The Intersection of Mining and Decarbonisation: Challenges and Opportunities

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ABSTRACT

In the face of the climate crisis, a shift to a low-carbon economy is critical in preventing the loss of life and significant economic damage. However, the decarbonisation transition presents unique challenges, primarily concerning the supply and demand of critical minerals essential for technologies like electric vehicles, renewable energy storage, and hydrogen production. Certain "green" technologies require a significant increase in global mineral demand to be implemented even though they are pivotal in the fight against climate change. In particular, the high demand for batteries may stretch resource availability and production to its limits. This paper delves into the extraction constraints and emphasises the potential impacts if the demand for critical mineral resources surpasses the capabilities of the sector.

This paper presents optimisation solutions aimed at curbing the inevitable increase in mineral extraction. The goal is to manage its rate while adhering to supply and demand requirements based on confirmed and accessible mineral resources. The paper proposes the following practical strategies:

- the preferential use of electric bikes over electric cars to lessen the demand for minerals
- prioritising nuclear and hydroelectric power to reduce the dependence on battery-intensive renewable energy sources
- scaling up hydrogen capacity to offer an alternative solution for widespread electrification.

The paper also advocates for policy tools such as carbon taxes and renewable incentives which can play a vital role in reducing carbon production and achieving a balanced economic evaluation of technological alternatives in the field of energy generation.

Canada and Australia can play a leading role in the global shift towards a low-carbon economy. The paper offers strategic recommendations aimed at implementing policies that would effectively decrease the expected demand for minerals, aligned with achieving climate targets. These include enhancing key mining operations, fostering nuclear projects, instituting a comprehensive carbon tax system, expanding natural gas pipeline networks, and initiating partnerships with hydrogen vehicle manufacturers. Despite the complexities inherent in this transition, the paper concludes that with strategic planning and investment, nations like Canada and Australia can lead the global migration towards sustainable energy and transport systems, which will help lower the world's carbon footprint.

INTRODUCTION

The urgency of climate change necessitates a swift transition to a low-carbon economy (IPCC, 2022). This monumental shift involves moving from traditional fossil fuel-based systems towards renewable energy sources and sustainable transportation alternatives. Although such a transition is considered vital in alleviating the detrimental impacts of climate change, it presents significant resource availability and sustainability challenges. A major challenge is the balance of critical minerals supply and demand, essential for manufacturing renewable energy technologies and electric vehicles.

Researchers from various disciplines have explored the predicament of diminishing mineral resources and escalating demand for renewable energy. For instance, Wang et al. (2023) from The Breakthrough Institute meticulously analysed the total metal demand needed for power generation under different temperature mitigation scenarios. Their study underscores a potentially significant surge in the production of certain materials, such as neodymium, fiberglass, dysprosium, solar-grade polysilicon, and tellurium, to fulfil the growing demand for the manufacture of renewable sources of energy. Their research highlights the need for ramping up mineral production and fostering public policies that support mineral resource development for clean technologies. They acknowledge that recycling contributes to the solution but will have limitations in meeting the escalating mineral demand.

Mills (2019) provided an economic perspective on the green transition. Through comparisons of energy outputs from identical investments in natural gas and solar, the author showed that natural gas outperformed solar photovoltaics (PV) cells (used for solar electric panels) by 600%. Mills brought attention to the hidden costs associated with renewable energy, stemming from the need to balance the electrical power grid due to the erratic electrical outputs of power generated using solar PV, thermal, and wind turbine technologies. Mills (2019) illustrated the exorbitant costs associated with battery storage when compared with natural gas and warned of the slowing growth in renewable technologies, stressed the need for the substantial mining rates required for battery materials, and the relatively minor impact of electric vehicles on global petroleum demand. Considering all these challenges, Mills believes that hydrocarbons will remain the world's principal energy source for the foreseeable future.

Michaux's (2021) analysis conducted at the Geological Survey of Finland (GTK), presents an in-depth understanding of the impending metal crisis linked with decarbonisation efforts. It shines a spotlight on the massive volume of metals and minerals required to establish a low-carbon future. Michaux (2021) underlines the magnitude of the task ahead - transforming over 99% of the global vehicle fleets from fossil fuel-based vehicles to Electric Vehicles (EVs) and transitioning about 85% of our power generation from hydrocarbon-based to renewable energy sources.

Adopting a unique bottom-up approach, Michaux's report underscores the physical material requirements for this transition, contrasting the typical top-down method centered mainly around estimated costs and CO_2 footprint metrics (Michaux, 2021). His report evaluates the feasibility of the new global ecosystem and the long timescales involved in mineral extraction and the manufacturing cycles from invention to commercialisation.

Michaux's (2021) comprehensive analysis concluded that a vast number of additional power plants are required to fulfil non-fossil fuel electrical power needs, highlighting the practical limitations of such an expansion. It further explored the requirements of various non-fossil fuel systems as solutions to balance the demand, where each solution showcased clear advantages and disadvantages compared to each other and existing fossil fuels. One significant aspect of Michaux’s (2021) report highlights the importance of the material requirements for energy transition (i.e., moving away from fossil fuels), such as the mass of lithium-ion batteries needed for electric vehicles. Michaux’s research suggested a potential shortfall in global reserves is imminent to support the quantity of batteries required for the energy transition; emphasising the need to rethink the EV battery solution to be less mineral-intensive.

Overall, Michaux's (2021) analysis suggests that a significant reduction in societal demand for all resources will be necessary, highlighting that the existing renewable energy sectors and EV technology systems could merely be stepping stones to a different, and more sustainable solution. Michaux's work thus underscores the need for innovative solutions, realistic resource and timeline planning, and a comprehensive understanding of global energy demand and supply.

This paper presents optimised scenarios for decarbonisation that remains within the constraints of the available mineral resources and feasible production expansion timelines. The investigation is guided by the following crucial questions:

1. How much mineral resource is necessary for vehicles (both electric and hydrogen powered), power generation and battery storage in a low-carbon future?

2. What is the availability of these critical minerals based on proven resources and how much does production need to increase by?

3. What government policy decisions reduce total mineral resource demand?

In addition to the detailed analysis and scenarios provided in this paper, an interactive bespoke website is introduced, called Ausenco Energy InSite. This tool allows users to estimate the total metal demand under various circumstances and manipulate the variables discussed in the analysis, creating custom scenarios. This tool serves as an essential resource for stakeholders and decision-makers, offering a hands-on exploration of the complex dynamics between metal demand, decarbonisation efforts, and the potential constraints on resources. Examples of the global metals supply and demand in mining sectors in Canada and Australia are presented to demonstrate the tools effectiveness.

Key inputs to the paper and optimisation development

The analysis assumptions used in this paper are:

- sectors such as building heating, steel manufacturing, cement production, and other industrial systems will successfully achieve decarbonisation.

- common minerals/materials like iron, aluminum, and sand are not considered, even though their production rates are anticipated to rise

- the energy and metal demands from vehicles hinge on the distribution of vehicle types (whether hydrogen, EV, or electric bikes), the metal required per kWh of installed battery capacity/engine size, the distance vehicles travel, and their efficiency on a kWh/km basis, and the weight and kilometers travelled by long-haul vehicles

- energy demands for decarbonising power systems and industry are determined by current emissions, the power necessary to replace industries like steel manufacturing, and the current power distribution

- upon establishing the energy demand, the distribution of renewable energy is selected. This choice guides estimates for the total minerals required for those systems and the battery capacity needed for renewables

- the total metal demand is a composite of the minerals required to build EVs, hydrogen vehicles, power plants, and the battery facilities for the power plants.

Key critical minerals used for EVs, power generation, and batteries

Key minerals used for battery and power generation are shown in Table 1 as percentages of either battery mass or installed power.

Table 1 Basis for mineral demand for batteries and power generation systems.

