam collapse (2015): **~$32 million**
- 126 deaths in the DRC (2011–2015): **~$9 million**
- 96 deaths in the non-coal mining sector in the US (2006–2010): **~$925 million**

Differences vary greatly among countries: a fatal injury in the UK was valued at around £1.6 million in 2016, while a life in Zambia is valued at about $0.25 million.[301]

Injuries are also a major concern for mining companies, owing to "lost time at work," as well as other possible social and financial implications. No comprehensive estimate of the cost of mining-related injuries and illnesses is available, but UK data suggests how much they might cost in a developed country: several weeks of injury or illness were valued at tens of thousands of British pounds in equivalent cost.

The geographies of future nodule-collection workforce are hard to predict, but combining the fatality, injury, and illness estimates along with country-specific death costs could give a sense of the financial costs of injury and death for nodules versus land ores. Given the discussion above, the fact that the occurrence of fatalities, injuries, and illness in deep-sea nodule collection will be several times lower than in land-based mining implies that the overall financial cost is likely to be lower as well.

Cultural Disruption

The United Nations Declaration on the Rights of Indigenous Peoples, the International Labor Organization's Indigenous and Tribal Peoples Convention, and the World Bank Operational Manual OP 4.10—Indigenous Peoples have validated and codified the special relationship and cultural bond of indigenous

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298 (Elenge, Leveque, & De Brouwer, 2013)

299 (Miller T. , 2000).

300 (Viscusi & Masterman, 2017).

301 (Executive, 2017).

peoples to their ancestral lands; the collective nature of that attachment; and the rights to practice their spiritual and religious traditions, maintain, protect, and access their religious and cultural sites, control their ceremonial objects, and repatriate their human remains.[302]

Mining and other development projects have frequently breached those rights, sometimes maliciously, other times through corporate ignorance of indigenous traditions, beliefs, and worldviews.

Complications arise from the fact that land is often owned by an indigenous community but parceled out for individual or family use over generations, with actual ownership residing with the community, which also retains memory of such agreements, often through oral tradition. Furthermore, mineral rights are separated from land rights and owned by the state. Unaware of traditional ownership patterns, corporations frequently coerce sale of parcels for mining or other development, destroying community structure, resource base, and abilities of others to maintain livelihoods. Indigenous inhabitants, who are generally poor and uneducated, have few resources to resist such incursions.

Examples below include cases involving metals other than the four metals studied in this paper since the issues discussed are applicable to the mining process in general.

- In Indonesia, 29 villages were critically affected by tailings from the world's second-largest copper mine, Grasberg Mine. Located in the highlands of Papua, Indonesia, Grasberg produced 1.2 million tonnes of copper in 2018. It also generated 700,000 tonnes of waste rock and tailings daily. Acidic leachate from waste rock covers eight square kilometers nearly 500 meters deep and leaches acid into Lorentz National Park. Tailings the color and consistency of wet cement were pumped directly into the Agabagong River, which flows into the Aikwa River and Arafura Sea. All life in the rivers was destroyed, and 90 square miles of rich freshwater habitats and wetlands were poisoned or buried. The damaged area could no

longer be used for fishing, hunting, or gathering forest products, including the Kamoro people's staple food, sago palm.[303] In 2008, Norway sold its shares in Rio Tinto, then the owner of Grasberg Mine, as a result of environmental concerns.

- In Guatemala, metal mining has had devastating impacts on indigenous peoples' land and resources, food sources, and culture. Mining activities have contaminated rivers, lakes, and groundwater; left toxic wastes that damage soils; driven away animals on which the people depend for subsistence; and devastated local ecosystems. These impacts have also impaired indigenous peoples' human rights, including their rights to food and water and their right to a healthy environment, and have caused dramatic loss of biodiversity in indigenous lands.[304]

- Throughout South America, mining operations have taken land illegally or unethically from indigenous communities, impeded free transit, and prevented indigenous people from using the land to raise stock and harvest subsistence resources such as firewood, mushrooms, wild fruits, natural materials for craft, and plants for culinary and medicinal uses. Mining has also wounded the forest, which in these people's tradition is the habitat of the spirits, the forces in favor of and against humans, and the place where one consults one's destiny and where one gets the answers for future decisions, as well as the mountains, which are sacred to high-Andean cultures as divinities whose supernatural powers care for and protect the inhabitants of the high plains and govern their destinies.[305]

- In Canada's vast Northwest Territories, mining companies have not understood fundamental principles of the worldview of the Dene people (also known as Athapaskan), who have occupied the land for thousands of years. Whereas the Dene people reject notions of discovery, claim, or domination over land as disrespectful behavior, resource-extraction companies have operated under the assumption that there is nothing wrong with taking what is there to

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302 (United Nations, 2007); (ILO, 1989); (World Bank Group, 2005).

303 For more information on the Grasberg case and the river of waste, see case study (MMSD, 2002) and (Perlez & Bonnerdec, 2005).

304 (Aldana & Abate, 2016).

305 (Pedilla).

be discovered and claimed in unoccupied wilderness areas. As one Dene elder explained, "There are no empty spaces. All spaces are used by something: fox, fish, trees, humans, wind, northern lights. It might look empty, but all is used." Also alien to corporations is the Dene cosmology that the entire landscape is alive with spiritual energy, which exists in all entities and flows in reciprocal directions as relationships between everything. All things associated with the land, including dirt and rocks targeted for mining, are considered sacred beings emerging from the landscape who have their own characteristics, power, and relationships with the Dene, who are mutually responsive to their attention, actions, and behaviors.[306]

- A few recent suits have ruled in favor of indigenous communities. In Xolobeni, South Africa, the Umgungundlovu community includes about 75 households and more than 600 people who raise their traditional land for food, grazing, water, firewood, medicinal plants, and livelihoods in agriculture or tourism. As the final resting place of many of the community's ancestors, the land has deep spiritual, religious, and cultural importance. When a large, open-pit titanium mine was licensed to operate on their ancestral lands, the community successfully sued to stop it. The court ruled that such projects require "free, prior and informed consent."[307]

- The 8,000-strong Dongria Kondh tribe has lived in the Niyamgiri Mountains of Orissa, India, for generations in a harmonious, sacred, and symbiotic relationship with nature. Their religion is based on respect for nature and traditional rules of restraint ("niyam") regarding everything that is acquired from nature, and their knowledge and secrets about the forest, plants, and wildlife are passed from generation to generation. One mountain, Niyam Dongar, is home to their divine god, Niyam Raja (King of Law). Felling trees on mountaintops is taboo and a sign of disrespect to that deity. In 2013, the tribe won a 10-year legal battle to prevent construction by the Vedanta Corporation of a three-megatonne per year bauxite mine that would supply ore to an alumina refinery. A 75 MW coal-fired plant was also planned to power the refinery. Central to the decision, which validated the Dongria Kondh's right to worship their sacred mountain, were the tribe's contentions that owning land on the mountain is central to tribe membership; that tree felling, mine construction, and blasting were an attack on their deity; and that removal of bauxite deposits, which sequester monsoon rains, would deplete the year-round mountain streams used for drinking and irrigation.[308]

While there is growing respect for the rights and beliefs of indigenous cultures, the nature of land-based resources provides little control over the location requirements for mining. The conflict between local cultures' rights and the mining industry is a fundamental, difficult to resolve tension.

In contrast to the impacts of terrestrial mining, the CCZ deep-sea nodule collection area has no direct cultural impacts, given their distances from human communities.

306 (Committee for Future Generations, 2016).

307 (Environmental Rights and Governance, 2018).

308 (George, 2014).

Summary of Social Impacts

Table 20. Social Impacts of Metal Production

		PRODUCTION FROM LAND ORES		PRODUCTION FROM OCEAN NODULES
Fatalities and illness	Med	Risks are significant and persistent. Fatalities and illness are common across diverse countries and mine types.	Low	Risks are low and derive from offshore production and shipping.
Vulnerable populations	Med	Child labor is an issue in artisanal mines. Underprivileged people in developing countries are disproportionately impacted.	Low-Med	Potential spillover effect on manganese-mining-dependent economies, although the more exposed nations are in the bottom half of the cost curve, hence less vulnerable. This issue is addressed in the Economic Impacts section.
Financial and social costs	Med	Costs are proportional to the occurrence of fatalities and illness, which are much higher for land ores.	Low	Costs are proportional to the occurrence of fatalities and illness, which is much lower for nodules.
Cultural disruption	Med	Greater risk of cultural disruption, as land-ore deposits frequently share locations with areas of cultural import.	Low	No known cultural conflicts.
Overall	**Med**	**Medium Impact**	**Low**	**Low Impact**

CATEGORY 5: ECONOMIC IMPACTS

Economic Impacts at a Glance

IMPACT CATEGORY
Economic Impacts
• Land-ore mining is characterized by higher costs, greater underlying uncertainties and timelines for prospecting, sensitivity to global commodity prices due to higher positioning on the cost curve, depletion of economical high-grade ore sources, and operational disruptions from disasters and accidents. Mining on land creates more jobs than nodule collection. Many of these jobs are hazardous, and some are exploitative.
• Metals produced from nodules are expected to fall in the bottom quartile of the cost curves. Combined with higher confidence levels around resource quantity and quality, shorter lead times for production, and a single international regulator (ISA), nodule collection could lower the overall economic risk associated with metal production. Nickel, cobalt, and copper supply would enter into growing markets. The manganese market may be disrupted, as nodules could become the single biggest source of manganese produced at a low cost. Potential industrial and national economy impacts from a broadening manganese supply may be partially mitigated by ISA-dictated, special purpose, royalties-backed funds targeted to benefit sponsoring states and developing countries impacted by the industry. Deep-sea nodule collection will create fewer though safer jobs that are, in aggregate, likely higher paying.

In this section, we take a broad view of the economic implications of sourcing metals from land ores and from nodules. The discussion is structured around four topics related to economic impacts:

• Metal prices, costs, and supply

• Job creation

• National economies

• Global economic risk

Metal Prices, Costs, and Supply

Prices are among the most observable life cycle impact indicators. In metal markets, as with commodity markets in general, insights into future metal prices can be offered through movements in production cost structures, as well as through the dynamics of market demand and supply.