Metal	Electric[1] vehicles	Stationary NMC batteries[2]	Offshore wind[1]	Onshore wind[1]	Solar PV[1]	Hydroelectric[1]	Nuclear[1]
	kg/kWh battery	kg/kWh battery	t/MW installed	t/MW installed	t/MW installed	t/MW installed	t/MW installed
Copper %	17.9	11.9	51.9	28.5	41.3	100.0	27.9
Nickel %	13.4	2.3	1.6	4.0	-	-	24.6
Manganese %	8.3	0.1	5.1	7.7	-	-	2.8
Cobalt %	4.5	0.6	-	-	-	-	-
Lithium %	3.0	2.5	-	-	-	-	-
Graphite %	22.3	24.0	-	-	-	-	-
Chromium %	-	-	3.4	4.6	-	-	41.5
Zinc %	0.034	-	35.7	54.1	0.4	-	-
Rare Earth Metals %	0.2	-	-	-	-	-	-
Silicon %	-	-	-	-	57.8	-	-
Others %	0.1	-	-	-	0.5	-	1.8
Non-Critical %	30.3	50.1	2.3	1.1	-	-	1.4

1. (IEA, 2022a)
2. (Michaux, 2021)

Analysis approach and optimiser development

Figure outlines the approach to metal optimisation: blue items represent inputs, green items signify intermediate results, and yellow items indicate the final metal demand. This approach follows the framework outlined in the Key inputs to the paper and optimisation development section. The analysis can be scaled to any level (local, country, global, etc), provided that the necessary information is available utilising the Ausenco Energy InSite website; however, this paper performs the analysis on a global scale.

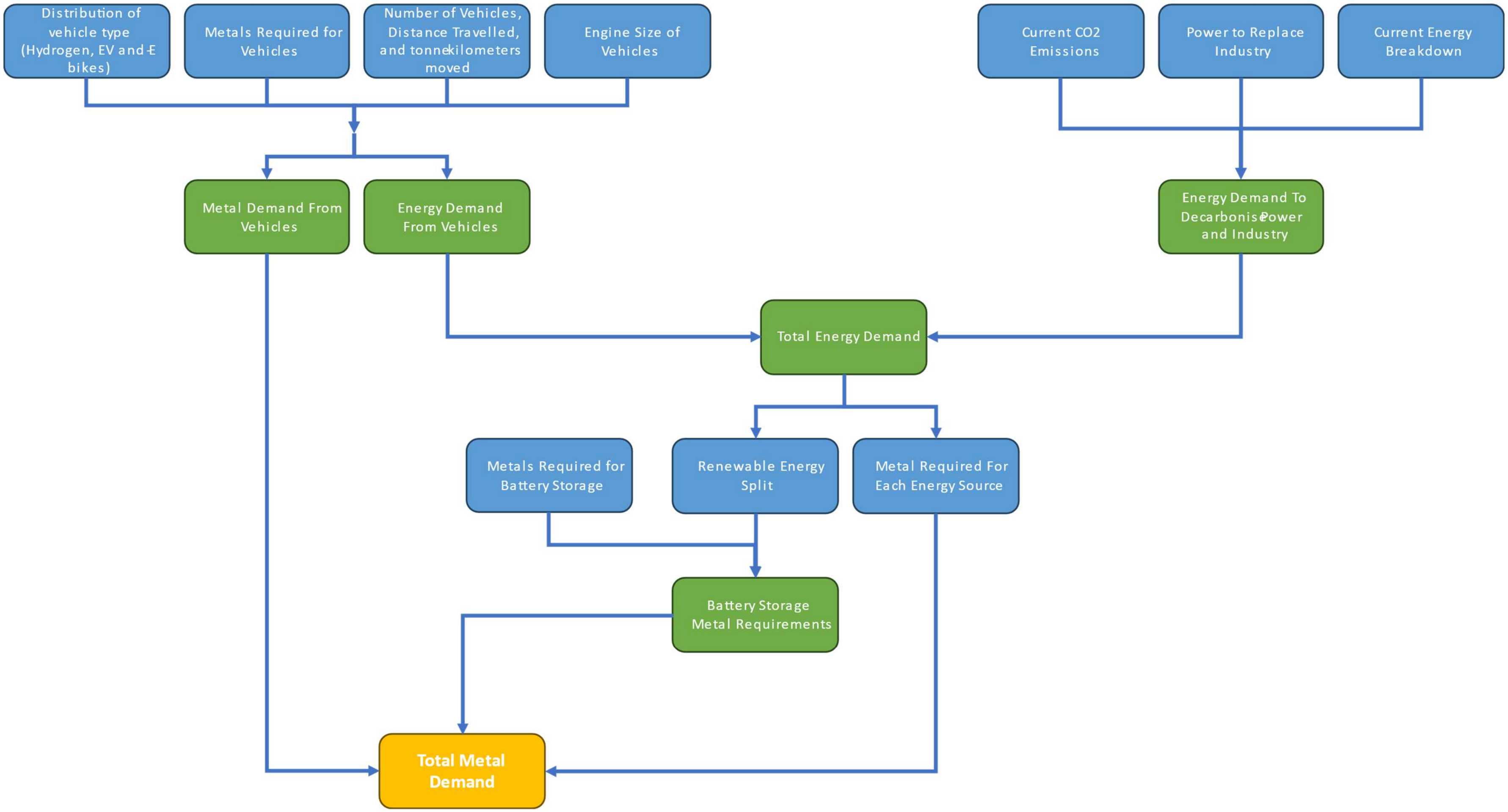

Figure 1 - Optimisation Analysis Flow sheet

Establishing the Baseline

According to the United Nations climate action mandate, the world needs to transition away from non-renewable sources to renewables to meet the 2050 climate action goals. (United Nations, n.d.). Secondary to the climate action goal is whether the mining industry can expand production at the rate required to meet the demand by the year 2050. Current climate models suggest that nearly complete reductions in CO_2 emissions are required by 2035 to restrict global temperature rise to 1.5°C. However, challenges present themselves due to the continually increasing CO_2 emissions (excluding the unusual years of the COVID-19 pandemic) and logistical difficulties associated with altering global systems.

The primary concern revolves around the capability of the mining industry to provide the necessary material swiftly enough to meet the 1.5 °C target, illustrated in Figure 2. The total demand for minerals, discussed in detail in the following sections, will determine the rate at which these materials must be extracted. Several key factors must be considered in the context of decarbonisation:

- the development of most mines takes between 10 to 15 years (from the initial drill hole), to market and raising funds for project development and design, construction and commissioning. (IEA, 2022c)
- power plants typically require up to 3-10 years for installation depending on the technology (from design to construction and commissioning) (IEA, 2022c)
- industrial scale decarbonisation cannot commence until these plants have been established and there is a sufficient supply of materials to sustain them.

Considering these constraints, to achieve the 1.5°C target within the next 12 years (from 2023), virtually all the minerals necessary for decarbonisation would need to be extracted immediately after the mining development time. The feasibility of this will depend on the total demand for minerals and the necessary increase in production. If meeting this demand is deemed impractical or impossible, the 2.0°C case allows a more gradual increase in production, in line with several countries' 2050 net-zero targets. In this scenario, a 27-year period is assumed (2023 - 2050). However, taking into account the optimistic assumption of a ten-year time frame for project development, the actual time frame to produce the necessary minerals decreases to 17-years shown in Figure 2.

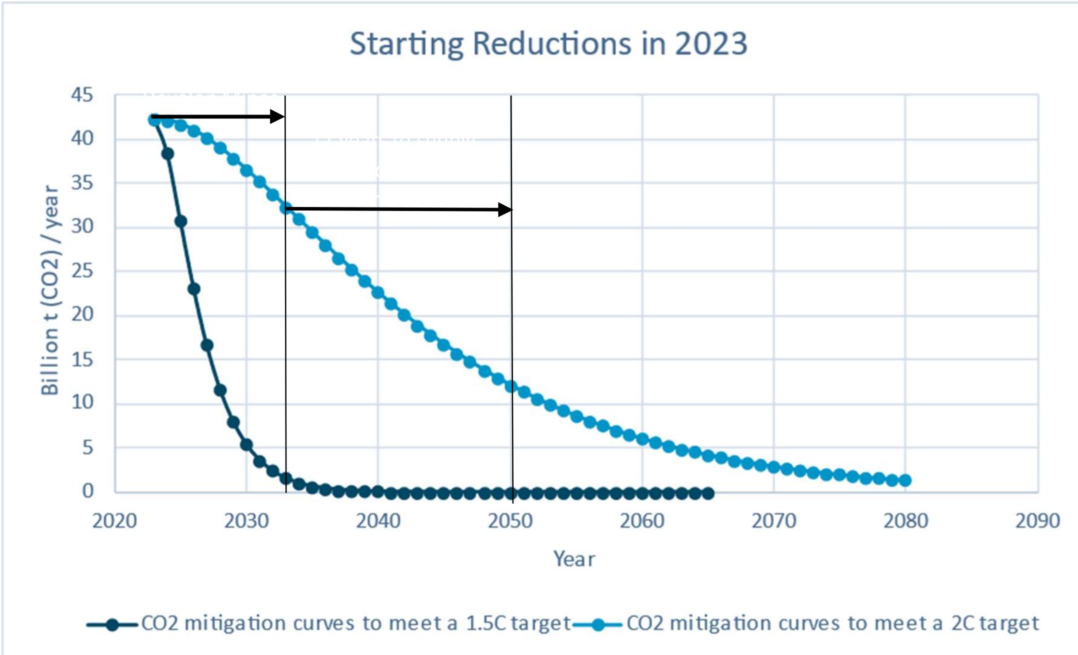

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Figure 2 - Allowable CO_2 production per year to achieve 1.5 °C and 2.0 °C targets (Our World in Data, 2019)