Our analysis focuses on two aspects: the underlying cost structures of producing the four metals from land ores and from nodules, and the relative production volume of nodule-derived metals compared to projected supply and demand. We explore both topics on a metal-by-metal basis.

Cost curves (see Figure 61) are typically used in the mining sector to understand metal costs and pricing. A cost curve presents a visual way of viewing metal producers as a function of their costs. Producers are represented with their production volumes on the x-axis, ordered by cost on the y-axis. The highest-cost producers are placed at the far right of the curve; the cheapest at the far left; and the width of the bar indicates the production volume of the individual producer.

When lower-cost resources are depleted, higher-cost mines are developed until demand is satiated. The price level is then determined as a function of that satiation level. When demand and supply are in balance, the price level typically settles around the 90th percentile of the C1 cost curve.[309] In tandem, a metal producer's relative position on the cost curve determines how well it will weather a commodity price cycle: producers with low-enough cost levels remain viable, while producers with too-high production costs are forced to find ways to reduce their production costs or drop out.

Under a unit of demand growth, prices rise to settle above the level required to bring on an additional production capacity to satisfy demand. As such, formerly priced-out and therefore uneconomic production methods or ore bodies may become economically viable. Under persistent dips in demand, the price drops, and highest-cost operations at the far right may cease production or go out of business.

As a silver lining, with lower prices comes more pressure as well as opportunities to innovate, and this can potentially generate significant changes to the cost curve in the longer term.

Where do metals produced from nodules sit relative to current metal producers from land ores? An illustrative case is that of nickel, representing approximately 50% of the economic value of a mined nodule. Figure 61 shows the projected cost curve of land-sourced nickel in 2025, when a few nodule operations may be in full production.[310] Juxtaposed in red is the projected cost position of nodule-sourced nickel for a reference project processing 6.4Mt (wet) of nodules per year. Metals produced from nodules sit toward the far left of the curve; this means nickel is expected to be produced more cheaply from nodules than from most land-ore sources.

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309   A C1 cost curve shows direct unit cash costs for the primary product, as incurred from mining through recoverable metal delivered to market, minus the revenue from its byproducts.

310   This cost curve shows pro rata unit cash costs, which allocate operating costs using economic allocation methods as also seen in the LCA.

Figure 61. Nominal Cost Curve for Nickel, 2025 Projection, with Anticipated Cost Position of Single Nodule System Processing 6.4 Mt (Wet) of Nodules[311]
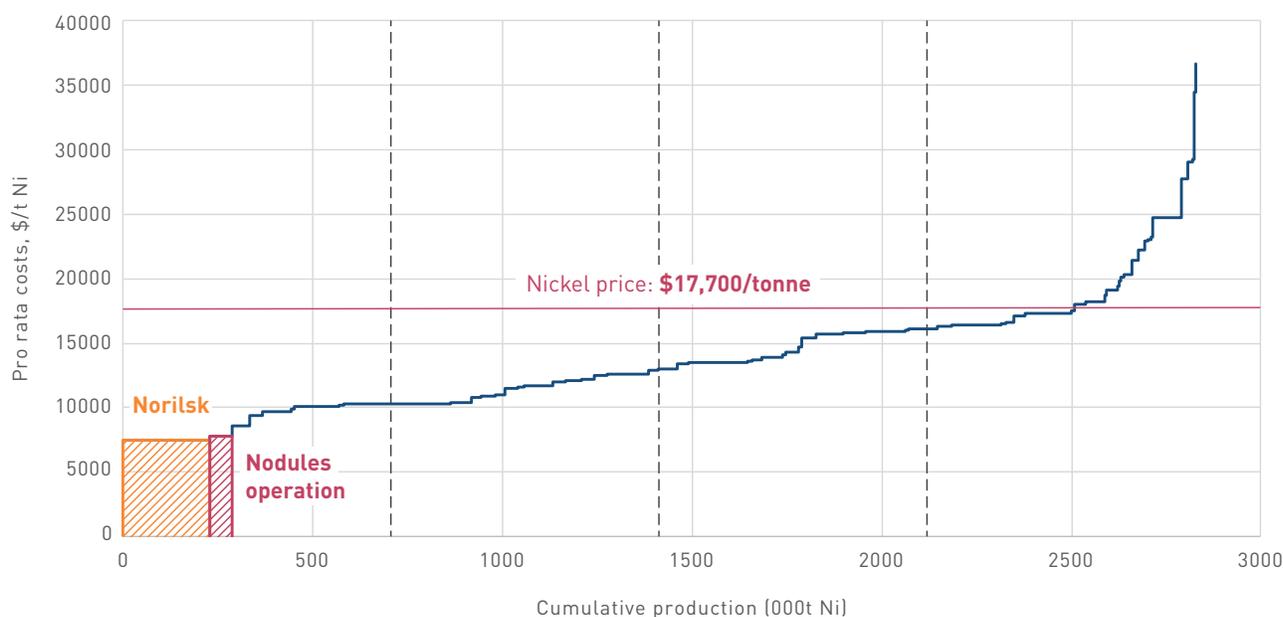
The lowest cost nickel producer today is the Norilsk mine in Russia, which supplies nickel at a lower allocated cost than nodules. Norilsk's large production volume has hovered around 200 kilotonnes per year for most of this decade, while a single nodule operation processing three to five million tonnes of dry nodules per year may output around 17%–30% of this amount (35–60 kilotonnes of nickel per year).[312]

What would happen to nickel prices if the nodules source is introduced? If demand remained the same, a new low-cost source (as with nodules) that shows up far to the left of the 90th percentile line will broaden the production that occurs below this line, shifting down the new effective 90th percentile line. Under a typical market response, this would likely cause prices to drop. The effect may also be amplified if the producer is extremely low-cost or its relative production volume is quite substantial.

However, if the new low-cost source enters a growing market demand, as is expected with nickel sulfate, the price-lowering pressure could counterbalance price-raising pressures from the demand growth.

To better intuit the potential impact that the broadened nodules supply could have on the metal cost curves, we look at the demand projections and market sizing. Satisfying the one billion EV scenario inherently leads to an implied metal-demand time series through 2047 for the four metals. Figure 62 shows these implied demands, as well as 2018 historic production volumes and 2035 projected demands. Note that the market is slightly different for each metal. Nickel sulfate demand in 2035 is 98% attributable to EV battery use.[313] Cobalt sulfate is a tiny market, also dominated by EV use. Copper and manganese are larger commoditized markets. Copper plays a large role in EV manufacture, while the role of manganese is relatively small.

311   Market assessments and cost-curve projections performed by (CRU International, 2019).

312   (Statista, 2019).

313   (CRU International, 2019).

Figure 62. Metal Demand to Satisfy 1B EVs Scenario, 2022–2047[314]
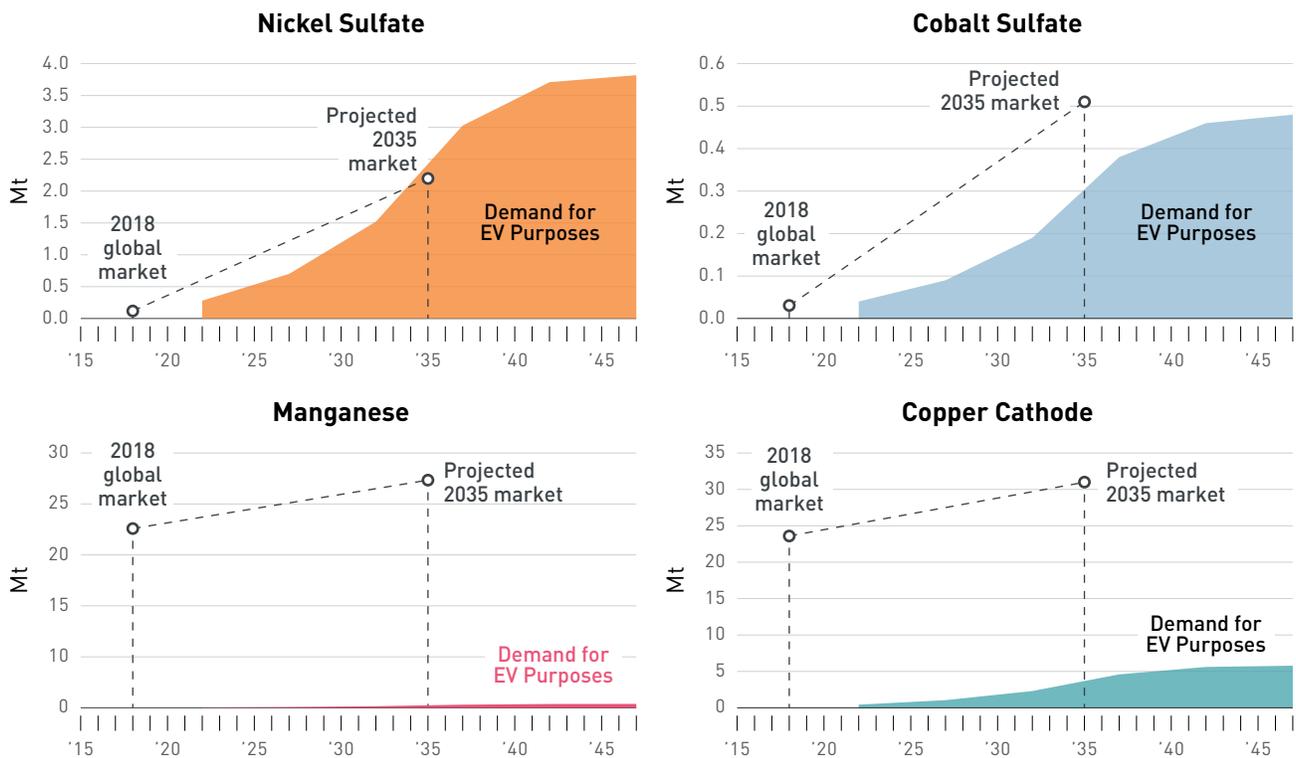
To link this analysis to the one billion EV scenario, we pick one metal against which to anchor our projections. After copper, nickel has the second-highest implied demand requirement. It is also the trickier metal of the two in terms of both production and market complexity: Class I battery-grade nickel sulfate is a small, niche market poised for high relative growth, whereas copper is a commoditized, existing market that is large relative to the new EV-driven demand. As nickel can be viewed as the real challenge to get to one billion EVs, we focus on nickel for the purpose of this market-sizing analysis.

We model a hypothetical future in which 100% of the nickel sulfate needed for the one billion EV demand scenario is satisfied using metals produced from nodules. The resulting projections are shown in Figure 63 in which a time evolution of new and total nodule

projects is plotted alongside EV-targeted nickel sulfate demand and the nodule-sourced supply. To keep pace with EV demand, between one and eight new nodule projects would need to be developed yearly through 2042. Assuming first operations began in 2025, after an approximately five-year initial ramp-up, by 2030 demand for battery nickel could be fully met by about 25 active partial- or full-scale nodule projects. Each full-scale project in this hypothetical model is assumed to process four to five million tonnes of dry nodules per year. Each of the current sixteen ISA exploration contract holders in the CCZ likely has enough resource to support multiple 4-5 million dry tonne projects inside their contract areas. By 2035, in this scenario 36 nodule projects in full-scale production mode, or 40 total effective projects, would be in place. The number of projects would theoretically peak at 71 in 2047.[315]

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314 EV projections based on (Morgan Stanley, 2017). Implied base-metal market demand assumes NMC-811 battery and 85 kilograms of copper required for harness and connectors. Nickel sulfate 2035 projection based on one billion EV demand scenario. Remaining 2035 market projections and 2018 market volumes taken from (CRU International, 2019).

315 Assuming phased ramp-up beginning in 2025. New nodule projects are assumed to ramp up to full scale of 4.36 megatonnes on average within three years - producing 10% during year one, 60% during year two, and 100% thereafter.

Figure 63. Nodule Operations Satisfying Morgan Stanley 1B EV Demand, 2022–2047[316]
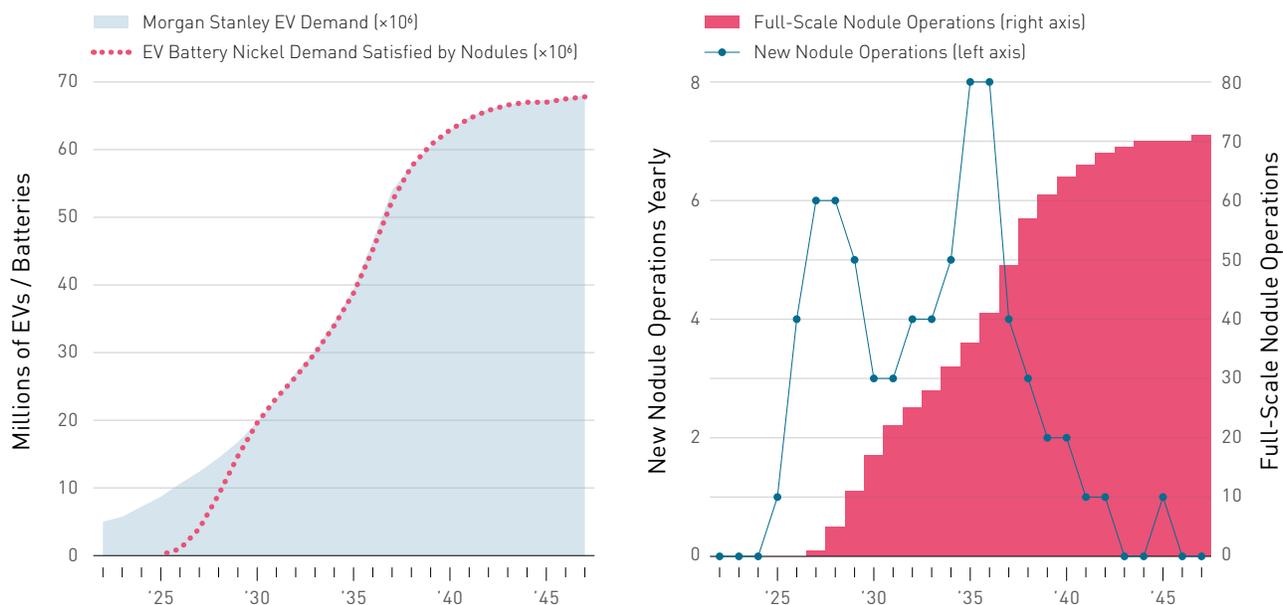
Note that in the market-sizing discussions that follow, we use projections at year 2035 rather than speculating out to 2047 when assessing the potential market impacts of nodule-derived metal supply. Nodule collection activity in five contract areas with three active projects each by 2035 seems plausible economically, technologically, and politically. Around three times as many (~40) would satisfy the full nickel sulfate demand for the Morgan Stanley projections for 2035. We use these two scenarios of 15 and 40 operations throughout this section.

Returning to nickel, 15 active projects by 2035 would produce a total of about 820 kilotonnes of nickel per year, or around four times the annual production from Norilsk today. Forty projects would produce around 11 times that of Norilsk.
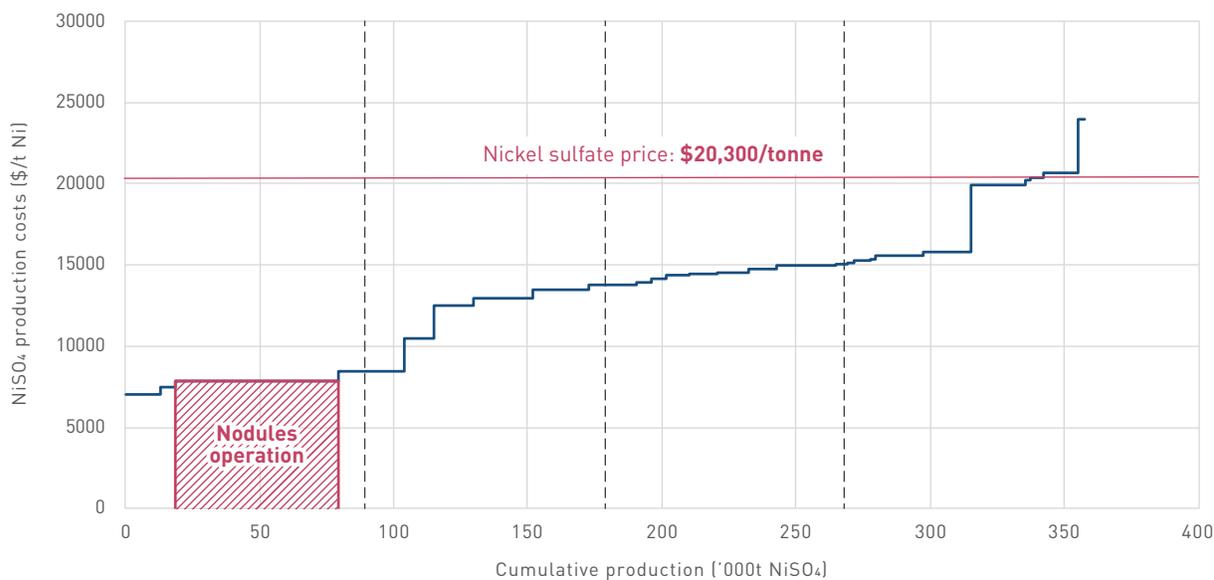
Since nickel sulfate is the nickel product market of relevance, we place these production numbers in the context of the growing nickel sulfate market. Battery-grade Class I nickel is driving the demand increase of nickel. The full nickel market is projected to grow from 2.3 megatonnes in 2018 (of which only 4% is presently turned into battery metals) to 4.5 megatonnes by 2035 (of which over one-third will be for battery metals). A large majority of this change is attributable to nickel sulfate, which is projected to grow by 17% per year, from 119 kilotonnes in 2018 to around 2 megatonnes in 2035.[317]

Figure 64 shows the pro rata cost curve for nickel sulfate, projected at 2025.

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316 Each full-scale nodule project is assumed to process 4.36 megatonnes of dry nodules per year, outputting 54.2 kilotonnes of nickel, on average. The equivalent satisfied EV battery demand is determined by dividing the total nickel output across all operations by 56.2 kilograms. New nodule operations are assumed to mature within three years, producing 10% during year one, 60% during year two, and 100% thereafter. EV demand numbers are inferred from (Morgan Stanley, 2017).

317 Two different estimates produce an expected nickel sulfate market of around 2 megatonnes in 2035. (CRU International, 2019) projects 1.8 megatonnes of nickel in nickel sulfate demand in 2035, of which 98% is attributable to batteries. The implied nickel sulfate demand from the one billion EVs scenario with scale-up as modeled in this section is 2.2 megatonnes of nickel in nickel sulfate for batteries.

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Figure 64. Nominal Cost Curve for Nickel Sulfate, 2025 Projection, with Anticipated Cost Position of Single Nodule System Processing 6.4Mt (Wet) of Nodules[318]

Nickel sulfate price: **$20,300/tonne**

Nodules operation

NiSO₄ production costs ($/t Ni)

Cumulative production ('000t NiSO₄)

The relative production volume of a nodule project (shown in red) versus present-day supply is apparent. However, under the stated projections, nickel sulfate demand would increase 15 times by 2035 and afterward continue to expand—the width of the cost curve would expand by 15 times—meanwhile 15 or 40 nodule operations would be at play according to our scenarios. Fifteen nodules operations in 2035 would supply almost 40% of the two-megatonne nickel sulfate demand. Forty nodule operations could supply 100% of the nickel sulfate for Morgan Stanley's projected EV demand, or 98% of the total nickel sulfate demand.

If the status quo of land-ore-based production is instead followed (i.e., nodules are not developed as a new source), barring a new influx of low-cost sources, the nickel sulfate filling this demand gap is expected to be produced from higher-cost processing routes. This includes production paths that use laterite ores that are currently more difficult to process into battery-grade sulfates, and those that expensively convert refined nickel into nickel sulfate. Many nickel

producers not currently producing sulfates would be expected to expand or adapt their production pathways to also output sulfates. Lower-cost sulfate producers typically have production pathways that can convert intermediates into sulfate, while higher-cost producers may use refined nickel such as powder and briquettes as the input, thereby absorbing the metal-exchange price plus conversion and delivery costs.