The Current Status - Mineral Production, Resources and Reserves

Table 2 (US Geological Survey, 2023) illustrates the current mineral production rates (kt/y), reserves (kt), and resources (kt) of the most critical minerals for decarbonisation.

As illustrated in Table 2 it becomes clear that at the current rates of production, reserves of key metals like copper and nickel may be depleted in around 40 and 30 years, respectively. However, it's important to note that new reserves and resources continue to be discovered and added, influenced significantly by the value of the commodity. Thus, the critical factor is not solely the size of the total reserve or resource but the production rate and the agility with which it can be ramped up to meet the evolving demands.

Table 2 Current metals and minerals production (kt/y), world reserves (kt) and world resource (kt)

Minerals	Current production (kt/y)	Reserve (kt)	Resource (kt)	Reserve time left (y)
Copper	22 000	890 000	2 960 000	40
Nickel	3300	100 000	200 000	30
Manganese	20 100	1 700 000	11 300 000	84
Cobalt	190	8300	16 700	43
Chromite	42 200	560 000	11 440 000	13
Molybdenum	255	12 000	8000	47
Zinc	13 000	210 000	1 690 000	16
Rare earths	300	130 000		433
Silicon	9150	Large	Large	N/A
Germanium	0.1	2.5	2.5	36
Lithium	130	26 000	63 000	200
Graphite	1300	330 000	470 000	253
Uranium	59	8070	15 647	136
Lead	4550	85 000	1 915 000	18
Vanadium	105	5382	57 618	51
Zirconium	1400	68 000		48
Platinum	0.19	70	15	368
Palladium	0.21	70	15	333

The Current Status – GHGe by Industry

Figure 3 represents the annual greenhouse gas emissions (GHG) estimated at 50 Gt CO_{2eq} in 2019 (Ritchie, et al., 2020) and surging to as high as 58 Gt CO_{2eq} by 2022 (Kharas, et al., 2022). 72% of emissions come from electricity generation. This analysis does not directly consider agriculture, as its connection with the minerals industry is not significant. Nonetheless, it's vital to consider that additional power capacity would be required if high-power systems like lab-grown meat become commercially viable, or if desalination plants are adopted widely. Hence, this paper primarily concentrates on strategies to mitigate the other 40.6 Gt CO_{2eq}.

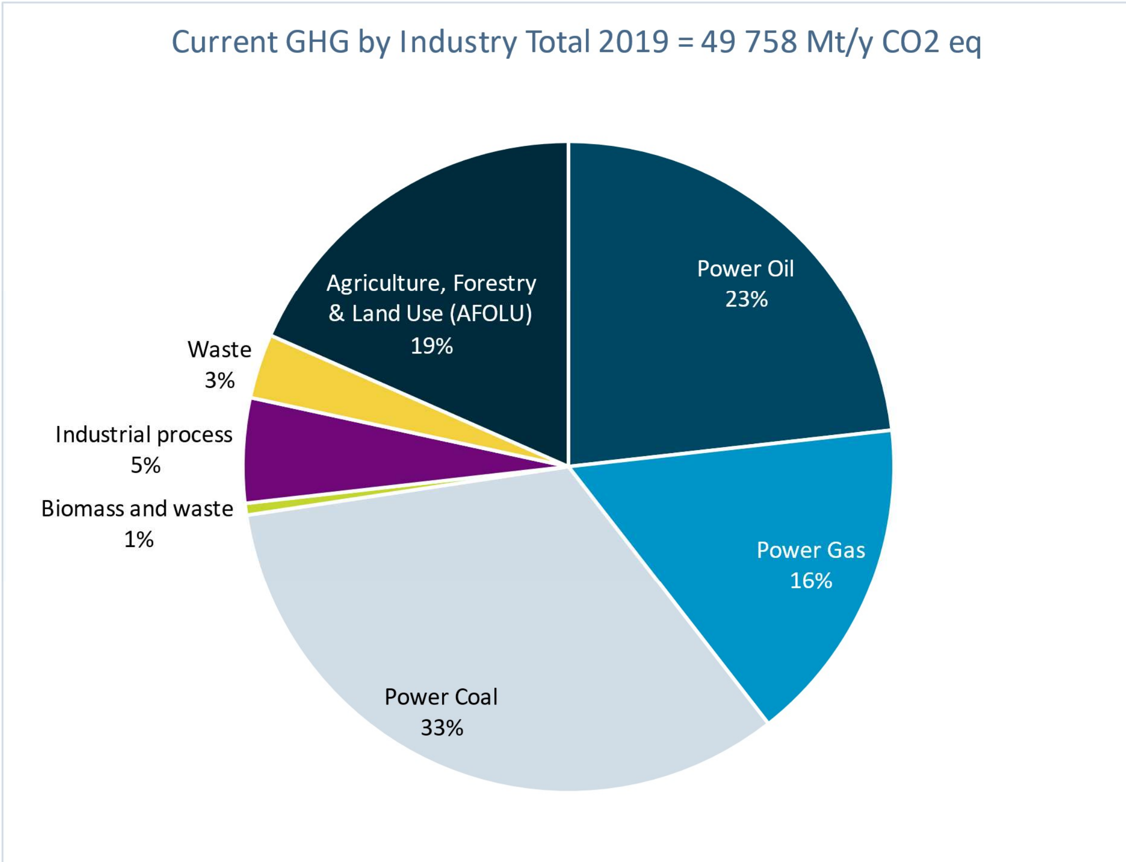

Figure 3 - Green House Gas Emissions by industry showing % make up and Mt CO_{2eq}/y produced by each industry.

The Current Status – Global Electrical Power Generation

Global electric power is predominantly generated by carbon-intensive industries. The largest step towards achieving decarbonisation would be to replace the 17 400 TWh/y of carbon-based energy. The current global breakdown of electrical power generation is shown in Figure 4.