However, nominal prices of nickel sulfate are only projected to rise in line with 3% inflation: from $17,058 per tonne in 2018 to $28,227 per tonne in 2035.[319]

If nodules are introduced as a new source of base metals, as with any lower-cost market entrant, downward pressure could be placed on the price line and slightly flatten the cost curve. This can potentially induce highest-cost producers to reduce their costs or leave the market, as well as deter new entrants. In tandem with its effect on producers, nodule production can present a long-term positive effect on consumer prices, counterbalancing price-rise pressures as nickel sulfate demand increases.

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318 Market assessments and cost-curve projections performed by (CRU International, 2019).

319 (CRU International, 2019).

As one representative economics metric, we compare the 2025 projected pro rata cost of nickel sulfate produced from nodule operations versus the median pro rata cost using land mines.[320]

Projected 2025 pro rata cost to mine and produce nickel sulfate:

- For metals produced from land ores:
  ~$14,500 USD per tonne contained nickel (median)

- For metals produced from nodules:
  ~$7,700 USD per tonne contained nickel

Figure 65. Nominal Site Costs for Manganese, 2025 Projection, with Anticipated Cost Position of Single Nodule System Processing 6.4Mt (Wet) of Nodules[321]
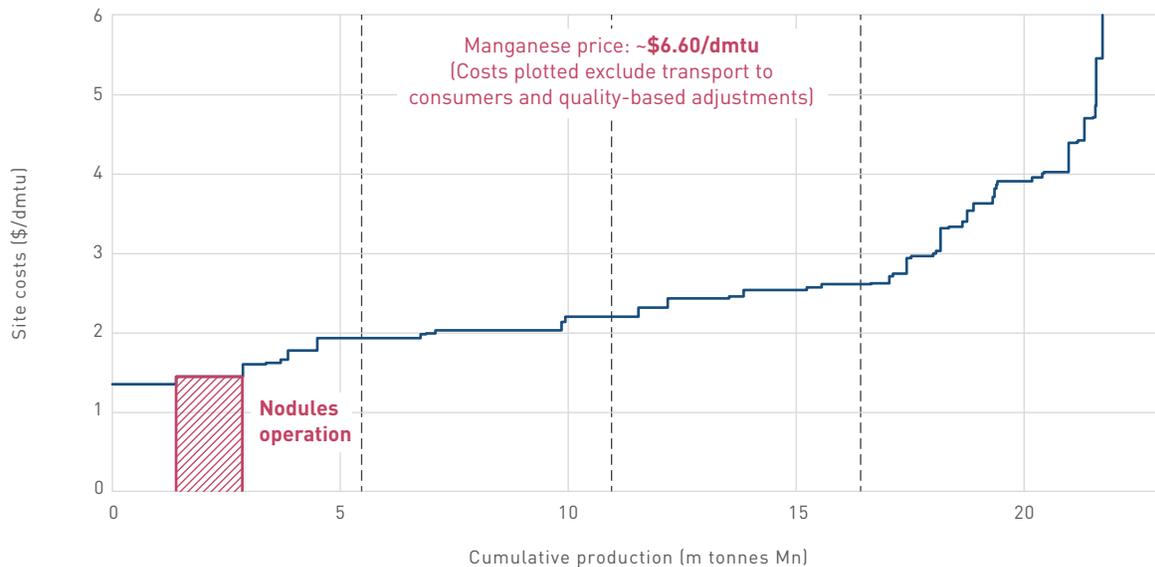
Manganese site costs per dry metric tonne unit (dmtu) projected to 2025 are shown in Figure 65.[322] Nodules again sit near the far-left side of the cost curve. Most of the highest-cost producers on the right side of the cost curve are based in China, while the smaller developing economies' producers tend to be lower cost. The manganese market is projected to grow at a modest 1.4% yearly rate, from 21.1 megatonnes in 2018 to 26.8 megatonnes in 2035. Manganese, with its high content in polymetallic nodules, would be produced in substantial volumes relative to the current market size. A single nodule project producing 1.4 megatonnes of manganese would alone supply 5% of the market by 2035. Five nodule-extraction areas, each with three fully operational production systems in 2035, would supply 19 megatonnes or 69% of the manganese market; forty operations satiating the nickel sulfate demand gap would produce 50 megatonnes of manganese, or 185% of the market.

The introduction of such a high-volume, lower-cost manganese source may significantly affect price dynamics; the possible impact of a broadened supply of a metal such as manganese on developing economies is discussed later in this section. A large influx of supply may in some cases exacerbate risks to national economies that rely on manganese mining and production. The outcome depends on realized demand increases, structural industrial shifts that may be triggered by changes in the supply landscape, and the characteristics of higher-cost producers.

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320 Median cost of non-nodules operations as projected by (CRU International, 2019) is used.

321 Market assessments and cost-curve projections performed by (CRU International, 2019).

322 Since most manganese operations do not produce byproducts, costs have been calculated on a site basis, therefore excluding ocean or inland freight to consumers and any quality-based pricing adjustments. Note that, in this graph, the projected manganese price sits much higher than the 90th percentile line—this is because site costs are a subset of unit costs.

Absent a large-volume, lower-cost source such as nodules, upward price pressures through 2023 are expected from underlying macroeconomic cost factors, but somewhat offset by new low-cost suppliers entering from South Africa and Gabon. In the long run, real prices are expected to slowly converge downward toward long-run marginal costs.

Next we turn to cobalt—a slightly unusual market as its supply is relatively inelastic to increases in demand or price movements. This is because cobalt is primarily produced as a byproduct of nickel and copper; cobalt market signals do not easily translate into supply increases. A high price or high demand for cobalt will not necessarily stimulate the development of new cobalt-producing projects, since the return on invested capital is primarily driven by nickel and copper prices. The supply of cobalt is therefore more closely linked to fluctuations of nickel and copper prices. Lacking its own agency, cobalt has volatile and spiky prices when the market is tight.

Demand for cobalt sulfate is projected to grow from 29 kilotonnes in 2018 to 510 kilotonnes in 2035, about 17 times higher. This is within the context of an overall cobalt market of 121 kilotonnes in 2018, projected to grow to 640 kilotonnes in 2035. The cobalt market would thus be dominated by cobalt sulfate, with the sulfate reaching 80% market share within 18 years, driven by growth in the battery market.[323]

Five nodule extraction areas with three active projects each by 2035 would produce around 80 kilotonnes of cobalt, or 16% of the cobalt sulfate market. Forty typical operations supplying the nickel sulfate demand gap could produce 215 kilotonnes of cobalt, or 42% of the cobalt sulfate market.

Absent the influx of a new lower-cost source as nodules, the cobalt markets are predicted to remain volatile. Cost increases are likely against the substantial increased demand.

Producing cobalt from nodules would potentially provide some counterbalancing effect to cobalt's price volatility, as nodules are a long-term resource with stable ore grade and more predictable volume. As we saw with nickel, the introduction of the nodule resource is poised to ease potential price pressures.

Figure 66. Nominal Cost Curve for Copper, 2025 Projection, with Anticipated Cost Position of Single Nodule System Processing 6.4Mt (Wet) of Nodules[324]

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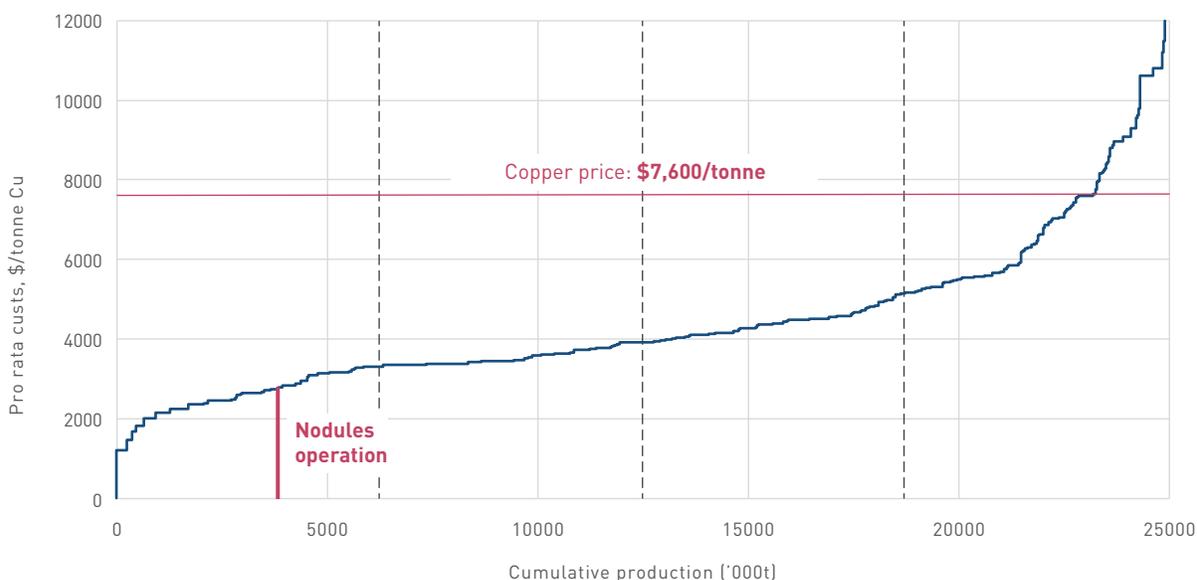
323   (CRU International, 2019).

324   Market assessments and cost-curve projections performed by (CRU International, 2019).

Finally, we look at copper. Nodules again sit in the bottom quartile of the 2025 projected cost curve (see Figure 66). Copper demand tends to follow industrial cycles and may also benefit from demand increases from the green transition, albeit to a lesser extent than nickel sulfate and cobalt sulfate given copper's larger market size and broad range of end uses. In aggregate, the copper market is anticipated to experience reasonable demand growth, from 23.6 megatonnes in 2018 to 31 megatonnes in 2035.

Five nodule extraction areas with three active projects each would meet 2% of the total global copper demand in 2035. Forty projects satisfying the nickel sulfate gap would meet roughly 6% of global copper demand, and 52% of the implied metal demand for EVs.