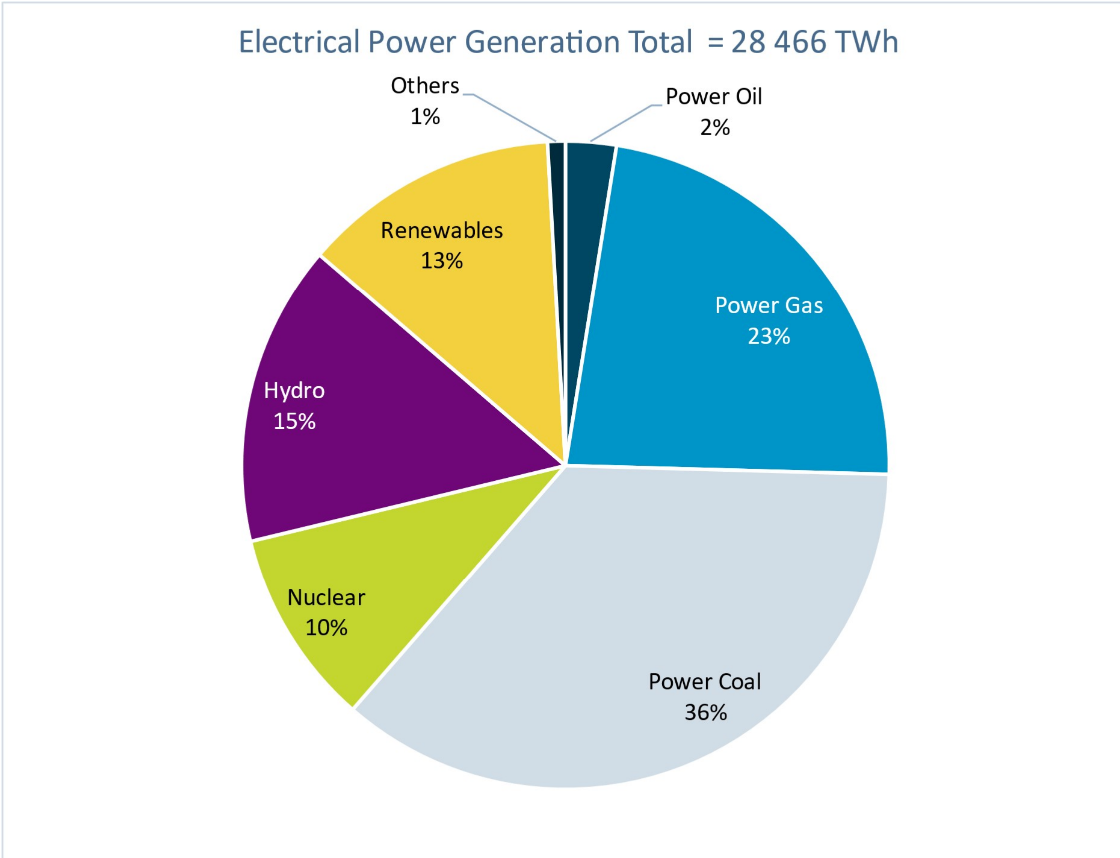

Figure 4 - Global electricity generation by source

Are There Enough Minerals and Energy Supply to Support Net Zero Targets by 2050?

Michaux (2021) completed an in-depth analysis of the total metal demand required for decarbonisation and electrification. The analysis determined that the total mineral requirements to decarbonise the global economy is dictated by:

1. The calculation of the number of transportation vehicles that must be replaced and the associated increase in grid power demand from both electric and hydrogen-powered vehicles.

2. The need to replace existing carbon-based power technologies, such as coal-burning plants.

3. The expansion of power storage systems, contingent on power storage duration due to solar and wind intermittency, and the materials that can be used.

Electric Vehicles (EVs) excel in short-range travel applications due to their high energy efficiency, lower emissions, and regenerative braking, which recovers a lot of energy in stop-and-go traffic. Electric motors perform better for short distance propulsion in passenger vehicles, grid-connected buses, light-duty vehicles, motorcycles, and bicycles. The limited range of EVs, due to current battery technology constraints, and the need for frequent recharging, make them less suited for long-distance and heavy-duty applications.

Hydrogen vehicles can either be fuel cell electric drive (FCEV) or hydrogen internal combustion engines (H_2ICE). This study assumes the use of FCEV to show the impact on PGM demand. They are more suitable for heavy transportation than EVs because of hydrogen's high energy density per unit of weight (15 kWh/kg vs 0.23 kWh/kg (Michaux, 2021)). Hydrogen functions better in applications such as Class 8 heavy commercial vehicles (HCV) trucks, long-distance rail, and maritime shipping. Hydrogen, due to its high energy density per unit of weight, can deliver the necessary power for these applications without significantly adding to the vehicle's weight. The refueling process for hydrogen vehicles, which is similar to conventional refueling, along with its long-range capabilities, make it an attractive solution for these heavy-duty applications.

Battery (200-300 Wh/kg) technology would need to continue improving at its current exponential rate until 2043 to match the current drive energy density of hydrogen (15 000 Wh/kg) or 2035 for gasoline (3100 Wh/kg). Battery density does not necessarily have to match hydrogen to be competitive in shorter ranges, but hydrogen's energy density advantage becomes more pronounced in long-haul transportation where the lower energy density of batteries significantly impacts weight and volume considerations.

How Many Electrical Vehicles Do We Require – Light Vehicles

Table 3 summarises the global electrical vehicle strain on battery production and energy systems (Michaux, 2021). It provides a stepwise estimate of the additional grid power required, resulting in an additional 6310 TWh of new power being required by the grid and an additional 642 Mt of batteries needing to be produced.

Table 3 Summation of worldwide electrical vehicle strain on battery production and energy systems (Michaux, 2021)[1]

Vehicle	kWh / vehicle (installed battery)	Million vehicles required	Efficiency (kWh/km)	Tkm travelled	TWh perfect efficiency	Efficiency [Grid to Drive] (%)[2]	TWh	Mt – Li-Ion batteries[3]
Passenger Vehicles	68[4]	695	0.19	5.4	1030	67	1530	206
Buses & Delivery Trucks	227	29	1.32	0.80	1060	67	1580	29
Commercial Vans, Light Trucks	153	601	0.31	7.9	2130	67	3180	402
Motorcycles	22[5]	62	0.09	0.16	15	67	22	6
Total	-	-	-	14.3	4230	-	6310	642

1. Based on Simon Michaux estimates – unless otherwise referenced
2. Includes drive losses and power line losses
3. 0.23 kWh/kg battery
4. (Electric Vehicle Database, 2023)
5. (Toll, 2019)

The impact of EVs on power and mineral demand can be significantly reduced through efficient use of transport. For example, converting passenger vehicles to buses would reduce the grid demand by ~1250 TWh due to higher passenger efficiency (50 passengers per vehicle vs 1.5 for passenger vehicles). Further, if internal combustion engines (ICE) vehicles were instead replaced with E-bikes, the total weight of batteries required would reduce from 206 Mt to 2.0 Mt, a substantial reduction, though this would necessitate significant social change and city design adjustments.

Transitioning to Hydrogen Fueled Vehicles – Heavy Transport

Hydrogen vehicles have some notable drawbacks when utilised as transportation systems

- most hydrogen is derived from steam methane reform (SMR), which releases CO_2
- low-carbon methods, such as electrolysis, are energy inefficient, requiring ~50 kWh/kg for separation from water and an additional 2.5 kWh/kg to compress to 700 bar for fuel cell use, plus additional power for transportation bringing to total to nearly 58 kWh/kg. (Michaux, 2021)
- dependence on several rare earth metals and platinum (~0.26 g/kW (Heraeus, n.d.) based on installed motor size)
- hydrogen's atomic size poses significant challenges in terms of transportation, as it can cause embrittlement of pipelines and tanks not specially designed for it. This is due to hydrogen's ability to seep between molecules, weakening their bonds. Repurposing existing natural gas pipelines for hydrogen transport is therefore not straightforward.

Table 4 provides an estimate of the total power required to produce 200 Mt/y of hydrogen to power long haul industries resulting in an additional power load of 11 600 TWh.

Table 4 Total power and hydrogen needed per year to transition long distance vehicles from diesel/fossil fuel to hydrogen[1]

Vehicle / Industry	k Vehicles	Billion tonne-kilometers (Tkm)	TWh/Billlion units	TWh[4]	Mt – H_2
Class 8 HCV Trucks	29 000	-	0.26	7500	130
Rail Transport[2]	110	9 400	0.11	1070	18
Maritime Shipping[3]	120	72 100	0.041	2980	52
Total Production	29 230	81 500	-	11 600	200

1. Based on Simon Michaux estimates - GTK unless otherwise stated
2. Includes all kinds of rail (freight and passenger)
3. Includes all maritime shipping (small to very large vessels)
4. Includes inefficiency of creating H_2 by electrolysis and compression into tanks – total power required by H_2 production (58 kWh/kg) including 10% losses

Table 5 outlines the total tonnes of PGMs needed in long-haul vehicles to catalyse the hydrogen reaction in fuel cells. Both tables are reproductions of Simon Michaux's work (Michaux, 2021). Class 8 HCV trucks require the most hydrogen power and metal production followed by maritime shipping then rail transport.

Table 5 Tonnes of PGMs required[1]

Vehicle / Industry	kWh / Fuel Cell[2]	Mt – H_2	t PGM[3,4]
Class 8 HCV Trucks	370	130	2800
Rail Transport[2]	2400	18	70
Maritime Shipping[3]	40 500	52	1230
Total Production	-	200	4100

1. Based on Simon Michaux estimates – GTK unless otherwise stated
2. Platinum in fuel cell driven by power required by engine
3. Small amount compared to vehicles of platinum, palladium and rare earth metals are required to produce the hydrogen needed
4. Platinum can be replaced with palladium in fuel cells

If all light vehicles transitioned to hydrogen, total PGM demand to build the first generation of vehicles would increase from 4.1 kt to 26 kt, and addition grid power demand would also rise due to hydrogens production inefficiency from electrolysis (green hydrogen) from 6 300 TWh to 15 400 TWh excluding heavy transportation. However, some of the metal demand could be offset by recycling catalytic converters in ICE vehicles, which typically contain 5-14 g of platinum and palladium per vehicle. This could replace 9-19 kt (Waste Advantage, 2021) of the required metal.

How Much Power Generation is Required?

The overall power demand to decarbonise the economy is estimated in Figure 5. This figure shows the cumulative increase in global energy demand, indicating a total grid power of 48 460 TWh. However, this need is partially met by existing renewable and nuclear energy, leaving an additional 37 730 TWh of power that needs to be generated. Notably, hydrogen vehicles require nearly twice as much power as electric ones due to the substantial energy expenditure necessary for the production of green hydrogen via electrolysis. The replacement of non-renewable power is a sizable task, whereas industrial processes demand relatively less power. The current annual power requirements stand at approximately 2 800 TWh (BP, 2022) of which renewables and nuclear energy contribute 10 700 TWh.

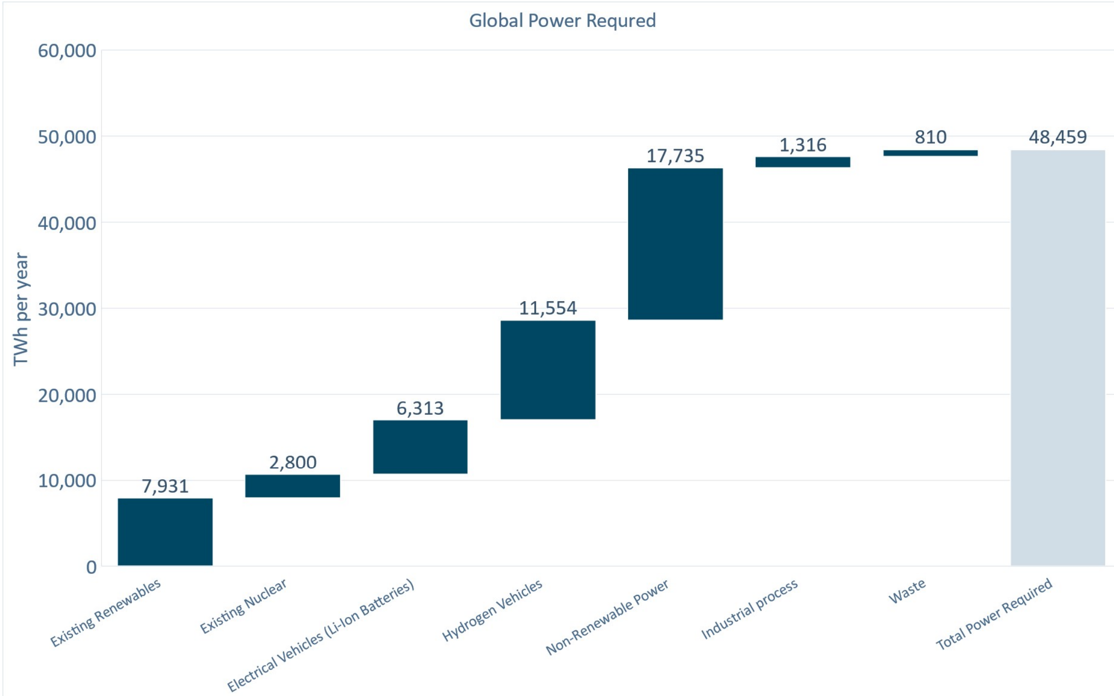

Figure 5 - Total power required to replace carbon emitting sources.

The balance of energy between solar, wind, hydroelectric (hydro), and nuclear sources impacts the total mineral demand. Solar and wind energy generation lead to the highest mineral demands, followed by nuclear, and then hydro. However, there are not substantial differences in mineral demand between these power systems. Key minerals required for renewables include zinc, copper, and silicon, while nuclear power primarily uses copper, chromium, and nickel. Hydro, despite having the lowest metal demand mainly for copper, cannot be solely relied upon due to geographical constraints and significant environmental impact.

Importantly, the suitability of these renewable power sources is highly region-specific. For instance, the efficacy of solar power significantly depends on the region's sunlight exposure, wind energy depends on wind patterns, and hydro power depends on the availability of water bodies and mountains. Conversely, non-renewable power sources are less region-specific but contribute considerably to greenhouse gas emissions. Therefore, a thoughtful combination of these resources, based on regional specifics, will be crucial in achieving the decarbonisation targets. The currently targeted energy split to meet global energy demand is presented in Figure 6.

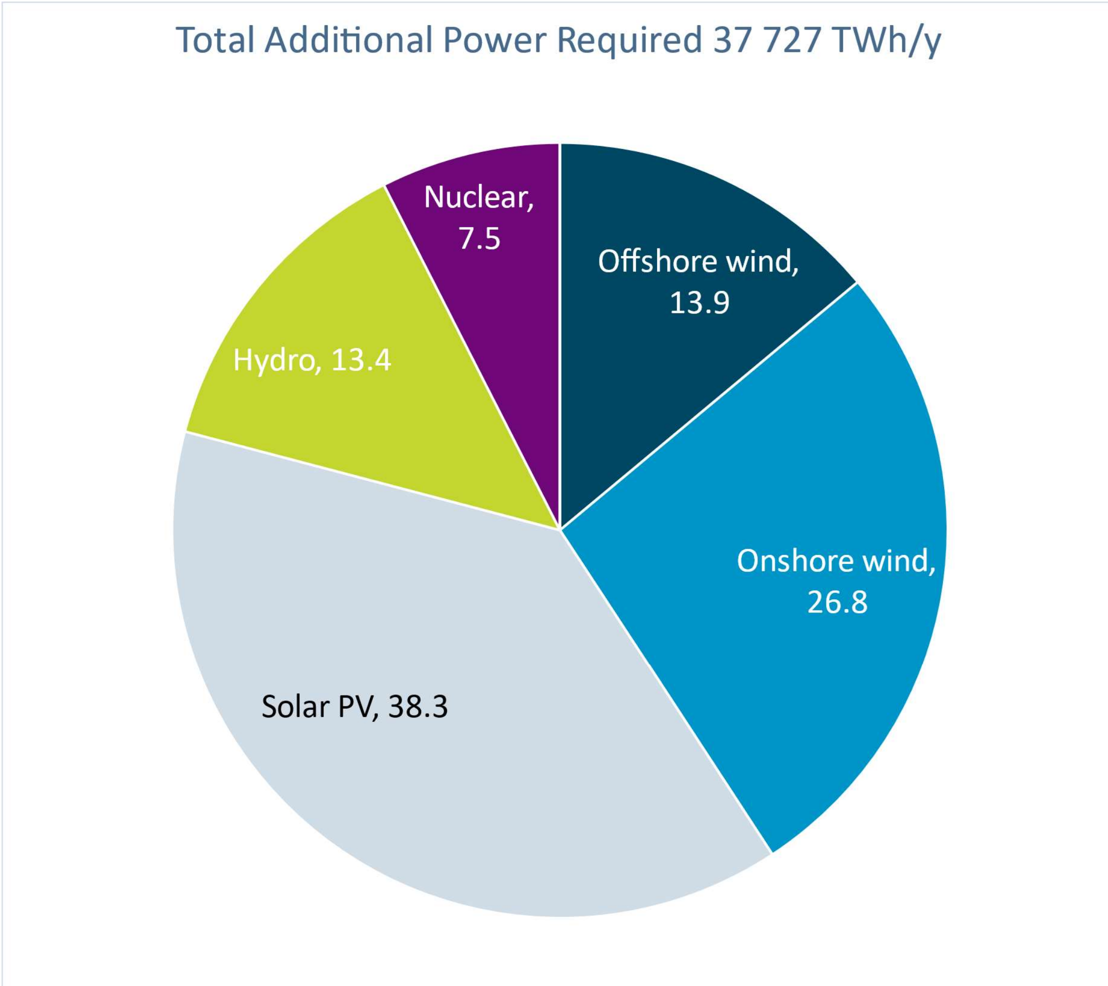

Figure 6 - Breakdown of New Power Requirements (Michaux, 2021)

How can we store energy?