The price impact of introducing nodule-based copper should have a lower magnitude than may be expected with nickel sulfate or the other metals, given the relative market sizes. Copper value chain lacks the complexities of nickel, and it is price elastic, unlike

cobalt. As the copper product required for batteries and wiring is not niche, and nodule-based production volume would be relatively small compared to the total market, the effects of adding a nodule-derived supply to the growing copper cathode market are expected to look like a straightforward addition of a lower-cost supplier into a broadening demand.

Figure 67 summarizes the supply-and-demand market sizing for each of the four metals, relative to nodule projects, projected to the year 2035.

As a reminder, market projections are specific to the precisely defined scenario analysis exercise of one billion EV batteries and a single metal source type. It is not anticipated that 100% of metals will be sourced from nodules, nor that 100% will be sourced from land ores. Numerous factors and limitations will determine the final source mix. However, this type of single-source scenario analysis is useful in forming intuitions about the relative forces at play.

Figure 67. Nodule Operations versus Metal Markets in 2035[325]

(a) Nodule Operations to Satisfy EV Metal Demand

- Output from 40 nodule operations (Mt)
- Metal demand for EV purposes in 2035 (Mt)
- Number of nodule operations to meet EV demand in 2035
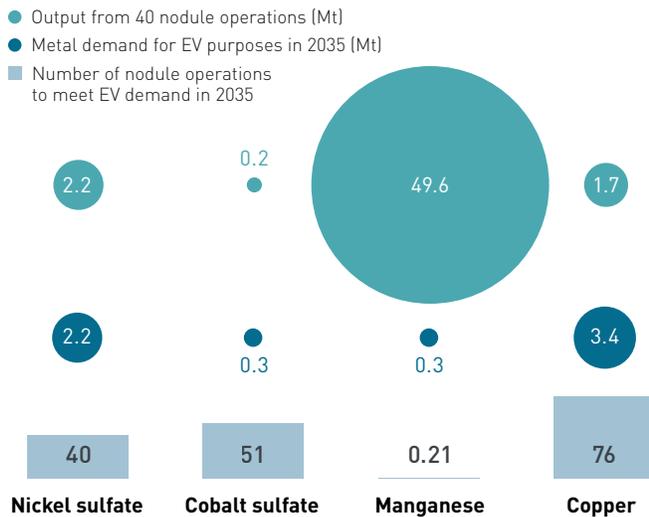
(b) Output of 40 Nodule Operations versus 2035 EV and Global Market Demand
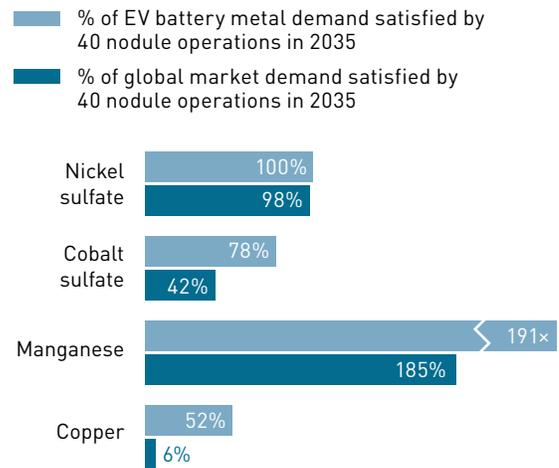
- % of EV battery metal demand satisfied by 40 nodule operations in 2035
- % of global market demand satisfied by 40 nodule operations in 2035

In summary, for three of the metals, production from polymetallic nodules seems to open access to a broader metal supply that is useful to maintain reasonable prices. It may also help ensure that dependent industries like EV manufacturers become and remain economically viable. Nodules seem likely to provide a favorable balance against upward price pressures and price volatilities for nickel, cobalt, and copper, to varying degrees.

In the case of manganese, if we assume static end markets, higher-cost producers would need to adapt their methods or risk loss of economic viability. It is also plausible that new end-use markets or novel products may develop, thereby broadening demand as the industry evolves.

Importantly, many costs associated with social and environmental side effects of mining have not been built into the land-ore-based cost curves. For instance, fallouts from tailings dam collapses and human deaths translate into actual monetary costs to producers. This leads large tailings facilities to be currently "underpriced," causing the products of such facility users and final metal products to therefore also be underpriced. This systematic underpricing may start to be rectified following the two recent disasters in Brazil: unit costs and price levels for land-ore developers would be expected to rise to reflect this, while nodule production costs would remain constant.

Job Creation

Extraction field operations for both nodules and land ores require a variety of management, engineering, technician, and manual roles. Both also generate indirect jobs, including construction of mining equipment, ships, and roads, and to varying degrees they can stimulate development in an ecosystem surrounding the operations. The processing and refining phases of the two production methods are similar, so there is not much of a difference in the quality or types of jobs in these phases between the two sources. Plant locations will be driven by similar forces—economic optimization—although the location flexibility of nodule processing also enables

greater opportunity for emphasis on environmental optimization during the site-selection process.

The primary contrast between jobs generated by the two sources will be in the number and quality of jobs in the resource-extraction phase. Nodule collection will likely create fewer but higher-paid and less manual-labor jobs. Land-based production will generally create more jobs that would be lower paid and less automated. Land ores may also generate greater indirect job effects in the supporting ecosystems developed around the physical mines. For instance, in Canada, the rate of additional indirect jobs is around 48% for mining and manufacturing.[326] Nodule collection, on the other hand, will dramatically reduce unsafe mining jobs as well as guarantee no child labor.

Below we examine the nature, quantity, and potential locations of jobs for each metal source, focusing on direct jobs in the extraction phase.

Land-based mining directly employs a variety of roles across the exploration, construction, and operation phases of a mine. This involves designers, engineers, manufacturers, and construction workers to design and build the mines, plants, machinery, and associated roads and infrastructure. Geologists and technicians explore potential sites and confirm the mineral richness of a resource. Engineers design the mines and equipment both on-site and remotely. Construction managers and workers clear the site, break through rock, and create scaffolding and other extraction infrastructure. Technicians excavate ore and separate valuable metal from mined ore. Equipment operators often work from control centers miles away, in addition to on-site manual jobs. Supporting office roles also include managers and technicians to plan and execute mining operations, monitor work conditions, maintain waste material, manage labs and services, and manage personnel.[327]

Looking at Australia as an example of a mature mining ecosystem, in 2013, 28% of workers across the mining industry held an advanced diploma (equivalent to three years of higher education, just below a bachelor's degree) or higher, compared to 38.9% across all

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326   (Mining Association of Canada, 2018).

327   (Holtcamp, 2019)

Australian industries. The top-five job categories were drillers, miners, and shot firers (54,900 employees), metal fitters and machinists (26,600 employees), truck drivers (14,500 employees), other building and engineering technicians (14,000 employees), and electricians (8,200 employees). The median weekly full-time earnings (in Australian dollars, close to 1:1 parity to the US dollar in 2013) were $2,071 for metal-ore mining, $1,825 for exploration, $1,500 for construction material mining, and $2,117 for other mining support services. Most of these were higher than the $1,152 weekly salary median across all industries, but below the $2,301 median salary for coal mining and $2,493 for oil and gas extraction.[328] In Canada, the average pay for a mining or production industry worker in 2017 was around (in US dollars) $1,800 weekly, notably higher than the manufacturing and construction sectors.

We can estimate the human effort required to generate metals for one billion EVs by simply considering the workforce employed by a country's mining industry and dividing it by the yearly metal output of that industry. Using the copper comparables leveraged in the fatalities calculations, we applied this logic to estimate human effort per kilotonne of metal output. Typical ranges for copper were between five and 15 worker years per kilotonne of metal. Note that these numbers are specific to the extraction phase of metal production; we are not including processing and refining phases, nor indirect jobs. After allocating the metals, a weighted mean estimate of 5.2 was obtained for copper. We also estimate 4.4 for nickel and reuse this estimate for manganese. Non-artisanal cobalt estimates ranged from 28 to 39—this number is higher due to cobalt's typically very low grades and high economic value.

The range of human effort per amount of contained metal is shown in Figure 68, along with the projected productivity improvements by 2035 and 2047 included in our dynamic study.

Figure 68. Direct Mining Jobs (Worker Years per Kilotonne Metal Output), Land Ores
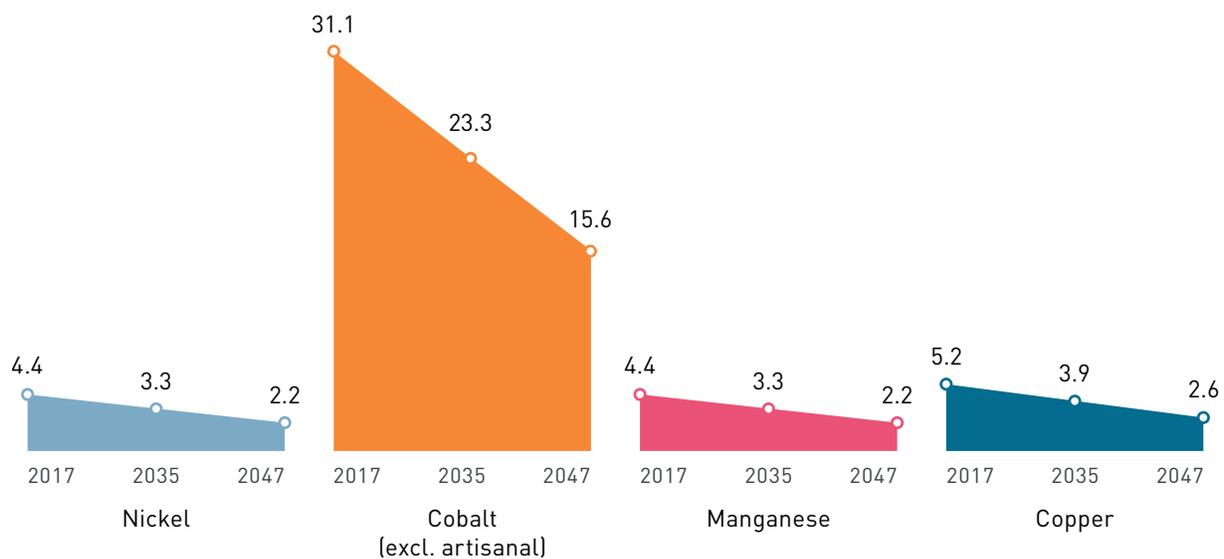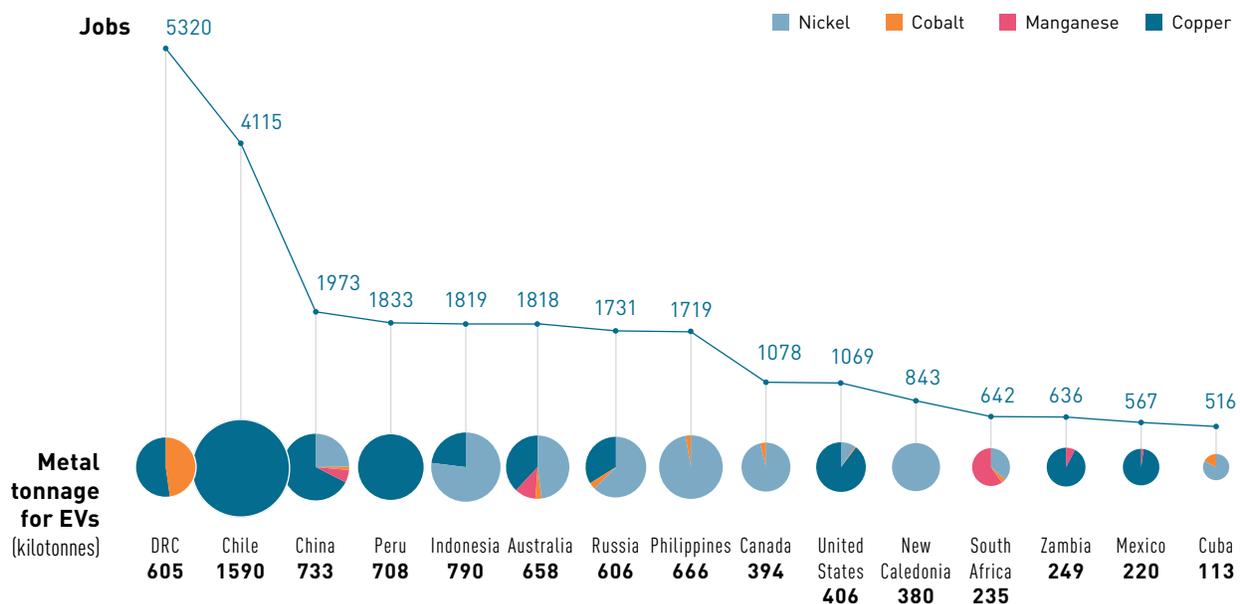
First assuming no dynamics, applying these rates directly, and scaling to one billion EVs—and notably excluding the highly manual-intensive artisanal mines of the DRC—yields an estimated 936,000 worker years to generate metals for one billion EV batteries and connectors using land ores.

We separately estimate the artisanal labor effort attributable to one billion EVs. Artisanal mines in the DRC employ an estimated 110,000–150,000 workers, depending on the season. If after allocating away byproducts we are left with approximately 75,000 worker years attributable directly to cobalt production from artisanal mines, the human effort associated with an 18-kilotonne artisanal cobalt output is 4,167 worker years per kilotonne of output. That is, cobalt from artisanal mines requires two to three orders of magnitude more labor than the other metals. If DRC artisanal mines continue to represent around 17% of the country's output, assuming constant productivity, an additional 2.65 million worker years of artisanal labor would be involved in reaching one billion EVs using land ores. This would raise the total from 936,000 to 3,590,000 worker years.

Next, we incorporate productivity dynamics. As mechanization, automation, and machine learning capabilities progress, mining industry trends have historically seen and continue to project efficiency improvements.[329] We assume 25% aggregate per-tonne productivity improvements by 2035 and 50% by 2047, halving the worker effort involved in producing the same kilogram, and subsuming any opposing effects from dropping ore grades. Under these assumptions, the total human effort to reach one billion EVs by 2047 is 600,000 worker years (excluding artisanal labor). Including anticipated productivity improvements, these projections correspond to an estimated 27,700 direct jobs in 2035, or 32,000 direct jobs at peak production in 2047.

Using US Geological Survey data and assuming 2017 country allocations of mine production, with worker-year rates as calculated above (geographically uniform by metal but dynamic over time), we estimate country-specific jobs for the one billion EVs scenario. Figure 69 shows the projected mining jobs directly created to supply battery metals in 2047. Juxtaposed against the job numbers for each country are the tonnage of metal being produced in contribution to the one billion EVs. (Once again, artisanal mines are excluded.)

Figure 69. Metal Production and Jobs by Country for Battery Metals, Following Morgan Stanley 1 B EV Scenario, 2047 Snapshot, Land Ores (Excluding Artisanal Mines)

Jobs: DRC 5320, Chile 4115, China 1973, Peru 1833, Indonesia 1819, Australia 1818, Russia 1731, Philippines 1719, Canada 1078, United States 1069, New Caledonia 843, South Africa 642, Zambia 636, Mexico 567, Cuba 516

Legend: Nickel, Cobalt, Manganese, Copper

Metal tonnage for EVs (kilotonnes): DRC 605, Chile 1590, China 733, Peru 708, Indonesia 790, Australia 658, Russia 606, Philippines 666, Canada 394, United States 406, New Caledonia 380, South Africa 235, Zambia 249, Mexico 220, Cuba 113

329   Characterizations of mining productivity dynamics can be found in Deloitte's Mining Outlook Report (Deloitte, 2019) as well as (Brandon, 2012).

If we estimate artisanal mine effort under the same productivity trend improvement, and again assuming artisanal mining would continue to represent 17% of DRC output, the total human effort to produce one billion EVs with land ores grows from 600,000 worker years to 2.3 million worker years. Between 86,000 and 117,000 artisanal DRC jobs in 2035, or between 148,000 and 202,000 in 2047, are attributable to mining EV battery metals.

Turning now to nodule collection, this new industry comes with a stronger focus on high-tech jobs, as well as jobs in construction, operations, maintenance, and ship transport. The high-tech aspect derives in part from the role requirements of collection-vessel personnel. These roles manage the control system of seabed collector vehicles and are similar to the command-and-control jobs found on offshore oil rigs. Around half of collector vessel jobs would be dedicated to such tasks, while the remainder would be standard marine operations jobs. The support vessel would employ engineers and maintenance crew to provide repair and maintenance services for the seabed collector vehicles. Meanwhile, transport vessels would employ personnel performing standard shipping functions. Additional ground-support teams would also support the offshore vessel operations.

Indirect jobs related to nodule collection would arise from the manufacture of the ships, as well as the high-tech efforts related to collector system research and development, product design, manufacture, and maintenance.

Nodule collection additionally would employ designers, engineers, manufacturers, and construction workers to design and build the ships, collection systems, plants, and machinery. Systems engineers would research, design, and manufacture the collection systems for bringing up nodules from the seafloor, while engineers and technicians would manufacture the large production and support vessels. A lower-level ongoing effort would be required for site exploration and seabed sampling, as expansive resources have already been characterized and identified as economically viable to mine.

Given the similar nature of job requirements for nodule collection command-and-control tasks, median salaries of nodule-collection operations are expected to more closely resemble those of the offshore oil and gas industry. In the example of Australia given above, this median salary was 20.4% higher than metal-mining salaries. In general, the standard of salaries for comparison for nodule collection is expected to be that of sophisticated oil and gas industries, which are higher in comparison to the lower-level and more manual-intensive mining-industry jobs in developing countries.

To quantify the jobs created by nodule collection, we focus on the direct operational jobs. Under the operating-fleet assumption described earlier, the operations team consists of 174 personnel: one collector vessel (crew: 52), one support vessel (crew: 30), onshore support (staff: 20), and a four-vessel shipping fleet (crew: 18 each). No future productivity gains are assumed for crew sizing dynamics. Allocating and scaling this number yields 150,000 worker years of direct extraction and shipping-operations jobs for producing metals for one billion EVs. This corresponds to per-tonnage human efforts of 1.4, 3.7, 0.03, and 0.5 worker years per tonne for nickel, cobalt, manganese, and copper, respectively, lower than those projected for land ores. Note that this number is sensitive to assumptions about the plant location; if, for instance, twice the shipping fleet is needed to ship nodules to a more distant plant, the workforce increases from 150,000 to 210,000 worker years.

In terms of geographic locations of jobs created by the nodule industry, the nature of this industry and operations lends itself to creating jobs dispersed among many international players. The ISA may likely impose some job-related obligations on contractors involved in polymetallic nodule collection, including requirements to train nationals from sponsoring states and developing nations in the skills needed to operate in these positions. Additional job and economic benefits for sponsoring states are described in the National Economies subsection. Note that environmental factors can also more easily play a role in driving which countries process and refine the nodules.

Estimated direct employment for extraction operations to produce metals for one billion EV batteries and connectors, including productivity dynamics for land ores:

- For metals produced from land ores: **600,000 worker years (if including artisanal: 2.3 million)**

- For metals produced from nodules: **150,000 worker years**

National Economies

Metal production from both land ores and polymetallic nodules can produce positive and negative impacts on national economies. On the positive side, higher demand for metal provides opportunities to create new jobs, drive up national incomes, catalyze innovation, and build up supporting industrial ecosystems. Sustained price drops can enable other metal uses to suddenly become profitable, with newly cheaply manufactured products appearing, sparking new innovations, creating industries, and making end products more affordable. Either narrow or broad populations may benefit from these developments.

While it is tempting to think about economics simply in terms of prices, and to assume that lower prices for consumers are generally a good thing, the full picture is more complex. If a country is dependent on high-cost producers—i.e., producers placed on the right side of the cost curve—this generates risk, since price drops could make those mining operations economically unsustainable, with potential direct consequences to jobs and GDP. Rising prices can similarly be disadvantageous, by tempting new high-cost producers to enter the market; if price rises are short-lived, these new players subsequently drop out of the market.