To adequately install renewable energies like solar and wind a certain amount of surge capacity is required to compensate for the intermittency of their power output. Currently that fluctuation is handled by natural gas facilities. Storing the energy in some form of battery system will be required to minimise the use of fossil fuels.

The duration of battery storage required to support renewable energy is a contentious subject, with estimates varying significantly. The lowest estimate is 2 days, while the highest is up to three months (or 84 days (Michaux, 2021)). These estimates largely depend on the location of the power plant and the environmental factors that effect it.

The number of battery facilities were estimated using storage capacities of two, 28, and 84 days. Assuming that only the highest capacity battery facilities were being installed, which is equivalent to Moss Landing, which can store 2 330 MWh. With 85% storage efficiency considered, the intermittent renewable demand is 35 kTWh/y, which is then divided by the total storage capacity time. The results for NMC [Nickel Manganese Cobalt], lead, and salt batteries are shown in Table 6. Other battery technologies are possible such as pumped storage and hydrogen but are currently impractical as a global solution due to the geographic requirement of pumped storage and the inefficiency of green hydrogen production.

Table 6 Battery metal weight comparison

Capacity (days)	TWh	Number of facilities	NMC battery 270 Wh/kg (kt battery)[1]	Lead battery 50 Wh/kg (kt battery)[1]	Salt battery 160 Wh/kg (kt battery)[2]
2	193	82 955	715 873	3 865 717	1 208 036
28	2706	1 161 374	10 022 228	54 120 033	16 912 510
84	8118	3 484 122	30 066 685	162 360 100	50 737 531

1. (May, et al., 2018)
2. (Wood Mackenzie, 2023)

Although NMC batteries have the higher energy density, the battery storage facility weight doesn't hinder facility development, unlike electric cars which operate more efficiently with higher density batteries as they need to carry the weight of the car and the battery. Therefore, NMC batteries are the worst choice in this case, as they are most reliant on critical minerals. Lead batteries, predominantly dependent on lead, would exhaust most of the world lead reserves to build enough facilities (Table 2). So, for storage battery systems, salt batteries, primarily relying on sodium and aluminium, are the preferred options due to the abundance of these materials. However, even with just two days of capacity 82 950 battery facilities would have to be built which might prove prohibitive regardless of mineral requirements. Many facilities are still being built with NMC batteries instead of salt, such as the Oneida Energy Storage plant in Canada (Leggate, 2023) and the Liddell Battery plant in Australia, (Parkinson, 2022).

Other technologies will likely be necessary instead of batteries, for example natural gas plants with carbon capture, or small nuclear reactors that can quickly ramp up and down. Improved energy conversion for hydrogen storage will also be needed. Pump storage systems could be adopted in some areas but not all.

Establishing the Base case minerals required to achieve NetZero targets

Whether there is enough metal to transition to a renewable economy depends largely on the storage capacity required for renewables. Based on current reserves and resources, there is sufficient metal to decarbonise the economy assuming only two days of NMC storage is required as shown in Table 7. However, time is a limiting factor. Based on practical timelines, it is unlikely that the mining industry can provide this much material to limit global warming to 1.5°C. The results in Table 7 provide the "base case" scenario and the world current metal demand trajectory.

Table 7 shows the contributions of each sector to the total metal demand. Electrical batteries and NMC battery storage account for nearly 90% of all the decarbonising mineral demands. This would require significant increases in mining production for several critical minerals. Existing cobalt resources and reserves would be expended, copper production would need to increase by 80%, equivalent to 18 more Escondida Mines (Escondida represents ~4.5% of world copper production) or 180 Highland Valley Copper Mines. To fuel the battery demand lithium and graphite production need to ramp up significantly. Note that uranium is shown in kt/y as it is continuously expended while the other minerals are shown as totals to build the necessary systems.

Table 7 Base Case Metal Demand

Metals	Electrical vehicles	Hydrogen vehicles	Power plants	NMC battery storage 2 day capacity 193 TWh	Additional required mineral total	Current production	Increased production cases		Reserve + Resource	
	kt	kt	kt	kt	kt	kt/y	1.5 °C (% Increase)	2.0 °C (% Increase)	kt	% required
Copper	115 099	-	42 535	144 022	301 656	22 000	1371%	81%	3 850 000	8%
Nickel	86 324	-	2208	28 399	116 932	3300	3543%	208%	300 000	39%
Manganese	53 006	-	3913	-	56 919	20 100	283%	17%	13 000 000	0%
Cobalt	28 775	-	-	6878	35 653	190	18 765%	1104%	25 000	143%
Chromite ore	0	-	3163	-	3 163	42 200	7%	0%	12 000 000	0%
Zinc	216	-	27 325	-	27 542	13 000	212%	12%	1 900 000	1%
Rare earths	1082	-	403	-	1484	405	366%	22%	-	-
Silicon	0	-	26 528	-	26 528	9150	290%	17%	-	-
Lithium	19 255	-	-	30 451	49 706	130	38 235%	2249%	89 000	56%
Graphite	143 441	-	-	290 657	434 098	1300	33 392%	1964%	800 000	54%
Uranium (kt/y)	0	-	157	-	157	59	265%	16%	23 718	1%
Lead	0	-	-	-	0	4550	0%	0%	2 000 000	0%
Others	671	-	223	-	894	1655	54%	3%	88 000	1%
PGM	0	4.1	-	-	4	0.4	1009%	59%	170	2%
Total	447 870	4.1	106 455	500 407	1 054 736	118 040	-	-	34 075 888	-
Total %	42.5%	0.0%	10.1%	47.4%	-	-	-	-	-	-

Canada vs Australia Mineral Production

Table 8 shows the comparison of Canada and Australia's mineral reserves to meet total decarbonisation demand. Of the over 300 000 kt of copper that will be needed, Canada's reserves (7600 kt) only represent 2.7% while Australia's large copper deposits could provide nearly 35% of the copper required. Canadian deposits represent 12.5 y of production while Australia's represent 23.8 y. Canadian uranium however is very high grade and low cost making it more competitive in the near term (IAEA; NEA, 2020).

Table 8 Canadian and Australian Mineral Contribution to Decarbonisation

Metals	Minerals for decarbonisation (US Geological Survey, 2023) (IAEA; NEA, 2020)		
	Global requirement (kt)	Canada (% reserves)	Australia (% reserves)
Copper	249 716	3.0	38.8
Nickel	106 690	2.1	19.7
Manganese	56 919	-	474
Cobalt	33 172	0.7	4.5
Chromite ore	3 163	-	-
Zinc	27 542	6.5	4 234
Rare earths	1 484	55.9	283
Silicon	26 528	-	-
Lithium	38 724	2.4	16.0
Graphite	329 276	-	-
Uranium (kt/y)	157	1 254	2 384
Lead	0	-	-
Others	894	-	-
PGM	4.1	-	-

Although there are sufficient reserves for all the critical minerals, the significant time to develop each mine, and the number of new mines required to meet the metal demand is daunting. So, reducing the total demand should be prioritised, along with increasing mining production and exploration, particularly in any country that wants to be a larger player in the decarbonisation economy, such as Canada or Australia.

For example, Canada's energy consumption comes from three primary sources, natural gas, refined petroleum products (RPPs) and natural gas liquids (NGLs), which together account for approximately 60% of Canada's energy demand share (Canada Energy Regulator, 2021). Canada's large reserves of natural gas and oil, 10% of world's reserves, contribute to the heavy focus on fossil fuel consumption and storage but also provides opportunity to transition to a net zero economy (IEA, 2015). Coal remains below 5% of the energy consumption with hydro-electric, nuclear and other renewable sources making up the remainder of the balance. Achieving Net Zero CO_2 emissions in Canada would require a hydrogen and nuclear transition in the short term. Canada's large uranium deposits would act as a steady supply of energy with steam methane reforming (SMR) with carbon capture and storage (CCS) responding to disturbances in energy demand. This stable base load of power would allow the development of additional hydro and other renewable energy sources such as 'green hydrogen' as well as adequate storage facilities in the form of hydro pumping and hydrogen storage.