Figure 70. Gabon, Ghana, and South African Producers Low on Manganese Cost Curve (2018E)[330]
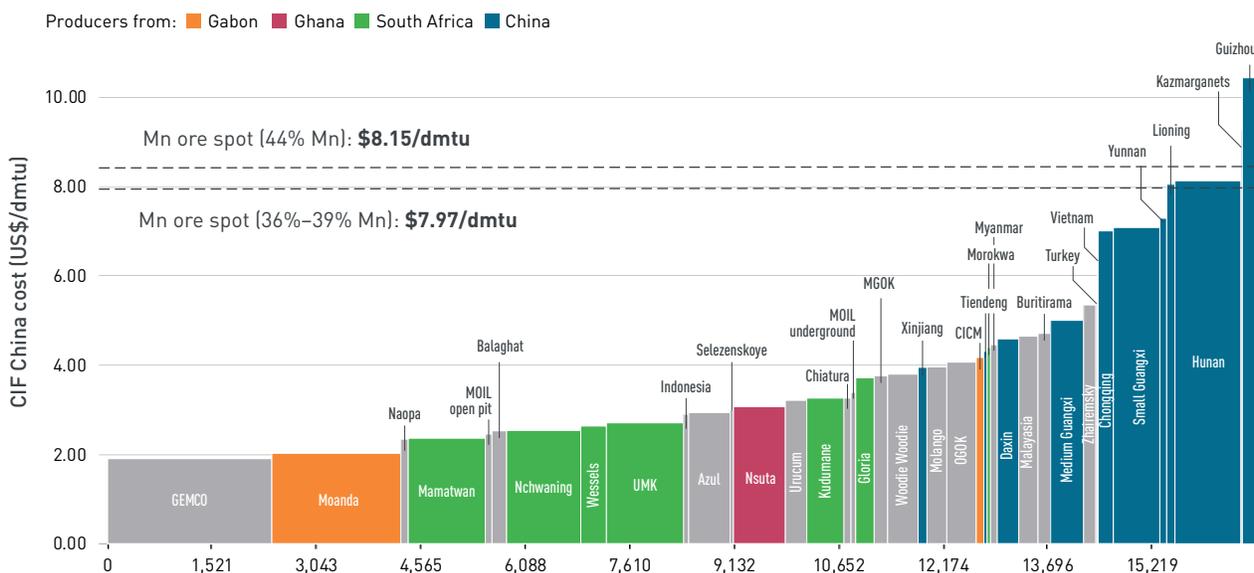
330 Cost, infrastructure, and freight (CIF) China costs are plotted per dry metric tonne unit (dmtu) of manganese metal in a 36%–44% grade manganese product. Spot prices for two standard ore-grade examples are shown. Source: (Bank of America Merrill Lynch, 2018). Producer-country pairs shown in gray: GEMCO (Australia), Naopa (Mexico), MOIL (India), Balaghat (India), Azul (Brazil), Selezenskoye (Russia), Urucum (Brazil), Chiatura (Georgia), MOIL (India), MGOK (Russia), Woodie Woodie (Australia), Molango (Mexico), OGOK (Ukraine), Buritirama (Brazil), Zhairemsky (Kazakhstan), and Kazmarganets (Ukraine).

Metal production can lead to vulnerabilities in national economies in multiple ways. Countries that are concentrated in a specific part of the value chain, that are less innovative and unable to adapt their technologies to changing industrial dynamics, or whose economies are too highly dependent on a single industry may also be more vulnerable. This can make an economy sensitive to commodity prices and shifts in reserve stores, and more likely to see shocks propagate throughout the country. Economic gains and losses are therefore typically not homogeneous, and sometimes one economy's gain is another economy's loss.

The introduction of a new, large, lower-cost supply of manganese is a case in point. Here, we look at three examples of how producing metals from polymetallic nodules may or may not lead to national economic vulnerabilities.

Some key national players in manganese production are Australia, China, Gabon, and South Africa. South Africa is a large resource player: it holds roughly 80% of the world's manganese reserves, including 92% of the world's high-grade manganese ore within its Kalahari Basin. For Gabon, the manganese industry accounts for 10% of its GDP and employs thousands of people.[331] Both countries may seem vulnerable to a large influx of new supply. In both cases, their mines are also at the bottom half of the cost curve, hence, while their profits would be reduced, the viability of their operations is less likely to be in question. South Africa's national economy is furthermore somewhat less exposed. Since its mines are largely owned by multinational companies, with most profits going offshore, its GDP becomes less sensitive to changes to the manganese industry.

Figure 70 illustrates large manganese producers and their relative positions on the manganese cost curve. Australia's GEMCO occupies the lowest-cost position. In general, African nations tend to be well positioned on the manganese cost curve, with that position offering some protection from the influx of new manganese supply. In contrast, China's mines are positioned higher on the cost curve. They are more exposed to potential drops in manganese prices. On the other hand, China's economy is diversified, and the manganese industry accounts for only a small fraction of its GDP.

Notably, such dynamics are not unique to the potential future introduction of nodules; these dynamics are present with the introduction of any new supply of a metal resource. Operations already high on the cost curve (i.e., to the right) face the risk that a new metal resource with lower unit cost may price them out. This may occur even in the absence of development of nodule projects—although to a lesser extent, unless a new source is as large as the nodule deposit in the CCZ. Negative economic impacts for either metal source may also be proactively mitigated: through collaborations in policy, offsets of possible job loss, involvement in the new nodule-mining industry, or targeted international support, as well as through ISA royalty policies.

A notable positive impact relates to the introduction of nodule production. There may be a large, sustained benefit to the national economies of ISA-sponsoring states as well as developing countries benefiting from the distribution of royalties collected by the ISA for the duration of nodule collection. Subject to specific sponsoring contracts, for many sponsoring countries, new income from nodule production projects could comprise a large portion (20%–60%) of their GDP. This will be true for many smaller South Pacific nations (such as Cook Islands, Kiribati, Nauru, Tonga) currently sponsoring ISA exploration contracts in the CCZ.

Note that such large-scale injections to a GDP should also be viewed with caution. The term "Dutch disease" was coined to describe the potential negative side effects as a country becomes resource rich, an apparent economic paradox named for the Netherlands' experience with natural gas in the 20th century. A country can experience loss of skill diversity across other industries, significant unemployment in other sectors, rising prices, and currency appreciation while mining is thriving. If the industrial structure shifts, producers are priced out, or resource income otherwise ends, a country lacking industrial diversity may struggle to absorb the newly unemployed. Because the CCZ nodule industry should be able to output nodules at meaningful rates for several decades, countries will have time anticipate and plan a transition toward less dependence on nodule-derived income in the long term.[332]

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331 (Postle, Nwaogu, Clark, & Heinevetter, 2015).

332 (AMC Consultants (A), 2019).

In addition, the ISA will collect royalties from all future holders of nodule exploitation contracts once they are in production. While the exact ISA royalty rate is still being negotiated, the median of scenarios currently under consideration is 2% ad valorem royalty on the contained metal value for the first five years, followed by 6% for the remainder of the project and an additional 1% environmental levy over the life of the project.[333] These royalties are to be equitably distributed to an environmental fund, among the ISA Member States, and to a special assistance fund for economies that could be negatively impacted by the CCZ nodules industry. To get a sense of the scale of these royalties, a single 4.36 megatonne per year operation would generate more than $2 billion per year in revenue, or $65–150 million in royalties directly to these funds. Forty active, mature projects in 2035 could generate as much as $5 billion per year for equitable redistribution by the ISA.

If nodules were the sole supplier of nickel sulfate for the full one billion EVs scenario, under the proposed scheme the total royalty fund (in nominal terms) generated through 2047 by supplying metals from nodules would be approximately $125 billion.

Against the backdrop of many economic benefits and some risks, the ISA has been notably proactive in attempting to offset negative economic impacts for countries' industrial development, jobs, national incomes, as well as environment. It has put forth requirements to ensure technology transfer to developing nations, involve sponsoring nations' workers in operations, compensate sponsoring states, and offset potential negative impacts to developing countries, as well as invest in further environmental studies.

There has not yet been a centralized, coordinated effort to hold land-ore-based mining operations in one country accountable for impacts on affected national economy of another country.

The introduction of nodules as a new source of metals would create several potential national economic impacts concurrently. Manganese is the main focus of the national economic vulnerability discussion with regard to nodules. ISA benefit programs are expected to attempt to counteract these negative impacts on the

one hand, while equitably distributing the economic benefits to developing countries, on the other hand. Relative extraction volumes of the other three metals would be far smaller, feeding clearly into markets where demand is growing so quickly that it will likely absorb the broadened supply. For those three metals, the broadened metal supply from nodules could help prevent price increases, increase resource predictability, and particularly for the case of cobalt, reduce volatility, with resultant national economic benefits.

Global Economic Risks

A number of risks are associated with any metal production operation. Fundamentally, risks translate to volatility in production costs and metal supply. These have direct impacts on prices to consumers and on industrial actors across the value chain—from individual mining operators to the countries whose jobs depend on them.

Volatility can come from variables like concentration and variance in resource supply, extreme events/ disasters, operations/technology, and politics:

- **Concentration of resources and supply chain** by few global powers can pose a very significant risk to the security of supply and resources.

- **Variations in resource availability** directly affect prices and output in the short run. Changes in mineralogy can clash with production-path designs, requiring further capital investment, which also raises costs and/or reduces yearly processing capacities, directly affecting prices and resource output.

- **Extreme events and disasters** may cause operational disruption and incur high costs, affecting metal supply and prices.

- **Operations and technology risks** can have both short-term and long-term price and supply effects: immature technologies may affect operations' reliability and hence capacity in the short run, while long-term risks arise if technology does not fully or cost-efficiently evolve and adapt to the evolving mineralogies and ore grades.

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333   Final Report on ISA Payment Regime for the Exploitation Phase of Polymetallic Nodules in the Clarion Clipperton Zone, MIT, June 2019

- **Political risk** is intricately entwined with the value chain and prices if there are changes to policies, laws, and regulations regarding metal production, exports, or the metal value chain.

Below, we summarize how each of these risks stacks up for production of metals from land ores versus nodules.

Concentration of resources and supply chain

- <u>Land ores:</u> **High risk.** There is a growing concern among several countries that a few high-volume producers such as China now control a significant portion of the EV battery material supply chain. This places global refined product supply and hence prices at risk, as such countries can use their control of the global supply as a geopolitical weapon—as China recently suggested it would begin doing with rare-earth metals. China accounts for 80% of global production of these metals.[334]

- <u>Nodules:</u> **Low risk.** The balanced international governance provided by the ISA helps secure production. The UN Convention on the Law of the Sea also enshrines anti-monopolistic provisions that will prevent an individual country from monopolizing the resources of the CCZ. Meanwhile, polymetallic nodules would broaden the supply and diversify its sources, further lowering risk.