Australia's economy has an even larger reliance on fossil fuel energy than Canada. Nearly 40% of Australia's energy consumption is from coal and 56% is from oil and gas (Geoscience Australia, 2023). The large coal deposits, 14% of total world reserves, and accessibility to oil and gas imports are major contributors to this composition of energy supply (Worldometer, 2023). A Net Zero CO_2 energy transition in Australia would require utilisation of its vast uranium supply and development of nuclear energy generation while phasing out its reliance on coal. Otherwise, Australia should target other renewable opportunities such as hydro, wind and solar. Storage of such energy would require significant investment in salt battery storage or hydro-pumping, which Australia has numerous low-cost potential sites (Blakers, et al., 2020).

OPTIMISATION CASES

There are opportunities to reduce mineral demand from the base case to make achieving Net Zero CO_2 by 2050 a more feasible goal. To achieve such a feat, the projected demand for battery minerals must be reduced as they represent 90% of forecast decarbonisation mineral demand. Meanwhile, power plants represent the other 10% and hydrogen powered vehicles will strain PGM supply. As many authors have shown before, meeting power plant demand is feasible through mostly renewables when only considering the requirements of the power plants themselves (Wang, et al., 2023).

1. The battery requirement for electrical vehicles, which represent 42.5% of projected metal demand, can be reduced by:
    a. Improving battery energy density
    b. Reducing the number of vehicles being produced
    c. Producing different kinds of vehicles
2. Hydrogen vehicles require a small but significant metal group (PGMs). Replacing electrical with hydrogen vehicles would significantly reduce projected demand for all other critical minerals while substantially increasing demand on PGMs.
3. It is argued above that battery facilities are unfeasible due to sheer number and minerals required. Therefore reducing the share of energy produced from renewables in favour of nuclear or hydro-electric will reduce the projected battery demand.
    a. Producing salt-based storage facilities instead of NMC storage facilities would reduce forecast total critical metal demand by 47.4%

To optimise the analysis, several constraints were developed:

1) Nuclear power must have at least 40 years of operation
2) Hydropower depends on location and cannot exceed 15% of global power demand.
3) Battery capacity was assumed to be fulfilled by sodium-based systems.

Actions to Reduce Metal Demand

Four main actions were investigated to reduce metal demand and the results of each action are shown cumulatively in Table 9. It is assumed that NMC batteries are not pursued as a long-term strategy and are instead replaced by salt batteries or other technologies.

Action 1 – Maximise Hydroelectric and Nuclear Power

Increasing the share of nuclear and hydroelectric (hydro) power reduces the total mineral use for power plants by 6%. This is reduced significantly further if NMC batteries are used for renewable storage. The main advantage of focusing on nuclear and hydro power is the reduced requirement for battery storage and a steadier energy flow to the grid.

Action 2 – Minimise electric cars

There are many ways to reduce the number of electric vehicles used. One potential solution is to instead produce electric bikes (E-bikes), as they require 100x less metal to produce compared with EVs, while providing a similar outcome. As EVs can be less effective for long distance travel, E-bikes are a simpler and cheaper alternative that significantly reduces battery metal for a similar outcome, but with much shorter manufacturing times. Most EV owners also possess an internal combustion vehicle to compensate for these shortcomings (Davis, 2021). This redundancy poses significant problems, not only due to the metal demand required to manufacture an EV but also because the CO_2 emissions produced during the construction of an EV are higher than those generated by ICE vehicles (IEA, 2022b).

This outcome would require a rethinking of most North American style cities to be built more densely and reduce city sprawl to reduce car use overall. For rapid decarbonisation, adoption of E-bikes would be the fastest solution to reduce mineral demand. Shifting from personal EV vehicles to E-bikes reduces the total metal requirement by 25.6%.

Action 3 – Replace electric vehicles with hydrogen powered vehicles

Replacing the remaining electric vehicles such as buses and light-duty trucks with hydrogen powered vehicles has the greatest impact on reducing mineral demand, with a decrease of 50.3%. But it significantly increases the demand on PGMs and electrical power. Hydrogen powered vehicles could replace personal EVs but, like EVs, they also incur long lead times and high production costs. Further, hydrogen power requires a significant increase in power supply to produce green hydrogen on a large scale. Since there is not a current substantial hydrogen economy there would be an even higher lead time to development. However still from a mineral reduction perspective, pursing a hydrogen-based economy rather than EVs produces the best outcomes for reducing overall mineral demand.

Action 4 – Utilise blue hydrogen

Hydrogen can be produced by exploiting natural gas and carbon capture technology. Hydrogen can be produced through numerous ways incurring different CO_2 emissions and different costs, including: (IRENA, 2020) (S&P Global, 2023)

1. grey hydrogen is produced by steam methane reform (SMR) or coal gasification and has the highest carbon footprint (~1.3 $US/kg hydrogen)

2. blue hydrogen is produced like grey but includes carbon capture and storage (CCS), reducing atmospheric CO2 emissions to 5-15% those of grey hydrogen (~2.0 $US/kg hydrogen)

3. turquoise hydrogen involves the pyrolysis of natural gas, producing solid carbon black that is easier to store than CO_2(~6.0 $US/kg hydrogen)

4. green hydrogen is produced through renewable means, like electrolysis, biogas, and anaerobic digestion. (~14 $US/kg hydrogen)

Steam methane reform without carbon capture requires 97% less power input than SMR with CCS (blue) and electrolysis (green). (ZAPANTIS, 2021)

Even with carbon capture there are environmental concerns with continuing to use natural gas due to fugitive gas emissions, energy reductions, and because SMR-CCS methodologies don't fully eliminate total emissions. Some experts (Howarth & Jacobson, 2021) argue against blue hydrogen and advocate for the immediate transition to green hydrogen, which minimises CO_2 emissions. However, green hydrogen requires much more electrical power and therefore more minerals, while natural gas conversion technologies are already proven and widely available. Therefore, from a mineral minimisation perspective a mixture of blue and green hydrogen would be the best solution in the short term.

Longer term solutions should apply increasing carbon taxes on blue, and turquoise hydrogen to help green hydrogen be more competitive and encourage better carbon capture techniques, though acknowledging that green hydrogen will increase power and mineral demand, resulting in other environmental impacts and higher non-CO_2 emissions.

Therefore Action 4 to utilise blue hydrogen, while not perfectly carbon neutral, would further reduce projected total mineral requirements by an additional 14.0%, which results in a total reduction in the projected mineral demand, due to a decreased power demand and a near total reduction in battery demand for vehicles.

Actions 1 to 4

The combined implementation of actions 1-4 provides the best outcome in terms of minimising mineral production but not necessarily for reducing CO_2 when action 4 (blue hydrogen) is included. There is a substantial power increase when replacing electric vehicles with green hydrogen (10 000 TWh/y), while using blue and turquoise hydrogen production methods reduces the power consumption from the base case by 17 000 TWh/y and 27 000 TWh/y from action 3.

Table 9 Mineral Minimisation Cases – (Salt Battery Storage)

Metals	Base case	Action 1: minimising power plant minerals	Action 2: E-bikes	Action 3: replace electric vehicles with H_2	Action 4: blue / turquoise - H_2 production
Copper	157 634	143 452	107 011	39 242	7 911
Nickel	88 533	89 646	62 316	3 777	2 469
Manganese	56 919	55 575	38 793	3 568	692
Cobalt	28 775	28 775	19 665	0	0
Chromite ore	3163	5269	5269	5890	4104
Zinc	27 542	16 562	16 494	23 418	3069
Rare earths	1 484	1 323	980	345	45
Silicon	26 528	16 014	16 014	22 872	3141
Lithium	19 255	19 255	13 159	0	0
Graphite	143 441	143 441	98 027	0	0
Uranium	157	474	474	474	474
Lead	0	0	0	0	0
Others	894	804	592	191	25
PGM	4.1	4.1	4.1	26	26
Total	**554 329**	**520 595**	**378 798**	**99 803**	**21 956**
% Change	**-**	**6.1%**	**25.6%**	**50.3%**	**14.0%**
% Cumulative Change	**-**	**6.1%**	**31.7%**	**82.0%**	**96.0%**
TWh/y	**37 727**	**37 727**	**36 219**	**46 814**	**20 669**
kt metal / TWh	**14.7**	**13.8**	**10.5**	**2.1**	**1.1**

Table 9 shows the mineral minimisation cases, illustrating that minimising power plant minerals, substituting E-bikes for cars, replacing electric vehicles with H_2, and leveraging blue/turquoise H_2 production dramatically decrease the overall mineral requirements. In the optimised scenario, nuclear power would produce nearly 70% of the power, with hydro at 15% and renewables accounting for the rest.