Resource availability

- <u>Land ores:</u> **Medium to high risk.** Since locations, mining complexity, and resource quality are more highly variable or unpredictable in land-based mining, there is greater inherent uncertainty in yearly yield, and hence in prices. Land ores experience the risk of a mine not producing enough, or of processing costs being higher than expected versus projected sales and prices. Many undeveloped copper deposits are classified as complex, while there is substantial risk that cobalt resources may be depleted without a broadening of supply; the World Bank estimated in 2017 that climate-change-focused policies might increase cobalt demand sevenfold by 2050.[335] Resource quality is also decreasing, as the better

deposits have been developed and exploration success rates for new deposits have fallen off.

- <u>Nodules:</u> **Low risk.** In contrast, resource quantities are more easily and less intrusively surveyed. There is no lengthy, high-uncertainty prospecting process with low success rates. Engaging in nodule collection also lessens the cobalt-output risk by substantially increasing supply; the amount of cobalt in CCZ reserves is estimated to be three to six times greater than the entire terrestrial cobalt reserves base.[336]

Extreme events and disasters

- <u>Land ores:</u> **Medium to high risk.** There is risk of economic loss due to mine collapses, tailings-dam collapses, and other disasters, which can have extreme ramifications and are not uncommon. This leads to equipment damage, time and costs to reconstruct and restore, loss of operational days, and potential human health costs. Extreme weather events such as cyclones also have substantial operations impacts.

- <u>Nodules:</u> **Medium to low risk.** Risk of a comparable disaster to mine collapse, e.g., ship collision, is low. There is the risk of occasional extreme weather events, predicted to happen at an estimated rate of one hurricane every three years. This can be planned for, with fail-safe disconnect systems designed to move vessels out of the path of severe storms and return when they pass. Risks are possible equipment damage and loss of operational days, which would be factored into the development plans of most CCZ exploration contract holders.

Operations and technology risk

- <u>Land ores:</u> **Medium to low risk.** Technologies for mining are mature, some fundamentally unchanged for over 100 years. As lower-grade ores need to be developed, new technologies may evolve gradually. However, there is a longer-term risk that innovations may not keep up with long-term drops in ore grade. Many mining systems are reaching the limits of innovation; automation, artificial intelligence, and better system integration are currently driving

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334 (Financial Times, 2019).

335 See (Valenta, Kemp, Owen, Corder, & Lebre, 2019) and (Arrobas D. L., Hund, McCormick, Ningthoujam, & Drexhage, 2017).

336 (USGS).

efficiency savings, but there is a limit to what this can do without fundamental breakthroughs in mining and processing technology.

- Nodules: Medium risk. Nodule-collection technology is comprised of variations of mature existing technologies, but these integrated systems have not been proven for commercial-scale production and need further development to prove reliability. System reliability and further technology maturity tests are currently in progress. Long-term technology risk is low, however, because once technologies are proven, with its surveyed supply and measured ore grades, nodule collection is not anticipated to require risky or uncertain technology changes.

Political risk

- Land ores: Medium risk. Policies can change unpredictably with transitions of ruling parties or revolutions, particularly in developing countries. For instance, the DRC's pending ban on export of cobalt and copper concentrates resulted in a shift by major DRC producers to bring refining steps into the DRC.[337] The risk furthermore compounds with the numerous individual country actors.

- Nodules: Low risk. The International Seabed Authority is a single, unified intergovernmental authority regulating the collection of ocean nodules. Political risk of the mining value chain is therefore low, limited to a single entity concerned with protection of the environment and the stability and longevity of the industry, although higher-level supply chain risks may still arise.

Summary of Economic Impacts

Table 21. Economic Impacts of Metal Production

	PRODUCTION FROM LAND ORES		PRODUCTION FROM OCEAN NODULES	
Global Prices and Unit Costs	Med-High	Higher unit costs due to more energy- and personnel-intensive mining and purification from lower grades, as well as (for laterites) fewer byproducts. Smaller, concentrated, and/or riskier supplies cause price volatilities.	Med-Low	The lower unit costs of nodule-based production and broadened supply could shift the cost curve, flattening it slightly so that higher-cost producers are compelled to improve performance or leave the market. Metals would be produced into an expanding market, mitigating the risks of too low a price drop or flattening.
National Economies	Med-Low	Mining is already having a significant impact, both good and bad ("resource curse"), on developing economies.	Med-Low	Significant GDP contributions to sponsoring states and ISA royalties, with some of the funds channeled by the ISA as aid to negatively impacted economies. Most developing economies low on manganese cost curve, but some potential impacts if supply broadens without expanded demand.
Jobs	Med	Mining-related jobs with potential hazards remain, although greater automation results in efficiencies that require fewer workers.	Med	Fewer but safer and higher-quality jobs.
Economic Risk	Med-High	Greater risk from prospecting, uncertain future costs as resource availability and ore grades change, and significant risk of security of supply. Also substantial economic impacts from mine collapses and other disasters.	Med-Low	No ore-grade dynamics risk since the nodules are well surveyed. Extreme weather events are planned for and more rare. Some technology risk as product development is still under way.
Overall	Med	Medium Impact	Med-Low	Medium to Low Impact

VII. CONCLUSION

The urgent transition away from fossil fuels is driving a very large, transitional demand for base metals. It is critical that we source these large amounts of base metals with the lowest environmental, social, and economic impacts possible. In this paper, we focused on four specific base metals required for the electrification of the global passenger fleet and compared the impacts of two sources of these metals: conventional ores on land and polymetallic nodules on the seabed in the CCZ. While the focus of this paper was EV batteries, the availability of these metals is important for a plethora of other uses, including other renewable technologies, all of which face significant benefits if metals may be supplied from less-impactful sources.

By comparing the cradle-to-gate impacts of producing metals from these two different sources in depth, this paper focused on the question: How does conventional and green mining of land-based deposits compare to proposed projects to collect seafloor nodules as a source of supply for the anticipated expansion in metal demand? We examined all major categories of impacts: climate change (including global warming potential and carbon sequestration), nonliving resources, biodiversity, social, and economic impacts. Our analysis suggests that producing metals from seafloor polymetallic nodules could have significant advantages over land ores across nearly every impact category, with an important caveat: further environmental-impact-assessment work is required to baseline and evaluate the impact of nodule collection on seabed wildlife and ecosystem function.

Sourcing this large transitional base metal demand from land resources—by developing new land mines and ramping up production of existing ones—would risk further wildlife extinctions in some of the most biodiverse places on this planet, place an additional gigatonne-sized burden on the world's carbon budget, and put a substantial amount of stored carbon at risk—all at a time when we are struggling to reverse the relentless upward trend in the world's emissions. This significant increase in land mining would need to be offset by a gigatonne-scale carbon capture and storage solution, or we risk greater rises in temperature and other climate change impacts. More land-based mining will also mean more disruption of forest habitats; more long-term local land disruption and pollution; social displacement; more carbon-sequestration impacts; more freshwater usage, more groundwater pollution; more human death and decades-long human-health impacts. Some of these negative consequences could be mitigated by aggressively stepping up investment in energy and water efficiency, electrification of mining equipment, mechanization and automation, increasing efforts to prospect high-grade ores, and investing in revolutionizing current production methods. All of these strategies need to be pursued.

However, it is difficult to see how these strategies could match all the potential advantages resulting from sourcing metals from ocean nodules. The land mining sector is fundamentally challenged—ore grades are falling, production is moving to more biodiverse places, accessing ore bodies requires either breaking or tunneling through significant tonnage of waste rock, and toxic levels of heavy elements often found in land ore bodies still need to be removed, stored, and maintained indefinitely. Arguably, the main advantage of using land-based sources to meet the transitional demand in base metals is that it would avoid the need to disturb a large area of sparsely populated and insufficiently understood seabed in the CCZ by disturbing over three times smaller area of land—albeit that smaller land area carries much higher total biomass, biodiversity, and carbon storage capacity.

In contrast, sourcing this large transitional demand of base metals by developing the CCZ nodule resource would likely mean significant disruption of the parts of the CCZ seabed allocated for nodule collection as well as adverse job and national economy impacts in countries reliant on mining metals contained in the CCZ nodule resource. The ISA aims to protect the CCZ environment and biodiversity by designating 34% of the total CZZ area into nine preservation zones and further mandating each contractor to set aside

10%–30% of their contract areas as no-take zones. However, even if as much as 41-54% of the total CCZ area remains undisturbed, at this time not enough is understood about the CCZ ecosystems and its wildlife to be reasonably sure that biodiversity loss will be adequately mitigated, and ecosystem function and wildlife populations restored. More work is required on the efficacy of these measures.

Developing-economy impacts may be mitigated by programs planned to counter potential economic or job losses: several ISA sponsoring states from the South Pacific would get an opportunity to add a significant new source of GDP, and the ISA has taken further steps to ensure equitable approaches to ocean allocations, multinational agreements on best policies, and royalty distribution and support to sponsoring nations. A large number of issues present with land ores would be reduced, such as emissions burdens, energy consumption, and production costs, while many others could be virtually eliminated, including many land ecosystem services impacts, land disruption, groundwater pollution, cultural rights infringement, incidence of child labor, human fatalities and health damage.

In return for the host of benefits presented by nodule collection, the main clear and tangible negative impact is harm to organisms and ecosystems unique to the CCZ seabed. The trade-off is whether the environmental, social, and economic advantages of nodule-derived metals outweigh the environmental costs to wildlife inhabiting the CCZ seafloor.

Where should we source the transitional demand of base metals to make sure we build the world's greenest, most ethical EVs? More generally, how do we rebuild our world on better, more sustainable foundations? Every industry has a responsibility to take a data-driven, life cycle approach to examining the environmental, social, and economic impacts of supply chains it is part of. All stakeholders have the responsibility to formulate an educated opinion using the data available. It is our hope that this study has contributed to that education and data-gathering mission.

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