POLICY

The outcome of the present analysis, as well as its potential practical application, will inevitably be shaped by policy decisions. Even though the optimisation models may appear straightforward, their actual implementation poses significant challenges. This section elaborates on several such challenges and suggests potential solutions, emphasising the importance of expanding the mineral extraction to ensure the successful deployment of low-carbon technologies.

The Massachusetts Institute of Technology (MIT) has developed a software tool referred to as "EN-ROADS" (MIT Management Sustainability Initiative, 2023) that allows the simulation of various policy decisions affect on climate change. This tool provides an estimate of their effectiveness if such policies were enacted in a specific year (2023 for this example). If no action is taken, climate change is projected to increase global temperatures by 3.3°C by the year 2100. The minimum temperature increase allowed by these models is 1.2°C by 2100, which represents the warming that has already occurred.

The implementation of a carbon tax emerges as the single most effective solution for reducing the projected increase in global temperatures, with a potential reduction of 0.8°C at a rate of \$250/t-CO_2. This substantial impact is primarily attributed to the straightforward way the tax affects all sectors of industry, creating incentives to reduce carbon emissions by the most efficient means available (MIT, 2022). Additional measures such as further taxing carbon-based power sources and subsidising renewable energy and nuclear power could result in a combined decrease of 0.7°C compared with the "do nothing" case. Enhancing efficiency in buildings and industry, as well as further electrification, could contribute to a further reduction of 0.5°C. Reductions in methane production and other heat-trapping gases could further lower temperatures by 0.4°C, which is a significant consideration if the use of blue and turquoise hydrogen is pursued.

A critical factor to consider is the trade-off between cost, the reduction of CO_2 emissions and mineral removal. For instance, a low-cost electric car is priced around 40 000 CAD, while a good electric bike costs approximately 3500 CAD. In circumstances where an electric bike can practically replace an electric car—and by extension, an internal combustion engine (ICE) car—it could do so at a tenth of the cost and with a hundredfold reduction in resource use, resulting in a larger CO_2 reduction per unit. Therefore, it can be much more effective from a mineral and CO_2 perspective to occasionally use an ICE vehicle rather than produce a new EV, given that shorter distances are better suited to electric bikes while longer journeys are more efficiently undertaken by hydrogen vehicles, leaving little justification for personal electric vehicles.

Several mineral reducing policies and comments are provided below:

Adoption of nuclear energy and expansion of hydroelectric

- adopting nuclear energy has been a struggle due to significant social resistance, and permitting for nuclear energy along with waste deposition has been challenging
- Canada and Australia could be leaders in the nuclear industry by exploiting their uranium resources. Canada has the highest-grade deposits worldwide in the Athabasca Basin. Australia has lower grade deposit but twice the reserves of Canada.
- many of the cost overrun and installation time concerns could be mitigated by collaborating with South Korean and Japanese commissioning teams that consistently install plants in three to five years (Jhoo, 2016).
- expand hydroelectric utilisation where applicable.

Minimise car use, and encourage public transport, genuine ride sharing, bicycle use and E-bike use.

- various measures that can encourage bike ridership include wide cycle-safe lanes, clear signage, segregation from motor vehicles where possible, use of high-quality material for cycle lanes, and so on. (Hull & O'Holleran, 2014)
- cities in Canada and Australia were designed with cars in mind, making it difficult to choose other modes of transportation. Developing public infrastructure that competes with cars in regard to safety and speed could substantially minimise mineral demand
- the decision to drive a car instead of transit or biking is largely due to the lack of good infrastructure, driving is done by default because it's fastest, providing safer and faster options than driving induces demand for other transportation systems. (Buehler, et al., 2016)

Action 3: Hydrogen vehicles for long distances

- hydrogen vehicles are still in their early stages, and a wide hydrogen distribution system does not yet exist, expanding production is very important to reducing metal demand.

- incentivising companies to build blue and turquoise hydrogen facilities and working with car manufacturers to create low-cost hydrogen powered vehicles can encourage their use.

Action 4: Blue and turquoise hydrogen economies

- incentivising the production of blue and turquoise hydrogen would speed up the adoption of hydrogen as a gasoline replacement more effectively than electric vehicles or waiting for green hydrogen to meet scale demand.

CONCLUSIONS AND RECOMMENDED PATH FORWARD

The path towards a low-carbon economy is a formidable challenge, made even more complex by the anticipated resource constraints. The data clearly indicates that batteries, particularly for electrical vehicles and renewable storage, are the primary limiting factors to decarbonisation due to their significant impact on global mineral demand.

Reducing CO_2 emissions from energy production has the most substantial effect on global temperatures. Enacting robust policies such as applying high taxes and subsidies in this category could potentially result in a 1.5°C reduction from the predicted levels without intervention. However, it's worth noting that power generation only accounts for 10% of the total minerals required for decarbonisation.

Conversely, the reduction of battery use in electric vehicles and renewable energy storage could mitigate up to 90% of the mineral demand associated with decarbonisation. By concentrating on non-battery-intensive solutions, such as nuclear and hydroelectric power, we can notably diminish the demand for battery storage. Incorporating salt-based batteries further reduces the mineral requirements of storage systems. Likewise, a shift towards hydrogen-powered vehicles for long-distance transportation and E-bikes for short commutes can result in the lowest possible metal requirement for a decarbonised economy.

To implement the current base case globally would require the following:

- 37 700 TWh of power added to the grid (a 133% increase)
- 9000 additional power plants of the largest size, necessitating 106 Mt of critical minerals
- replacement of small duty vehicles with electric vehicles, requiring 448 Mt of critical minerals
- replacement of transportation vehicles with hydrogen-powered vehicles, necessitating 4.1 Mt of PGMs and 200 Mt/y of hydrogen
- substantial increases in critical mining development over the next decade to provide enough metals by 2050
- 82 000 large-scale battery facilities, based on the two-day storage scenario, installed by 2050

Despite all these measures, limiting warming to 1.5°C by 2035 seems unachievable and even keeping it within 2.0°C by 2050 is highly challenging.

While this base case scenario poses significant hurdles, the path towards carbon reduction will greatly depend on the strategies chosen. This analysis highlights the critical need to reduce mineral demand as a primary strategy for addressing these challenges.

Encouragingly, transitioning to electric bikes instead of electric cars would result in a 25% reduction in global metal demand. Further, by prioritising nuclear and hydroelectric power, battery demand in renewables can be decreased substantially. Meanwhile, drastically expanding hydrogen capacity can result in over a 50% reduction in mineral demand, given its reliance on PGMs.

Canada and Australia are well-positioned to play a leading role in this low-carbon transition. Key strategic actions should include:

- expanding mining operations and exploration for critical metals such as copper, zinc, nickel, uranium, and PGMs
- developing more nuclear projects to replace existing coal and natural gas power plants, while exploiting vast uranium resources
- establishing a comprehensive carbon taxing structure to incentivise blue and turquoise hydrogen production and encourage a shift towards green hydrogen production through carbon taxes
- expanding natural gas pipeline network in place like Alberta and British Columbia to facilitate the rapid scale-up of hydrogen production capacity
- collaborating with manufacturers of hydrogen-powered vehicles to stimulate production and make hydrogen vehicles competitive alternatives to ICE vehicles.

These steps, although not exhaustive, are critical starting points for this complex and nuanced transition. Achieving a sustainable, low-carbon economy will necessitate ongoing innovation, policy adaptation, and international cooperation. Yet, with strategic planning and investment, Canada and Australia have the potential to emerge as leaders in the global shift towards sustainable energy and transportation systems.

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